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Increasing material efficiencies of buildings to address the global sand crisis

Xiaoyang Zhong [1✉], Sebastiaan Deetman[1,2], Arnold Tukker[1,3] and Paul Behrens [1]

There is a rapidly unfolding sand supply crisis in meeting growing material needs for infrastructure. We find a ~45% increase in global building sand use from 2020 to 2060 under a middle-of-the-road baseline scenario, with a 300% increase across low-and-lower-middle-income regions and a slight decrease in higher-income regions. Half of this demand may be avoidable using several material efficiency strategies in concert. International cooperation is essential for addressing vulnerabilities and inequalities.

Buildings provide the basic human needs for shelter and social infrastructure and form the foundations of societies. The construction of buildings is also highly material-intensive and consumes a large amount of metallic (for example, steel and copper) and non-metallic minerals (mainly concrete, brick and glass)[1]. Previous studies have investigated the environmental impacts of building material production, along with potential mitigation strategies[2–4]. The scarcity of these materials has also seen recent attention[5] and prominent commentaries[6–8] have pointed to severe global sand crises impacting regions as diverse as Cambodia, California, the Middle East and China. Sand overexploitation has commonly driven ecosystem destruction/collapse (for example, shoreline erosion, biodiversity and food loss, disaster resilience degradation) and is set to intensify as building demands increase.

The use of sand and gravel has seen the fastest increase in use across all solid materials used by humans and now represents the largest share of material use (~68–85% by mass), surpassing fossil fuels and biomass[9]. Sand is used mostly for making concrete or glass (with concrete comprising over 95% of this use in the building sector) and requires chloride-free supplies (to prevent corrosion of other building materials) along with specific physical properties in terms of both size and shape. For example, desert sand is too smooth to be used as a binding agent for concrete and sea sand is too high in chloride levels for most construction purposes[10]. Most construction sand is extracted from rivers, lakes and shorelines. Sand in these areas has long been a common pool resource, open to everyone largely because monitoring and restricting access to sand is difficult and costly[6]. In a rapidly growing market this has led to overexploitation and degradation. Even when regulated, illegal sand mining and trade has been reported in ~70 countries, often involving highly organized gangs or 'mafias' operating with the complicity of regulators[11]. The livelihoods of an estimated 3 billion people living along rivers are remarkably threatened by long-term, unsustainable sand exploitation, along with deep impacts on ecology and land availability[7].

The coming decades are expected to see rapid growth in global building stock driven by population increases, urbanization and economic development leading to higher living space requirements per inhabitant. However, for the sake of environment conservation, natural sand mining is likely to see increasingly strict regulation or even be banned in many areas[12]. To meet the growing material demand for building construction and avoid environmental deterioration due to excessive sand mining, the UN Environment Program has called for action to reduce building sand use through material efficiency strategies[12]. These aim to avoid over-building and over-design (overusing sand-based materials such as concrete), increase recycled materials and increase the provision of alternative materials to natural sand[12]. However, we have a limited understanding of how sand demand evolves with building stock dynamics across the globe and where the reduction potentials of important material efficiency interventions may lie.

We develop a global dynamic model to investigate the amount of sand used in concrete and glass in residential and commercial buildings (representing nearly half of global concrete-related sand or one third of global total sand use; Supplementary Information Section 4.1) across 26 world regions by 2060. Sand used in non-building constructions (for example, roads) and non-concrete/glass materials (for example, mortar) is not considered. We evaluate this sand demand in a middle-of-the-road scenario that expects moderate population growth, economic and technological development and contains no new policies towards sustainable development[13] (consistent with the second Shared Socioeconomic Pathway (SSP2); Methods).

We show that, in this baseline scenario, annual global building sand demand sees a continuous increase from 3.2 Gt yr⁻¹ in 2020 to 4.5 Gt yr⁻¹ in 2060, seeing about 45% growth (Supplementary Information Section 4.2 provides a comparison against the literature). Over half of the cumulative sand demand is seen in upper-middle-income regions, led by the China region, Middle East and Southeastern Asia (Fig. 1a). However, these upper-middle-income regions see a decline in terms of both absolute and relative sense, from 1.9 Gt yr⁻¹ (60%) in 2020 to 1.8 Gt yr⁻¹ (40%) by 2060, mainly due to an overall population decline and stock saturation. High-income regions see similar declines. These trends are set against the rapid growth of the lower-middle-income regions, where annual demand more than triples from 0.7 Gt yr⁻¹ (22%) to 2.2 Gt yr⁻¹ (48%). The largest increase is seen in Western and Eastern Africa, where over 500% of current building sand demand is expected by 2060, followed by Rest of Southern Africa (419%), India (294%) and Rest of South Asia (269%) (Fig. 1b).

We explore how building sand use might be reduced by implementing six widely suggested strategies, including a relative reduction in floor area by (1) more intensive use, (2) building lifetime extension, (3) reductions in concrete content by lightweight design, (4) timber framing, (5) component reuse and (6) natural sand substitution by alternatives (Supplementary Table 4). We also explore how the adoption of all six strategies simultaneously impact sand

[1]Institute of Environmental Sciences (CML), Leiden University, Leiden, the Netherlands. [2]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, the Netherlands. [3]Netherlands Organization for Applied Scientific Research TNO, The Hague, the Netherlands. ✉e-mail: x.zhong@cml.leidenuniv.nl
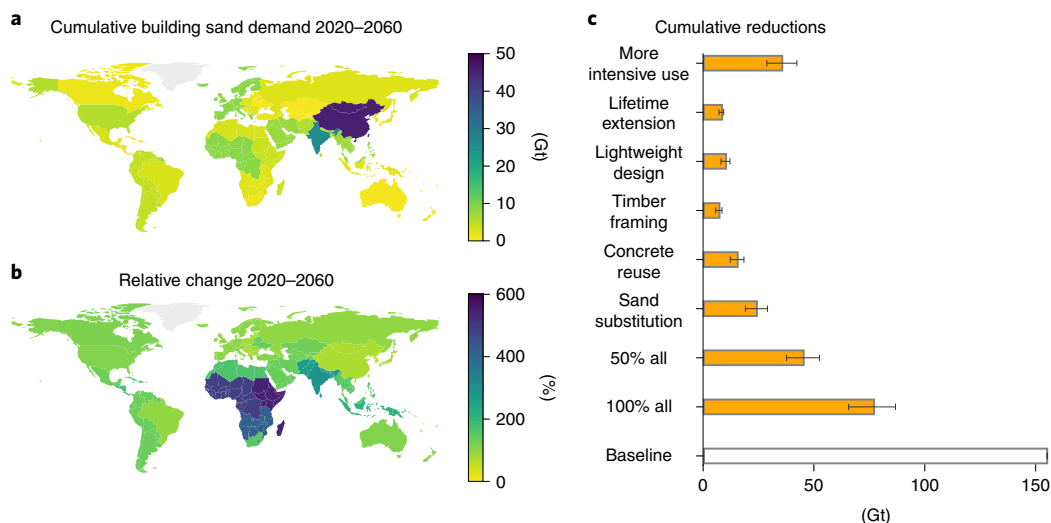
Fig. 1 | Building sand use and reduction scenarios in world regions. a, Cumulative building sand use during 2020–2060 under the baseline scenario. **b**, Baseline building sand use in 2060 relative to 2020. **c**, Cumulative sand reductions from material efficiency interventions. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

use. We assess both partial adoption (50% of total potentials) and complete adoption (100% of total potentials). See Methods and Supplementary Information Section 3 for full details.

We find that cumulative building sand over 2020–2060 can be reduced by 5 to 23% from adopting each of these strategies individually and by 50% if all strategies are fully implemented simultaneously (Fig. 1c). Among these strategies, more intensive use represents the largest cumulative sand reduction potential on a global level (~36 Gt) by avoiding surplus construction, growing urban regions in a compact way, reactivating vacant buildings and more. Through lifetime extension, ~8 Gt natural sand can be avoided due to less frequent demolition and therefore less new construction. For a given building construction demand, a notable amount of sand could be reduced by lightweight design (~10 Gt), timber building substitution (~7 Gt) and concrete reuse (~15 Gt). Replacing natural sand with substitutes for concrete and glass production represents a major reduction potential (~24 Gt).

Priority areas for reducing building sand demand in one region may be less important in another. For example, more intensive use is very important in Europe, the United States and China due to already spacious buildings (usually >40 m² per capita for housing)[14] and commonly high vacancy rate. However, there is a limited potential for more intensive use in most African countries where people generally have inadequate building access (often below 20 or even 10 m² per capita for housing)[14]. Policies to improve building longevity are especially important in regions like China and Japan, where the average lifespan is currently below 40 years, around half that found across European countries[14]. Similarly, the selection of alternatives to natural sand should be dependent on the local resource availability. For example, the use of crushed rock may only be a possibility in areas already close to suitable quarries (because of the high cost of transport).

Since sand is formed by erosive processes over thousands of years, natural sand is currently being extracted at a rate far greater than its renewal[12]. Given the lack of reliable data on sand reserves, it is questionable if the current supply can be maintained or increased in the future and therefore hard to evaluate if substantial increases in sand demand can be met[15] (Supplementary Information Section 5 gives more details on model limitations). The vulnerability of the building sector to sand supply, if defined as the ratio between future building sand demand and demand in 2020, is extremely unequal

across world regions (Figs. 1b and 2). On a global level, either more intensive use or sand substitution could reduce the building sand demand in 2060 to lower than that in 2020. This means maintaining the current sand supply is likely enough for building construction using either of these two strategies. A global implementation of strategies at their 50% potential could reduce 2060 sand demand by 45% (or 71% with 100% implementation), which is ~79% of the demand in 2020 (or 42% with 100% implementation). However, if the current supply stays the same none of the six individual strategies alone nor a 50% adoption of all could reduce demand sufficiently by 2060 for some rapidly developing regions, such as Africa and Southern and Southeast Asia. In Africa, a full adoption of all strategies and a nearly doubled natural sand supply from 2020 levels could be required to meet building construction demand by 2060.

International cooperation is probably essential in addressing the disproportionately distributed vulnerabilities of building sand demand, especially with respect to trade agreements. For example, Singapore has resorted to importing a total of 517 Mt of sand to meet a 20% land area expansion over the last 20 years[12]. However, this has led to soaring prices, environmental harm and export bans across neighbouring countries such as Cambodia and Indonesia[8,12]. Decentralization of exporting regions or even importing from remote regions (for example, Dubai and Saudi Arabia have previously imported from Australia[12] and Greenland is suggested to be a promising sand exporter[16]) might be a solution to sand scarcity across neighbouring countries. However, transport costs could be a challenge for long-distance shipping and the environmental and economic impacts of increased transportation remain highly uncertain. Trade agreements may be necessary in addressing these issues and avoiding or remediating environmental harm. Second, for sand-scarce countries it may be possible to import preprocessed or prefabricated building material elements (for example, windows or prefabricated concrete parts) that represent virtual sand (that is, sand embodied in products[10]), thus relieving pressures on domestic sand resources. Moreover, international cooperation in developing sustainable mining technologies and equipment (for example, stone crushers) is critical for a sustainable sand industry transition in lower-income countries.

Sand substitutes (manufactured sand, desalted sea sand and more) could play an increasingly important role but there are challenges involved in the full life cycle from extraction to use. First,
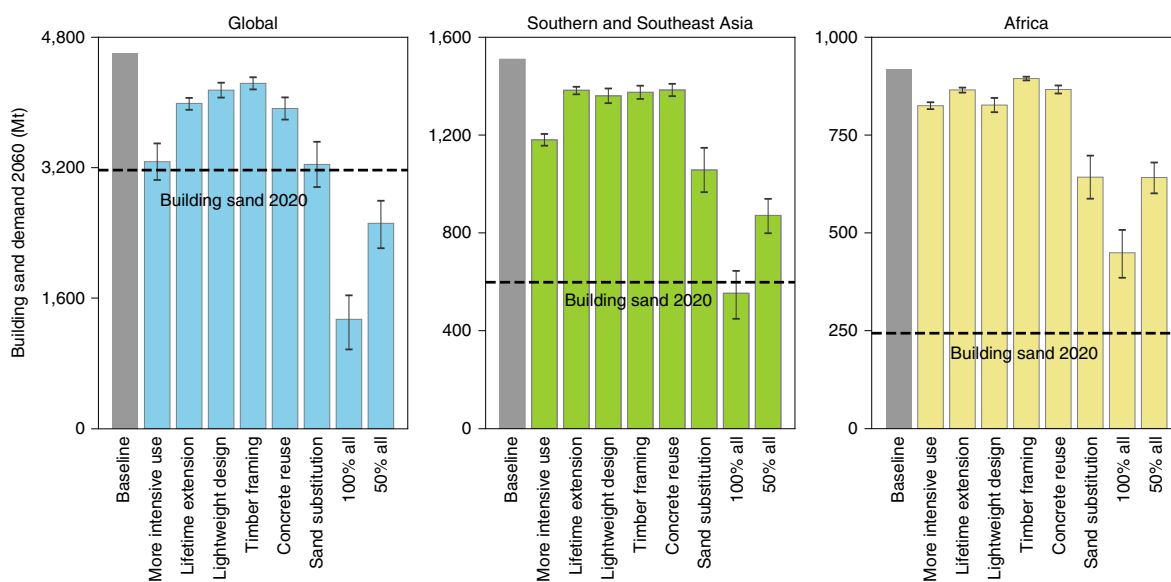
Fig. 2 | Building sand use in 2060 under the baseline and mitigation scenarios. The dashed horizontal lines represent building sand use in 2020. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

it is important to inventory locally available alternative resources and regulate the mining permissions. Quality control is a major task for the processing of manufactured sand and other alternatives for construction use. Standardized methods are needed to both control the fine content and impurities of these alternatives and also the addition of mineral and chemical admixtures to concrete to enhance the mechanical properties[17]. For in-use buildings using alternative sands, targeted quality inspections are needed to ensure no loss of function over time, especially when faced with environmental or climatic changes (for example, increased subsidence or changes in temperature and humidity). Finally, while laboratory-scale life cycle assessments generally show environmental benefits[17] from using sand substitutes in concrete, more research is needed for comprehensively monitoring and quantifying long-term environmental and social impacts of mining activities for sand alternatives (for example, rock-derived mining and quarrying and marine sand exploitation) to avoid problem shifting to other materials and negative tradeoffs.

A prominent barrier for a sustainable supply chain transition is the fragmentation of the sand and aggregate industry with 95% of global production represented by small and medium-sized enterprises (SMEs)[8]. The domination of SMEs brings several challenges not only in effective governance and accurate data collection but also for technological and equipment innovation since purchasing advanced fixed processing or manufacturing assets can be costly. Industry cooperatives or consolidation may be advantageous for applying stricter mining permissions and restrictions[8] but such developments come with their own dangers of regulatory capture and political influence[18].

In general, the implementation of material efficiency strategies investigated here would also yield substantial greenhouse gas emissions reduction[2,4] and therefore are also being driven by climate targets on a global level. Collaborative efforts to conserve sand and mitigate emissions provide large opportunities, from reducing local mining pressures to lowering overall greenhouse gas emissions, in a more efficient and sustainable building sector. This analysis develops a picture of global building sand dynamics and highlights major opportunities and challenges of building sand reduction across global regions. We hope this stimulates progress in this crucially important yet under-reported area.

Methods

We develop an integrated global dynamic building-sand model (GloBus) for the assessment of sand use for building material production. We use this to investigate the sand use reduction from different material efficiency interventions (model framework in Supplementary Fig. 1). We include four residential buildings types (detached houses, semidetached houses, apartments and high-rise buildings) in urban and rural areas and four non-residential buildings types (offices, retails and warehouses, hotels and restaurants and other commercial buildings). We evaluate sand used for concrete and glass in buildings by 2060. This period is particularly appropriate as projections suggest it will be within the period of a global population peak and a rise of living standards across lower-income regions which would remarkably shape the global building stock profiles (in the absence of extreme climate disruption)[2,4]. A brief description of the model components is given here with full details provided in the Supplementary Information.

Building concrete and glass use. We develop a stock-driven dynamic model to calculate the concrete and glass use for building construction on the basis of refs. [4,13,14,19]. Specifically, we first translate the regional socioeconomic trends (that is, population, gross domestic product, housing space per person and building type split) into the demand of residential and commercial building stocks on a yearly basis. We then calculate the annual construction (inflow) and demolition (outflow) of building floor space on the basis of documented lifetime distributions. To do this, we first calculate the demolition from the existing building stock using the lifetime model. Then, the construction can be calculated using the basic mass balance (inflow = outflow + stock change). We next estimate the concrete and glass inflows for building construction by combining floor space inflow with the material intensity (in kg m^{-2}), which in turn define the demand for sand-based as detailed below. For full details see the Supplementary Information.

Building sand use. Due to a lack of reliable data on sand use, previous estimates are mainly indirect, that is, based on the sand requirement as a ratio of other material requirements such as cement and bitumen[10,12]. Here, we estimate the sand use as a ratio for each metric ton of concrete and glass using weight ratios derived from a number of life cycle inventory databases and studies (Supplementary Information gives details).

Scenario development. We first explore a baseline scenario to represent the middle-of-the-road path that is consistent with the shared socioeconomic pathway SSP2. Data in the baseline scenario are mainly derived from the integrated assessment model IMAGE[13] and complementary studies[14,20]. We then explore eight scenarios whereby the first six give results when the interventions are implemented independently and the final two when all six strategies are adopted simultaneously at 50% (halfway towards total maximum potential modelled here) and 100% (total maximum potential). Details of all scenarios and interventions are available in Supplementary Information Section 3. Note that this study aims to explore potentials rather than predict the future. Given the data constraints, the model is subject to several limitations and may be improved in several aspects as discussed in Supplementary Information Section 5.

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Corresponding author(s): Xiaoyang Zhong

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Data collection	All data used in this study are derived from publicly available scientific publications. No software was used.
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Study description	We evaluate the natural sand demand in global residential and commercial buildings and the reduction potential through scaling up several widely suggested material efficiency strategies. The study is based on existing data that are publicly available.
Research sample	The socioeconomic and material-related data are all derived from the existing data and are all publicly available in the related publications (as described in our study).
Sampling strategy	Our datasets cover 26 world regions and represent the best available on a global level to our knowledge.
Data collection	X.Z collected the raw data from existing publications and deposited the data in excel.
Timing and spatial scale	The data were collected in 2021 from existing publications.
Data exclusions	No data were excluded from the analyses.
Reproducibility	All the results are reproducible with our custom code that is publicly available.
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