One Earth

Gold Standard for the Global Goals
1 ton of CO_2 offset

CellPress
OPEN ACCESS

Perspective

Sustainability of the global sand system in the Anthropocene

Aurora Torres,[1,2,*] Mark U. Simoni,[3,4] Jakob K. Keiding,[5] Daniel B. Müller,[3] Sophus O.S.E. zu Ermgassen,[6] Jianguo Liu,[2] Jochen A.G. Jaeger,[7] Marten Winter,[8,9] and Eric F. Lambin[1,10]
[1]Georges Lemaître Earth and Climate Research Centre, Earth and Life Institute, Université Catholique de Louvain, Louvain-la-Neuve, Belgium
[2]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA
[3]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[4]Geological Survey of Norway, Trondheim, Norway
[5]Center for Minerals and Materials, Geological Survey of Denmark and Greenland, København K, Denmark
[6]Durrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Canterbury, UK
[7]Concordia University Montréal, Department of Geography, Planning and Environment, Montréal, Canada
[8]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany
[9]Leipzig University, Leipzig, Germany
[10]School of Earth, Energy & Environmental Sciences, Woods Institute for the Environment, Stanford University, Stanford, CA, USA
*Correspondence: aurora.torres@uclouvain.be
https://doi.org/10.1016/j.oneear.2021.04.011

SUMMARY

Sand, gravel, and crushed rock, together referred to as construction aggregates, are the most extracted solid materials. Growing demand is damaging ecosystems, triggering social conflicts, and fueling concerns over sand scarcity. Balancing protection efforts and extraction to meet society's needs requires designing sustainable pathways at a system level. Here, we present a perspective on global sand sustainability that shifts the focus from the mining site to the entire sand-supply network (SSN) of a region understood as a coupled human-natural system whose backbone is the physical system of construction aggregates. We introduce the idea of transitions in sand production from subsistence mining toward larger-scale regional supply systems that include mega-quarries for crushed rock, marine dredging, and recycled secondary materials. We discuss claims of an imminent global sand scarcity, evaluate whether new mining frontiers such as Greenland could alleviate it, and highlight three action fields to foster a sustainable global sand system.

INTRODUCTION

In 2020 the global anthropogenic mass outweighed all of Earth's living biomass.[1] Sand, gravel, and crushed rock, together referred to as construction aggregates, constitute the largest share of the anthropogenic mass and are the most extracted solid materials by mass.[2] Development debates have centered on globally traded metals, fossil fuels, and precious minerals, which have a high value per weight. Neglecting construction aggregates, however, prevents the achievement of sustainability objectives.[3] Used as unbound materials in building foundations or to produce stabilized materials such as concrete or asphalt, aggregates are fundamental for satisfying societal needs for housing, industry, mobility, energy, and health. Since the 1950s, aggregates mining increased dramatically due to human population growth, urbanization, infrastructure development, and changing lifestyles—for example, the increasing floor area per capita, expected to double from 2017 to 2060.[4] Developing coastal areas and addressing climate change and sea-level rise also require vast volumes of aggregates for land reclamation and flood protection. The scale of aggregates extraction and the projected doubling of demand from 24 to 55 Gt per year in 2011–2060[2] (Figure 1) is likely to push affected ecosystems closer to the brink of irreversible damage, and fuels concerns over a global sand scarcity and social conflicts.[5]

Mineral extraction and construction are the most significant global geomorphological shaping force of the 21st century and a major contributor to climate change.[7] The anthropogenic sediment flux from mineral extraction and associated waste, civil engineering excavations, and dredging in 2015 was estimated at 316 Gt, which is 24 times the amount of sediment supplied annually by the world's rivers to oceans.[8] Regionally, one particular challenge is to protect sand and gravel resources from overexploitation. They are often easier to extract than other aggregates, but have a high ecological value and provide essential ecosystem services such as flood protection, food production, and groundwater storage and filtering.[9] Ecosystem degradation associated with mining threatens species and ecosystems such as wetlands, rivers, coastal dunes, or seagrass meadows.[10,11] Ecological restoration of mining sites is lengthy and rarely leads to a complete recovery.[12] As local sand and gravel supplies become increasingly constrained in high-growth regions, supply systems become more complex, illicit supply networks may emerge,[13] and extraction moves to distant deposits and new frontiers such as the southwestern fjords in Norway or Greenland.[14]

Reducing the impacts of sand mining and transitioning toward a less carbon-intensive, less ecologically destructive, and more resource-efficient circular economy in the construction sector

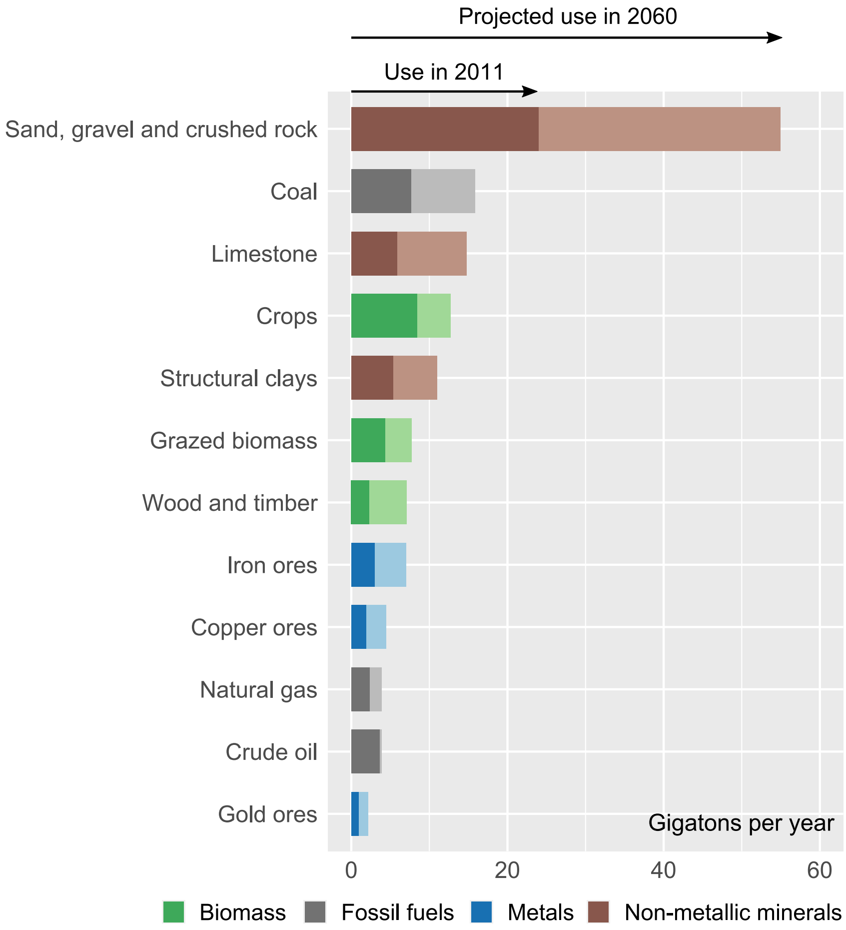

Figure 1. Global annual material extraction in 2011 and projected extraction for 2060[2]
Adapted from OECD.[6]

are global priorities,[15] as underlined by the fourth United Nations Environment Assembly in 2019 (UNEP/EA.4/RES.1 and 19). Balancing protection efforts and extraction to meet societal demands requires designing sustainable pathways at a system level. From a supply perspective, the construction aggregates material system needs to be better understood to quantify the potential for substituting natural sand supply and to evaluate how demand can be reduced by, for example, extended building lifetimes or less-material-intensive lifestyles. From a human-environment perspective, the impacts of current and potential production pathways across the aggregates supply chain must be considered simultaneously to benchmark sustainability performance and prevent problem shifts. However, knowledge is compartmentalized across disciplines (e.g., resource geology, political ecology, biology) and over segments of the supply network (e.g., mining, urban development), resulting in overly narrow views on sand sustainability.

Here, we present a new perspective on global sand sustainability that shifts the focus from solely evaluating local impacts of sand mining to understanding the entire sand-supply network (SSN) of a region as a coupled human-natural system. The system's sole purpose is to supply materials for building the physical stocks that satisfy societal needs. The SSN's framework links physical material stocks and flows of construction aggregates to their sustainability outcomes—security of supply, environmental accountability, and socioeconomic development—to model, analyze, and communicate their dynamic interplay. In what follows, we describe the theoretical underpinnings of the framework, use it to define the system attributes of SSNs, and introduce the idea of transitions in sand mining. We then apply the framework to discuss claims of an imminent global sand scarcity, evaluate whether new mining frontiers such as Greenland could alleviate it, and highlight three action fields to foster a sustainable global sand system.

CONCEPTUAL FRAMEWORK OF SAND-SUPPLY NETWORKS

The SSN framework is informed by the theories of socioeconomic metabolism,[16] telecoupled human-natural systems,[17] and complex adaptive systems,[18] which are all rooted in systems theory.[19]

The theory of socioeconomic metabolism proposes that, similar to living organisms, society maintains a metabolism through inflows of materials and energy from the environment. The physical system, expressed through material stocks and flows, forms the backbone of SSNs. Sociometabolic research uses material flow analysis (MFA) to describe the structure and dynamic changes of material stocks and flows over time and space.[20] MFA systems help understand and communicate the physical configuration of raw-material supply systems such as SSNs, even without quantification. Their primary strength resides in using empirical data and mass balances for robust mathematical models that facilitate monitoring, scenario development, and policymaking (see https://minfuture.eu/).

The telecoupling framework characterizes the spatial relationships and interactions between multiple, distant interrelated coupled human and natural systems (CHANS).[17] With its focus on socioeconomic and environmental interactions and feedbacks across space, this framework brings together place-based and process-oriented research.[21] Telecoupled systems are composed of (1) CHANS fulfilling roles of sending (for example, mining regions), receiving (urban areas with construction sites), and spillover systems (transport corridors); (2) flows among these CHANS of information, materials, organisms, and capital; (3) agents (supply chain actors); (4) causes driving the flows (demand for housing); and (5) effects on people and nature of these flows (farmland loss). A narrower focus may leave mining's environmental and social impacts unreported and uncompensated. MFA and telecoupling focus attention on the entire

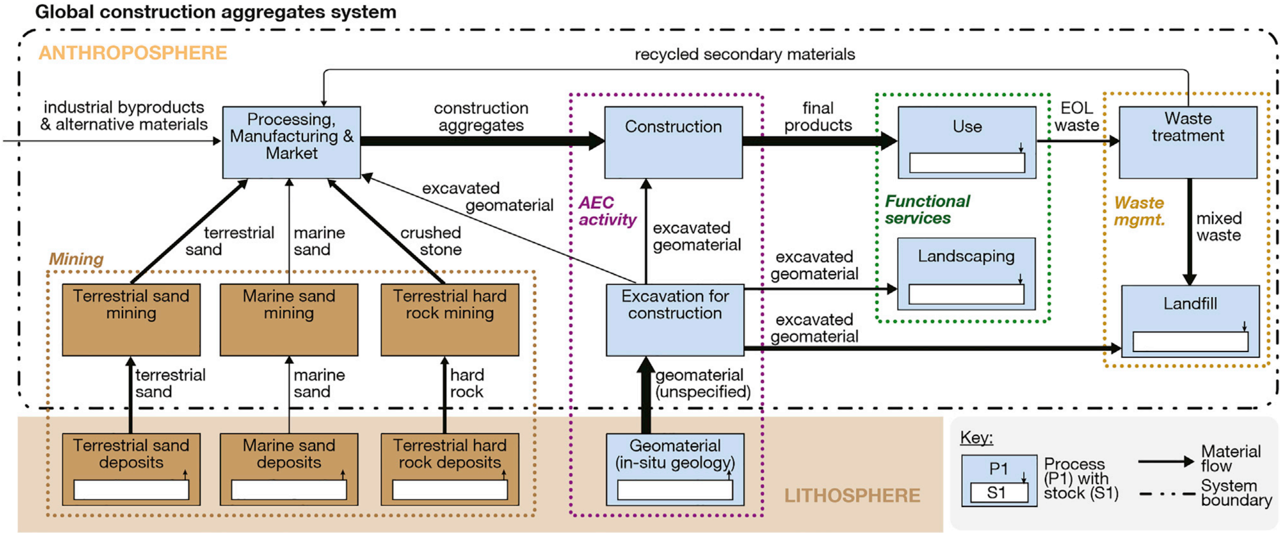

Figure 2. The global construction aggregates system represented as a generalized qualitative material flow analysis system

Boxes indicate material transformation and storage processes. Dotted lines group these into different industry subsystems: mining; architecture, engineering, and construction (AEC); functional services (e.g., shelter provided by in-use building stocks); waste management. EOL, end-of-life. White boxes represent stocks; up-pointing arrows denote stock reduction and down-pointing arrows stock accumulation. Arrow width indicates the relative size of the flows based on expert judgment because robust global data are lacking. Although the global flow for excavated geomaterial remains unquantified, for Norway, as an example, the annual production of hard rock excavation material for infrastructure projects alone is estimated to be on the same order of magnitude as that of formal hard rock aggregates mining.[24] Fluvial sand mining is included within terrestrial sand mining.

material system with all supply chain interactions and distant impacts.

The spatial relationships between geological stocks and consumers determine the geographical coverage and structure of SSNs. Yet societal needs and decision-making processes ultimately shape the dynamic evolution of SSNs and their associated physical and social landscapes. A multitude of agents contribute to creating, changing, or disrupting aggregates flows. They learn, adapt their behavior, modify the use of sand (e.g., prioritize extraction from certain deposits, identify substitutes) and respond to human-environmental impacts (e.g., enforcement of rules, biodiversity protection). Hence, SSNs evolve in time and space as complex adaptive systems in response to disruptions such as local mineral depletion,[22] government policies, technological innovation, or changing consumption patterns, all of which modify SSN structure and functioning.

The construction aggregates material cycle

A generic, global MFA system helps visualizing the construction aggregates cycle as a sequence of activities that transform, distribute, and store material as stocks, connected by material flows (Figure 2). MFA can be applied at different scales, and highlights the importance of considering different materials and sources and their linkages across the material cycle.[23] MFA systems can be used to map and evaluate SSN configurations, monitor physical stock changes, and anticipate and model how stocks and flows are influenced by agents' decisions, such as government policies promoting resource and energy efficiency and greenhouse gas (GHG) emission reductions.

Aggregates do not typically complete a geological rock cycle over a human lifetime and are generally considered to be nonrenewable, finite resources.[25] Unconsolidated sand and gravel can be mined from terrestrial or marine deposits and are also part of the geomaterials excavated during construction activities. The geology and genetic origin determine the distribution, size, and composition of natural stocks. Terrestrial sand deposits include areas suitable for open dry pit mining such as floodplains and adjacent river terraces, ephemeral rivers, glacial sediments, dunes, and freshwater systems where sand is dredged from riverbanks or active river channels. Marine aggregates extraction occurs in shallow waters and during the dredging of ports, nourishment operations, and land reclamation. The dredged sand must be washed to remove the salt and prevent spallation of concrete and corrosion of reinforcements. Instead of mining unconsolidated sediment deposits, the "sand" grain-size fraction (0.0625–2 mm) and coarser products can be produced artificially by crushing rocks (e.g., sandstone, limestone) or by recycling secondary materials such as concrete or masonry. Crushed rock can be equally suitable or superior for some applications, thanks to better control over mineralogical composition and shape.

Mined aggregates generally require processing and blending to fulfill the specifications for value-added products (e.g., ready-mix concrete, asphalt) and direct use in geotechnical engineering and landscaping. Upon entering the market, products are transported to end consumers where the architecture, engineering, and construction industry uses them to build, maintain, and replace existing anthropogenic stocks. Construction typically starts with the *in situ* excavation of geomaterial for site preparation. Excavated material may be either processed for further use on-site, stored for site restoration, used in off-site landscaping, or delivered to landfills. Anthropogenic material stocks such as buildings and infrastructure provide a range of functional services to society. Their service lifetime determines the metabolic turnover rate of the construction aggregates system. End-of-life waste management can redirect construction and demolition waste flows and convert them into recycled secondary materials.

The telecoupled system

In the receiving systems of SSNs, the construction, demolition, and renovation rates of the built environment drive the aggregates demand. While fast-growing countries are investing in new construction,[2] high-income countries face the challenge of upgrading or replacing their aging infrastructure. For instance, up to 80% of the building stock that will be in use in Europe by 2050 already exists today.[26] Declining household size, increasing total floor area per capita, and urban sprawl increase per capita material demand.[4,27] While the geographical distribution of geological resources determines where material with specific characteristics can be sourced, the availability is influenced by socioecological and economic constraints that limit the exploitation of resources. Whether and where sending systems are established is ultimately determined by resource accessibility, market demand (use, quantity), and transport costs. Spillover systems include: transport corridors experiencing traffic-related impacts; the climate system, affected by GHG emissions; and rural areas receiving construction and demolition waste generated in urban areas.[28]

Sand resource governance is shaped by interactions between private, public, and civil society actors. Suppliers include aggregates extraction enterprises and traders, be they private, state-owned, cooperative, or informal. The aggregates industry remains highly fragmented and dominated by small and medium-sized companies, with the top ten producers combined representing less than 5% of global production.[29] With increased barriers to obtaining mining permits, there is ongoing industry consolidation and vertical integration, which leverages the economies of scale and benefits from transnationality to reduce revenue cyclicity and volatility.[30] In Great Britain, for instance, the aggregates industry is dominated by five multinational companies operating in allied sectors such as asphalt, cement, and ready-mix concrete sales and contracting, which have increased their production share from 50% in 1991 to 70% in 2009.[31] Other agents are trade associations that develop professional industry standards and lobby for or against regulations, and civil engineers, architects, and owners that influence demand through design and product choices. Government entities include national geological surveys that collect and provide information on resource management. Other authorities develop and enforce regulations, issue mining leases, monitor compliance and reporting, and implement waste-management plans.

Next to materials, other flows include financial transactions, information exchanges, and biological species movements. Trade and shipping are among the most important pathways for the introduction of alien species.[32] Sand deposits contain countless microbial species that are still unknown to science,[33] mixed with seeds, spores, and eggs of many taxa.[34] For the enormous quantities that are transported by bulk carriers, biosecurity control measures such as sterilization by fumigation and autoclaving are too expensive and unlikely to kill all organisms.[35] The US Animal and Plant Health Inspection Service's quarantine regulations exempt sand, gravel, and rocks from their treatments. The result is an unpredictable threat of importing new aliens and potentially harmful invasive organisms from distant sending systems.[32]

Concrete production contributes ca. 7.8% of nitrogen oxide, 4.8% of sulfur oxide, 5.2% of particulate matter $< 10\ \mu\text{m}$, and 6.4% $< 2.5\ \mu\text{m}$ of total global emissions.[36] The aggregates production stage is responsible for 10.1% of GHG emissions and 53.4% of the health impacts of air-pollutant emissions, resulting in US$113.9 billion annually of external health damages from inhalation-related health issues due to particulate matter emissions from rock quarrying and crushing.[36] This stage also accounts for 41% of total water consumption in concrete production, making aggregates production a significant contributor to global water demand.[37] Being the heaviest and most voluminous solid-waste fraction, construction and demolition waste represent 35% of the total solid waste produced worldwide.[38]

In sending systems, mining of aggregates results in the removal and severe degradation of ecosystems, driving biodiversity loss and affecting their capacity to supply ecosystem services.[9,10,39] The geological, hydrological, ecological, and climatic settings influence the vulnerability to extractive activities. Sedimentary systems such as abandoned riverbeds or Holocene glacial deposits and hard rock deposits are closed fossil systems with zero replenishment rates over human lifetimes. While mining fossil systems depletes their resources, it presents a lower risk of cascading effects[40] than exploiting dynamic systems in which impacts display non-linear responses to changes,[41] extend over large regions, and are difficult to quantify.[41] In open, active sedimentary systems such as rivers, deltas, and some marine deposits, sand is continuously replenished. The sediment mass balance determines how much material can be extracted without severely damaging fluvial and coastal systems.[42]

Feedback loops

Climate change and the global demand for construction minerals

Urban population growth and associated infrastructure development may claim the entire carbon budget of a 2°C warming limit by mid-century. If developing countries reach building stocks levels similar to those of industrialized ones, the production of raw construction minerals alone would generate approximately 350 Gt CO_2 by 2050, which corresponds to 35%–60% of the remaining carbon budget.[7] While the largest share will come from the clinkering phase of cement and steel production, the relative contribution of aggregates production is expected to increase with longer transport distances.[43] Moreover, the use of building stocks is projected to contribute to 282–701 Gt CO_2 between 2010 and 2060.[44] The long life expectancy of buildings and infrastructure makes the system prone to legacies and lock-in effects that predetermine energy- and carbon-intensive pathways, which are costly to redirect.[45] For instance, 97.5% of the European Union's building stock is not sufficiently energy efficient to comply with future carbon-reduction targets.[46] Existing capital-intensive production facilities, supply chain structures, long-term lease contracts, regulations, and government policies cause inertia and constrain future pathways.[47]

Climate change threatens coastal infrastructure through sea-level rise and increasingly severe storms, with 190–630 million people living in areas projected to flood annually by 2100 under low-to high-emission scenarios.[48] Higher CO_2 concentrations and rising temperatures are projected to accelerate concrete and asphalt degradation.[49] Climate change impacts will

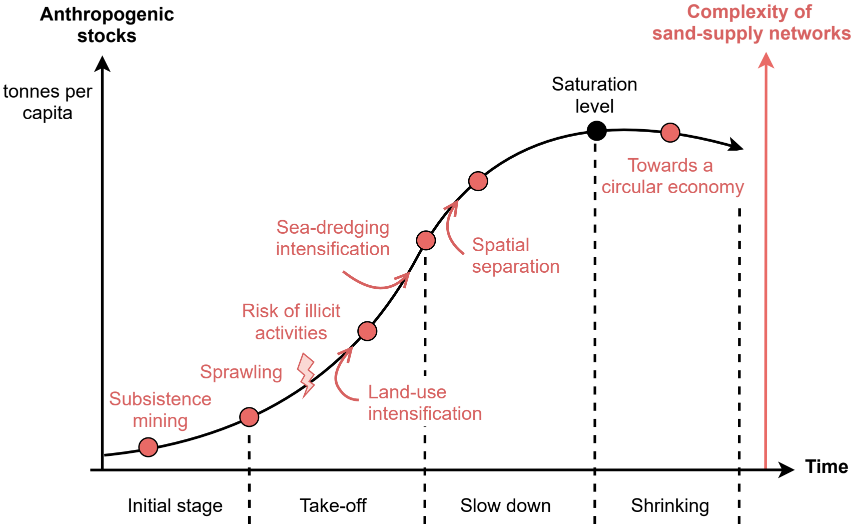

Figure 3. Idealized sequence of system configurations of sand-supply networks (SSNs) (red dots) corresponding to different evolutionary development stages of per capita in-use built environment stocks (in black, adapted from Cao et al. [61]) and characteristic approaches to overcome resource bottlenecks (red arrows)

therefore amplify the demand for aggregates for: (1) adaptation, such as redirecting coastal infrastructure investment further inland to facilitate migration to flood-safe areas,[50] investments in construction and maintenance of hard coastal flood defenses (estimated at $12–71 billion/year by 2100[51]), and mega-nourishments projects (e.g., Sand Engine project in the Netherlands); (2) mitigation, for rebuilding damaged infrastructure or coastal restoration; and (3) repair or renovation of infrastructure due to their decreased lifetime. These climate-induced infrastructure investments act as a positive feedback loop that contributes to further climate change and undermines sustainability efforts.

Shoreline destabilization and rebuilding

Coastal and river systems can be destabilized by aggregates removal. Riverbed incision, reduced sediment flow, and the degradation of coastal habitats can impair a system's resilience, leading to riverbank collapse and delta erosion and threatening local communities.[42,52] This might push affected populations to migrate to urban areas. Besides, in the aftermath of disasters, aggregates demand for rebuilding and restoration increases for years. After the 2016 Cyclone Winston in Fiji, the country suffered from shortages in construction minerals.[53] Both migration and restoration drive further mining.[54]

Human-environmental conflicts and regulation

Attenuating feedbacks occur when the demand for sand in receiving systems critically affects the sending systems' human-environmental dynamics.[9] Concerns about environmental or social harm may trigger conflicts between local communities and large-scale mining operations that might impact the receiving system. For example, shifts in sand flows have been observed in Singapore's SSN. Singapore's land territory has expanded by 130 km^2 in the last 40 years and has become a top aggregates importer from Southeast Asian neighbors. Since the early 2000s, temporary bans to sand exports to Singapore from Indonesia, Cambodia, Vietnam, and Malaysia were triggered by allegations of environmental and social impacts and illegal mining, including the disappearance of 24 Indonesian islands.[55–57] In response, Singapore's SSN continuously reorganizes. One of its newest suppliers is a quarry in western Australia, which shipped 1.1 Mt of high-quality sand for concrete production in 2020.[58]

EVOLUTION OF SAND-SUPPLY NETWORKS

Here we introduce a temporal perspective on SSNs. We describe an idealized sequence of SSN configurations under growing demand, reflecting an evolution toward greater system complexity and geographic scope, reaching eventually a turning point (Figure 3). We combine a deductive approach, drawing on theories of forest and sociometabolic transitions,[59,60] with an inductive approach by taking stock of insights from place-based research and identifying recurrent patterns. These evolutionary pathways are not deterministic, as different places may follow different trajectories, get locked in a particular state, or reverse to a previous state depending on endogenous and exogenous conditions (e.g., capacity to exploit other resources, economic recession). We draw from historical evolutionary patterns of cement stocks[61] that suggest that per capita anthropogenic stock growth follows a logistic growth curve, with four stages defined by speed and acceleration of stock accumulation.

State 1. Subsistence mining

When the demand and anthropogenic stocks are low and resources are plentiful, aggregates mining occurs locally.[62] Families or small-size companies exploit accessible, unconsolidated sedimentary deposits (e.g., river sand), which are easy to extract without sophisticated technology and skilled labor, and the least expensive source, with informal mining being frequent and socially tolerated—for example, the Usumacinta river in Mexico.

State 2. Sprawling

With increasing urbanization, demand grows at an accelerated rate. Sand mining becomes attractive as an alternative source of income. Numerous artisanal and small-scale miners and quarry workers dominate the aggregates industry and contribute to local economies[63] (see the Mosi-oa-Tunya declaration[64]). Mining expands to larger sites outside the geography of the market. Localized increases in demand lead to local bottlenecks due to overexploitation, land competition (with farming, fisheries), increased actual or perceived harm to people and ecosystems, urban encroachment on deposits, lagging exploration and licensing, and insufficient production capacities. These factors trigger conflicts to which government institutions respond by limiting sand extraction, which intensifies local supply shortages and increases prices. Local constraints and sprawling force the system to reorganize to find alternative supply options and to adapt the SSN configuration.

State 3. Emergence of illicit supply networks

Poor governance prompts the emergence of illicit activities in locations or at times of lower perceived transaction costs, using new approaches to minimize costs (e.g., violence, exploitation of local communities, corruption), such as India's multiple Sand Mafias.[13] Illicit mining and trade undermine sustainability objectives, intensify harm to people and ecosystems, and lead to tensions. In China, the high demand for aggregates and growing mining restrictions increased river sand prices by up to 600%, prompting extensive illegal mining in the Yangtze River Economic Belt, where more than 580 illegal sand and stone piers were detected in 2017.[65]

State 4. Intensification of mining activity

Growth in demand causes intensification and mechanization of mining pits and quarries. The industrialization of crushed rock plants requires advanced technology, a qualified workforce, and capital investments. It delivers higher volumes and a wider range of products, which allows for maximizing the volume of high-priced products and responding to dynamic demand. Crushed rock prices experience a long-term decline due to technological innovation.[66] Where suitable rock deposits are available, the initial reliance on natural sands shifts toward crushed rock,[30] as in China, Europe, and North America, where it has become the primary source of aggregates.[67,68] In Europe, in-stream sand mining was common in the 1950s to 1980s until more stringent regulations, nature and cultural heritage conservation, and competition with alternative sources led mining rates to drop to 0.1% of aggregates production.[69]

State 5. Sea-dredging intensification

With growing constraints to mining terrestrial aggregates, coastal regions increasingly exploit marine aggregates.[70] Marine resources extraction accelerates globally.[71] Technological innovation facilitates the dredging of marine deposits in waters down to 60 m deep, which can be directly landed into markets, often in coastal areas. Marine aggregates extraction is already a mature sector in South Korea, Japan, the United Kingdom, Belgium, and Denmark, where it represented 24% of total aggregates production for construction and coastal protection in 2006–2019.[72]

State 6. Spatial separation

Once demand outpaces supply due to inaccessibility or depletion of more proximal deposits, production is displaced to sites with good transport links and few constraints. Imports are common in regions with high population densities and urban and agricultural land uses, where it is difficult to establish new mining operations. For instance, California closed the last beach mining operation in the United States in 2020 due to community pressure motivated by concerns about erosion. This increased sand imports from Vancouver Island. Multinational companies such as HeidelbergCement operate mega-quarries for shipping high-quality aggregate products to domestic and international customers. The increasing spatial separation between production and consumption mirrors that of numerous commodities and has demonstrated impacts on sustainability.[60] Moving aggregates over longer distances requires more time, fuel, and transport infrastructure, thus increasing costs and emissions.[43,73]

State 7. Circular production

When per capita anthropogenic stocks reach saturation, material efficiency strategies (e.g., adopting new building design standards, urban densification) and less-affluent consumption patterns can decrease material needs. With growing waste production and increasing constraints to mining natural aggregates, markets benefit from the increased availability of secondary aggregates shifting toward a more circular economy. Recycling technology for construction and demolition waste, which is well developed, reduces both economic costs and the carbon footprint, especially for on-site material reuse.[74] Recycling rates vary among countries. For example, from less than 10% to over 90% across the European Union, representing10.6% of total aggregates production.[67] Most efforts amount to downcycling, but there is potential for high-quality recycling schemes.[74] The main obstacles are the variability of supply, distances to recycling facilities, the low cost of primary aggregates, and an underdeveloped market for recycled products.

APPLYING THE FRAMEWORK FOR SUSTAINABILITY

This study reveals three key features of SSNs. First, SSNs exhibit complex system properties that are reflected in the evolution of physical material stocks and flows over time. For instance, demand is non-linear and strongly influenced by legacy effects of existing production facilities and anthropogenic stocks that entail lock-ins into carbon-intensive pathways. Feedback loops between supply and demand are determined by resource constraints and agents' interactions, and are influenced by regulatory regimes, consumer choices, leakages, and climate change. Second, SSNs change from small-scale artisanal mining relying mostly on common-pool resources toward larger-scale regional supply systems that include mega-quarries for crushed rock, marine dredging, and the recycling of secondary materials. Diversification of supply provides alternatives for reorganization and makes SSNs more resilient to spikes in demand or changing prices. Third, transition pathways do not necessarily result in the greening of production as hypothesized by the ecological modernization theory or the environmental Kuznets curve, which posits increasing environmental degradation in the early stages of economic growth and a reversal trend with higher income.[75] Transition pathways are better theorized in terms of resource substitution and problem shifting. For example, a transition from fluvial sand mining to crushed rock production displaces impacts toward air pollution and water consumption. One expects the intensification of mining to go hand in hand with increases in economic and labor efficiency[3] and declines in energy efficiency, similar to agriculture.[76] As easily accessible sand deposits are exhausted, extraction is displaced toward more expensive deposits, potentially at greater distances from consumers or increased extraction difficulty. As such, sand extraction mirrors trends in fossil fuel extraction, where the ratio of energy invested to produce useful energy has declined over the last decades.[77] Ignoring SSNs' complexity can result in unsustainable "solutions," including problem shifts and unintended consequences of regulations.

Sand availability, scarcity, and prices

There are increasing concerns of a global sand scarcity, with claims that by mid-century the demand might outstrip the supply and prices will soar.[14,78] A first attempt at modeling the global supply of aggregates by Sverdrup et al.[79] is often cited to support such claims. While having made a substantial contribution, Sverdrup et al. acknowledge that reliable quantitative estimates of global aggregates reserves and extraction rates are lacking. A global assessment of geological stocks and their uncertainty is yet to be conducted, and the sand resources that the Earth's crust holds remain unquantified. Published resource and reserve estimates only represent selectively surveyed and aggregated estimates of potentially extractable quantities. These numbers continuously change in response to exploration and mineral development, prices, and technological innovation. Such estimates are too uncertain for projecting long-term physical exhaustion.[80] Geologically, sand resources are abundant in numerous forms and qualities in the geological cycle. Mapped unconsolidated sediments cover half of the global land area[81] and there are 1.42×10^8 km^3 of sediments in the continental margin of the global ocean.[82] Data on how much suitable material for aggregates production they contain are lacking. It can nevertheless be assumed that global physical sand depletion is unlikely, particularly when considering the multiple intervention options that can change the configuration of the construction aggregates system of Figure 2. In contrast, regional sand scarcity is an emerging issue,[83] with both physical scarcity ensuing when demand exceeds physical availability (e.g., due to unfavorable geology or depletion by mining) and economic scarcity resulting from the lack of access to deposits (e.g., due to encroaching urban growth) or avoidance of environmental destruction and opposition to mining.

The model by Sverdrup et al. assumes a functioning global market for aggregates with global prices. This assumption is questionable because, even though the authors note that market prices show "huge variations locally," it exaggerates the role of global supply networks. There are obvious gaps in international trade data (e.g., import-export statistics do not add up) and deficits in domestic numbers,[93] but statistics reveal that the international trade of construction sand and gravel represents only a fraction of the total market volume (less than 1% in China or the United States[66,94]). Moreover, commodity trade requires uniformity of the traded goods. Yet there are multiple aggregate types, each with unique applications, and no financial instruments for investors to trade sand at a global price. International shipping is usually the result of direct client-producer negotiations to obtain products that fulfill particular specifications with a unique price tag. Global trade will thus likely continue to play a subordinate role in meeting aggregates demand in the foreseeable future.

Claims of a current or future global shortage result from an overly narrow focus on natural sand mining that ignores the system perspective. The sustainability of sand supply should consider the diversity of potential raw-material sources and alternatives in the construction aggregates system. The primary substitute for mining natural sand is crushed rock, for which there are abundant geological resources.[68] The use of other substitutes such as recycled construction and demolition waste, municipal solid-waste incineration slag, or blast furnace slag (a by-product of steel production) is likely to expand in response to efforts for domestic supply security, circular economy, and climate change mitigation. Moreover, bio-based materials such as engineered timber are a promising alternative construction material for low- and mid-rise buildings that would contribute to carbon storage.[95] Yet wood products cannot functionally substitute the bulk uses of aggregates such as foundation, railway ballast, coastal protection works, and underground construction, or for large-scale infrastructure such as dams and airports. An integrated view for managing entire systems and assessing availability of aggregates and other alternatives is crucial to prevent problem shifts and avoid large cost overruns or project non-viability (Box 1). For example, the Denver International Airport project cost increased from $2.8 to $4.8 billion at completion in 1995 partly due to a failure to assess the availability of sand, gravel, and crushed rock.[96]

SUPPORTING SUSTAINABLE TRANSITIONS

Society faces the challenge of how to produce the sand, or more broadly the aggregates, needed to satisfy a doubling demand over the coming decades in a way that secures supply, maximizes resource efficiency, and aligns with the planetary boundaries and the SDGs. We propose three action fields to anticipate and guide where, when, and how sand demand will influence the sustainability of human-environmental systems:

1. A more robust qualitative understanding and quantification of the physical system: *What are the current supply routes for aggregates? Of which qualities? How long will the resources of existing sandpits and quarries last given expected consumption rates?* The lack of reliable statistics about geological and anthropogenic stocks and flows is a major gap. Cross-country comparisons are cumbersome due to data gaps and a lack of standardization for reporting material stocks and flows. To resolve these challenges, we advocate for developing an integrated physical system understanding based on established methods such as MFA to improve the mapping, monitoring, and reporting of the stocks and flows of the construction aggregates system as a basis for scenarios and decision support.[97] This approach requires (1) reliable data acquisition for relevant material stocks and flows across the aggregates material cycle; (2) differentiation of material types by source and quality (e.g., terrestrial or marine sand, poorly or well graded); (3) voluntary or mandated public reporting and institutional data sharing between industry and geological surveys, making information open and accessible (similar to the Dutch system: https://www.tno.nl/en/focus-areas/energy-transition/expertise/geo-data-it/); and (4) international data standards and platforms where harmonized statistics can be made available, such as the European Geological Data Infrastructure (http://www.europe-geology.eu/) or the UN IRP Global Material Flows Database visualized by http://materialflows.net.

Box 1. Greenland as an emerging supplier?

To further illustrate the SSN framework's usefulness, we examine the recent proposal by Bendixen et al.[14,78] that portrays Greenland's deltas as a sustainable sand source. The Greenland Ice Sheet is melting 7 times faster than in the 1990s, with global warming leading to increasing sediment flows and growing deltas.[84] From a supply viewpoint, Greenland's deltas could thus be considered a mining opportunity to meet global sand demand and support Greenland's development.

Receiving systems

Greenland's hypothetical role as a sand exporter rests on the assumption of a global sand scarcity that leads to increasing global prices, which can be alleviated through an international sand market. However, such projections need to consider the entire system and geographical variations of construction aggregates supply and demand, including substitution and resource efficiency. The most rapid growth in demand is expected in Asia-Pacific and Sub-Saharan Africa.[2] In Greenland's proximal markets such as the United States, Canada, Denmark, and the United Kingdom, the demand for aggregates is entirely or mostly covered by domestic extraction. For example, net-import reliance in the United States and Denmark is 1% and 5%, mainly from Canada and Norway, respectively.[68,85] This demand and import prices have remained generally stable since 2008.[86] Commitments to decarbonize the construction sector and promote Sustainable Development Goals (SDGs) and circular economy targets are likely to make local alternatives more appealing.

Existing sending systems

Imports in northern Europe are met through SSNs that include mega-quarries of crushed rock in southwestern Norway (Norsk Stein) and Scotland (Glensanda), each producing 9–12 Mt per year, with the competitive advantage of market proximity, a better-developed energy and transport infrastructure, and favorable geological and topographical conditions.

Greenland's geological stocks

Glacial and fluvial sediment systems in Greenland would be unlikely to meet high-quality requirements while being cost-competitive. First, Greenland's deltas are dominated by moraine material that has a grain-size distribution from very-fine-grained particles known as "glacier flour" to large stones. Commercial natural sand and gravel deposits suitable for concrete production would ideally have 60% gravel and 40% sand, with little fines.[87] Fluvial transport distances are short, and sediment deposits will likely be poorly sorted and geologically immature, with a higher probability of containing weak grains undesirable in concrete production.[88] Second, finding large deposits with a favorable grain-size distribution without large amounts of fines off the coast of Greenland will require expensive geophysical field campaigns as well as *in situ* drilling and sampling. The harsh climatic conditions and lack of energy and transport infrastructure to access deposits pose significant challenges to establishing production, processing, hauling, and loading facilities.[89]

Spillover impacts

A Greenlandic aggregates industry would face longer transport distances to potential North-Atlantic markets and substantially higher transport costs,[89] CO_2 emissions, and risks of biological invasions compared with current material supplied from more proximal sources. For example, a production in southwestern Greenland (e.g., Nuuk), would need to transport the cargo over 5-times longer distances to reach Copenhagen than current shipping routes from Norwegian quarries (Figure 4).

Impacts in sending system

Greenland's deltas are dynamic coastal systems, where the potential cumulative effects of mining, increases in sea temperatures, freshwater input, and declines in sea ice are poorly understood. They support a wide range of Arctic biota from shorebirds to benthic communities and whales such as the narwhal,[90] and provide spawning and foraging habitat for fishes,[90] being known as good fishing grounds.[14] Dredging activities and increased shipping traffic will negatively affect coastal habitats and ecosystem functions[91] and increase marine pollution, wildlife collisions, and noise.[92] Moreover, shipping increases the risk of invasive species being drawn to Greenland, potentially leading to adverse ecological and economic impacts. Social support or resistance by local communities will greatly influence mining prospects.

Broader SSN perspective

This overview suggests that Greenland's deltas are unlikely to yield a positive return on investment. Assuming that Greenland would be a competitive sand producer for international export without considering the broader SSN perspective provides an incomplete basis for decision making. Whether Greenland's economic development could benefit from establishing an aggregates industry remains to be demonstrated by more detailed feasibility studies. However, its contribution to the sustainability of the global sand system is questionable. Overlooking other leverage points in the physical system of a given market (e.g., Denmark)—such as on-site recycling of stocks, crushed rock from neighboring countries (e.g., Norway; Figure 4), increased material efficiency, and changing lifestyles—could create problem shifts to higher energy use and CO_2 emissions. The SSN framework makes the sustainability implications of supply changes more explicit, beyond the immediate geographical scope of mining projects.

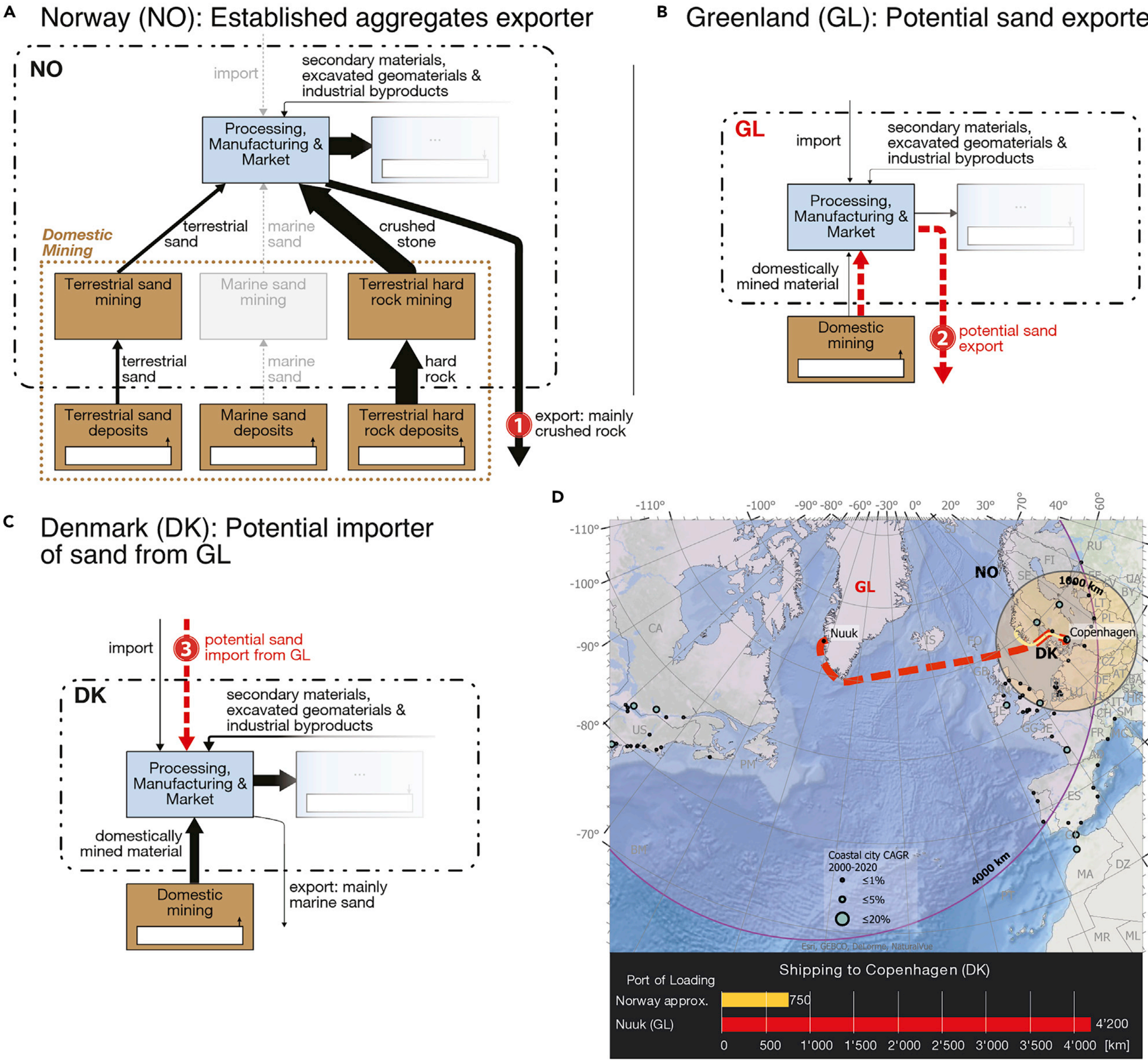

Figure 4. Illustration of key characteristics of current and potential construction aggregate flows between the subsystems of Norway, Greenland, and Denmark

The generalized and qualitative material flow analysis system diagrams are truncated to only show their relevant import-export relationships. Norway, the world's biggest exporter of construction aggregates, is Greenland's main competitor as hypothetical sand producer. The map compares shipping distances from Norway (A; yellow lines) and Greenland (B; red dashed line) to Denmark (C and D) with 4,000 and 1,000 km geodetic range circles around Nuuk (GL) and Copenhagen (DK), and coastal growth markets are shown as cities with ports ranked after compound aggregate growth rates (CAGRs). Geological sources for GL and DK are grouped into domestic mining because the statistics do not distinguish them. Important Norwegian producers, among them Europe's largest hard rock aggregate quarry operated through Norsk Stein AS by the German Mibau Holding Gmbh, are within a 1,000 km range of Denmark and other European growth markets.

2. Spatial mapping of the coverage and the impacts of SSNs: *From where to where are aggregates transported? What are the impacts on CHANS in sending*, *receiving*, *and spill-over systems?* Traceability of aggregates and supply chain certification are still in their infancy in the construction sector, but they are increasingly integrated into sustainable sourcing standards, environmental product declarations, and government procurement.[98] Spatiotemporal data and systematic mapping of the links between consumers, traders, and places of production would show how each supply stream is linked to specific environmental and social outcomes, allowing companies, governments, and researchers to understand the risks and identify policy interventions to optimize trade-offs in SSNs.
3. Disentangling the agency of SSNs: *How are decisions being made and by whom? How do they affect SSNs?* Interdisciplinary efforts to understand the decision-making processes that drive changes in SSNs will yield new insights into conditions that keep the system locked-in or that trigger shifts in its organization,

including leverage points for sustainable transitions. The generic transition pathways of SSNs presented above provide a basis to test theories on sand mining, supply chain organization, the emergence of illicit supply networks, and conflicts. Empirical case studies of SSNs can uncover causal relationships in SSNs and contextual factors. Agent-based models can be used to analyze SSNs, understand how agents make decisions, and anticipate outcomes of different governance initiatives such as taxes on construction minerals or voluntary sustainability standards.

Progress along these lines will contribute to ongoing efforts of the International Resource Panel and UNEP programs such as the Global Sand Observatory.[99,100] The SSN framework lays the foundations for avoiding and mitigating the unintended consequences of sand mining by addressing sustainability challenges at a system level, across multiple locations. It builds on a physical system model to map decision processes and information flows, and improves our understanding of the conditions that determine the uptake of alternative materials, changes in demand, and improvements in regulations. Ultimately, the sustainability of the global sand system is determined by human-environment interactions within Earth system's constraints.

ACKNOWLEDGMENTS

A.T. received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 846474. M.W. acknowledges DFG funding (via iDiv: FZT 118, 202548816). J.L. was supported by US National Science Foundation grant no. DEB-1924111 and Michigan AgBioResearch. We are grateful to two anonymous reviewers and Arnaud Vander Velpen, whose comments and suggestions greatly improved the manuscript.

AUTHOR CONTRIBUTIONS

A.T., M.U.S., D.B.M., J.L., and E.F.L. contributed to conceptualization of the manuscript; all authors wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., and Milo, R. (2020). Global human-made mass exceeds all living biomass. Nature *588*, 442–444.
2. OECD (2018). Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences (OECD Publishing).
3. Franks, D.M. (2020). Reclaiming the neglected minerals of development. Extr. Ind. Soc. *7*, 453–460.
4. Abergel, T., Brown, A., Cazzola, P., Dockweiler, S., Dulac, J., Pales, A.F., Gorner, M., Malischek, R., Masanet, E.R., and McCulloch, S. (2017). Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations (OECD Publishing).
5. Hernandez, M., Scarr, S., and Daigle, K. (2021). The Messy Business of Sand Mining Explained (Reuters). https://graphics.reuters.com/GLOBAL-ENVIRONMENT/SAND/ygdpzekyavw/.
6. OECD (2018). Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. Highlights (OECD Publishing).
7. Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., and Brattebø, H. (2013). Carbon emissions of infrastructure development. Environ. Sci. Technol. *47*, 11739–11746.
8. Cooper, A.H., Brown, T.J., Price, S.J., Ford, J.R., and Waters, C.N. (2018). Humans are the most significant global geomorphological driving force of the 21st century. Anthr. Rev. *5*, 222–229.
9. Torres, A., Brandt, J., Lear, K., and Liu, J. (2017). A looming tragedy of the sand commons. Science *357*, 970–971.
10. Koehnken, L., Rintoul, M.S., Goichot, M., Tickner, D., Loftus, A.-C., and Acreman, M.C. (2020). Impacts of riverine sand mining on freshwater ecosystems: a review of the scientific evidence and guidance for future research. River Res. Appl. *36*, 362–370.
11. Zou, W., Tolonen, K.T., Zhu, G., Qin, B., Zhang, Y., Cao, Z., Peng, K., Cai, Y., and Gong, Z. (2019). Catastrophic effects of sand mining on macroinvertebrates in a large shallow lake with implications for management. Sci. Total Environ. *695*, 133706.
12. Jones, H.P., Jones, P.C., Barbier, E.B., Blackburn, R.C., Benayas, J.M.R., Holl, K.D., McCrackin, M., Meli, P., Montoya, D., and Mateos, D.M. (2018). Restoration and repair of Earth's damaged ecosystems. Proc. R. Soc. B Biol. Sci. *285*, 20172577.
13. Magliocca, N.R., Torres, A., Margulies, J., D., McSweeney, K., Arroyo-Quiroz, I., Carter, N.H., et al. (2021). Comparative analysis of illicit supply network structure and operations: cocaine, wildlife, and sand. J. Illicit Econ. Dev. *3*, 1–24.
14. Bendixen, M., Overeem, I., Rosing, M.T., Bjørk, A.A., Kjær, K.H., Kroon, A., Zeitz, G., and Iversen, L.L. (2019). Promises and perils of sand exploitation in Greenland. Nat. Sustain. *2*, 98–104.
15. UNEP (2019). Sand and Sustainability: Finding New Solutions for Environmental Governance of Sand Resources (GRID-Geneva, United Nations Environment Programme).
16. Schandl, H., Müller, D.B., and Moriguchi, Y. (2015). Socioeconomic metabolism takes the stage in the international environmental policy debate: a special issue to review research progress and policy impacts. J. Ind. Ecol. *19*, 689–694.
17. Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., et al. (2013). Framing sustainability in a telecoupled world. Ecol. Soc. *18*. https://doi.org/10.5751/ES-05873-180226.
18. Levin, S.A. (1998). Ecosystems and the biosphere as complex adaptive systems. Ecosystems *1*, 431–436.
19. Von Bertalanffy, L. (1975). Perspectives on General System Theory: Scientific-Philosophical Studies (George Braziller).
20. Baccini, P., and Brunner, P.H. (1991). The anthroposphere. Metabolism of the Anthroposphere (Springer), pp. 10–46.
21. Eakin, H., DeFries, R., Kerr, S., Lambin, E.F., Liu, J., Marcotullio, P.J., Messerli, P., Reenberg, A., Rueda, X., Swaffield, S.R., et al. (2014). Significance of telecoupling for exploration of land-use change. In Rethinking Global Land Use in an Urban Era, K.C. Seto and A. Reenberg, eds. (MIT Press), pp. 141–161.
22. Barnett, H.J., and Morse, C. (1963). Scarcity and Growth: The Economics of Natural Resource Availability (Johns Hopkins University Press).
23. Petravatzi, E., Müller, D.B., Lundhaug, M., Liu, G., Cullen, J., Simoni, M.U., Dittrich, M., Cao, Z., Murguía, D., Hirschnitz-Garbers, M., et al. (2018). MinFuture Roadmap: A Roadmap towards Monitoring the Physical Economy (European Union). https://minfuture.eu/downloads/D5.3_Roadmap.pdf.
24. DMF (2018). Harde Fakta Om Mineralnæringen— Mineralstatistikk 2017 (Direktoratet for mineralforvaltning med Bergmesteren for Svalbard).
25. Přikryl, R., Török, Á., Theodoridou, M., Gomez-Heras, M., and Miskovsky, K. (2016). Geomaterials in construction and their sustainability: understanding their role in modern society. Geol. Soc. Lond. Spec. Publ. *416*. https://doi.org/10.1144/SP416.21.
26. European Commission (2018). The Commission presents strategy for a climate neutral Europe by 2050—questions and answers. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_18_6545.
27. Kennedy, C.A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K., et al. (2015). Energy and material flows of megacities. Proc. Natl. Acad. Sci. U S A *112*, 5985–5990.
28. Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., and Ren, J. (2018). Construction and demolition waste management in China through the 3R principle. Resour. Conserv. Recycl. *129*, 36–44.
29. O'Brien, J. (2019). Global aggregates growth examined by GAIN convenor Jim O'Brien. Aggreg. Res. Int. https://www.aggregateresearch.com/news/global-aggregates-growth-examined-by-gain-convenor-jim-obrien/.
30. Robinson, G.R., Jr., and Brown, W.M. (2002). Sociocultural Dimensions of Supply and Demand for Natural Aggregate—Examples from the

Mid-Atlantic Region, United States. US Geological Survey Open-file Report 2202-350. https://doi.org/10.3133/ofr02350.

31. OFT (2011). Aggregates. Report on the Market Study and Proposed Decision to Make a Market Investigation Reference (Office of Fair Trading).
32. Thakur, M.P., van der Putten, W.H., Cobben, M.M.P., van Kleunen, M., and Geisen, S. (2019). Microbial invasions in terrestrial ecosystems. Nat. Rev. Microbiol. *17*, 621–631.
33. Locey, K.J., and Lennon, J.T. (2016). Scaling laws predict global microbial diversity. Proc. Natl. Acad. Sci. U S A *113*, 5970.
34. CABI (2020). Soil, sand and gravel (pathway vector). In Invasive Species Compendium (CAB International) https://www.cabi.org/isc/datasheet/108259.
35. Nunes, I., Jurburg, S., Jacquiod, S., Brejnrod, A., Falcão Salles, J., Priemé, A., and Sørensen, S.J. (2018). Soil bacteria show different tolerance ranges to an unprecedented disturbance. Biol. Fertil. Soils *54*, 189–202.
36. Miller, S.A., and Moore, F.C. (2020). Climate and health damages from global concrete production. Nat. Clim. Change *10*, 439–443.
37. Miller, S.A., Horvath, A., and Monteiro, P.J.M. (2018). Impacts of booming concrete production on water resources worldwide. Nat. Sustain. *1*, 69–76.
38. UNEP (2015). Global Waste Management Outlook (United Nations Environment Programme; International Solid Waste Association).
39. Luo, X.-L., Zeng, E.Y., Ji, R.-Y., and Wang, C.-P. (2007). Effects of in-channel sand excavation on the hydrology of the Pearl river delta, China. J. Hydrol. *343*, 230–239.
40. Kondolf, G.M., and Podolak, K. (2014). Space and time scales in human-landscape systems. Environ. Manage. *53*, 76–87.
41. Schumm, S.A. (1979). Geomorphic thresholds: the concept and its applications. Trans. Inst. Br. Geogr. *4*, 485–515.
42. Hackney, C.R., Darby, S.E., Parsons, D.R., Leyland, J., Best, J.L., Aalto, R., Nicholas, A.P., and Houseago, R.C. (2020). River bank instability from unsustainable sand mining in the lower Mekong River. Nat. Sustain. *3*, 217–225.
43. Mallick, R.B., Radzicki, M.J., Zaumanis, M., and Frank, R. (2014). Use of system dynamics for proper conservation and recycling of aggregates for sustainable road construction. Resour. Conserv. Recycl. *86*, 61–73.
44. Davis, S.J., Caldeira, K., and Matthews, H.D. (2010). Future CO_2 emissions and climate change from existing energy infrastructure. Science *329*, 1330–1333.
45. Lin, C., Liu, G., and Müller, D.B. (2017). Characterizing the role of built environment stocks in human development and emission growth. Resour. Conserv. Recycl. *123*, 67–72.
46. BPIE (2017). 97% of Buildings in the EU Need to Be Upgraded (Buildings Performance Institute Europe). http://bpie.eu/wp-content/uploads/2017/10/State-of-the-building-stock-briefing_26Ott_v1.pdf.
47. Gruenhagen, J.H., and Parker, R. (2020). Factors driving or impeding the diffusion and adoption of innovation in mining: a systematic review of the literature. Resour. Policy *65*, 101540.
48. Kulp, S.A., and Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. *10*, 1–12.
49. Stewart, M.G., Wang, X., and Nguyen, M.N. (2011). Climate change impact and risks of concrete infrastructure deterioration. Eng. Struct. *33*, 1326–1337.
50. Wrathall, D.J., Mueller, V., Clark, P.U., Bell, A., Oppenheimer, M., Hauer, M., Kulp, S., Gilmore, E., Adams, H., Kopp, R., et al. (2019). Meeting the looming policy challenge of sea-level change and human migration. Nat. Clim. Change *9*, 898–901.
51. Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S., Marzeion, B., Fettweis, X., Ionescu, C., and Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. U S A *111*, 3292–3297.
52. Jordan, C., Tiede, J., Lojek, O., Visscher, J., Apel, H., Nguyen, H.Q., Quang, C.N.X., and Schlurmann, T. (2019). Sand mining in the Mekong Delta revisited—current scales of local sediment deficits. Sci. Rep. *9*, 17823.
53. Hailu, D., Ngonze, C., and Franks, D. (2019). Minerals in Post-disaster Reconstruction (UN Development Programme Blog). https://www.africa.undp.org/content/rba/en/home/blog/2019/minerals-in-post-disaster-reconstruction.html.
54. Fry, M. (2011). From crops to concrete: urbanization, deagriculturalization, and construction material mining in Central Mexico. Ann. Assoc. Am. Geogr. *101*, 1285–1306.
55. Lamb, V., Marschke, M., and Rigg, J. (2019). Trading sand, undermining lives: omitted livelihoods in the global trade in sand. Ann. Am. Assoc. Geogr. *109*, 1511–1528.
56. Global Witness (2010). Shifting sand. how Singapore's demand for Cambodian sand threatens ecosystems and undermines good governance (Global Witness). https://www.globalwitness.org/en/archive/shifting-sand-how-singapores-demand-cambodian-sand-threatens-ecosystems-and-undermines-good/.
57. Peduzzi, P. (2014). Sand, rarer than one thinks. Environ. Dev. *11*, 208–218.
58. Zakharia, N. (2020). Breakthrough for WA producer in Asian sand market. Quarry https://www.quarrymagazine.com/2020/12/03/breakthrough-for-wa-producer-in-asian-sand-market/.
59. Fischer-Kowalski, M., and Haberl, H. (2007). Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use (Edward Elgar Publishing).
60. Lambin, E.F., and Meyfroidt, P. (2010). Land use transitions: socio-ecological feedback versus socio-economic change. Land Use Policy *27*, 108–118.
61. Cao, Z., Shen, L., Løvik, A.N., Müller, D.B., and Liu, G. (2017). Elaborating the history of our cementing societies: an in-use stock perspective. Environ. Sci. Technol. *51*, 11468–11475.
62. Güneralp, B. (2015). Resource use for the construction and operation of built environments. In The Routledge Handbook of Urbanization and Global Environmental Change, K.C. Seto, W.D. Solecki, and C.A. Griffith, eds. (Routledge), pp. 101–116.
63. Hinton, J., Lyster, O., Katusiime, J., Nanteza, M., Naulo, G., Rolfe, A., Kombo, F., Grundel, H., MacLeod, K., and Kyarisiima, H. (2018). Baseline Assessment of Development Minerals in Uganda, *Volume 1* (ACP-EU Development Minerals Programme. United Nations Development Programme).
64. IISD (2018). Annex I. In International Conference on Artisanal and Small-Scale Mining & Quarrying (ASM18).
65. China Aggregates Association (2018). Many provinces are caught in a "sand grabbing battle"! the price of sand has risen by 600%! China Sand and Stone Association. http://www.zgss.org.cn/zixun/hangye/5332.html.
66. Wagner, L.A., Sullivan, D.E., and Sznopek, J.L. (2002). Economic drivers of mineral supply. US Geological Survey Open-file Report 2002-335 *2*, 335.
67. UEPG (2020). UEPG Annual Review 2018-19 (European Aggregates Association).
68. USGS (2020). Mineral Commodity Summaries 2020 (USGS). https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf.
69. Hámor, T., and Kovács, G. (2018). Riverbed aggregates dredging. Eur. Geol. J. *45*, 15–19.
70. Pascual, M., Ecorys, and Jones, H. (2018). Technical Study: MSP as a Tool to Support Blue Growth. Sector Fiche: Marine Aggregates and Marine Mining (European MSP Platform).
71. Jouffray, J.-B., Blasiak, R., Norström, A.V., Österblom, H., and Nyström, M. (2020). The blue acceleration: the trajectory of human expansion into the ocean. One Earth *2*, 43–54.
72. Danmarks Statistik (2019). Statistikbanken. https://www.statistikbanken.dk.
73. Brown, T. (2019). Construction Aggregates. Mineral Planning Factsheet (British Geological Survey).
74. Di Maria, A., Eyckmans, J., and Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: combining LCA and LCC to support sustainable policy making. Waste Manag. *75*, 3–21.
75. Stern, D.I., Common, M.S., and Barbier, E.B. (1996). Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development. World Dev. *24*, 1151–1160.
76. Meyfroidt, P., Roy Chowdhury, R., de Bremond, A., Ellis, E.C., Erb, K.-H., Filatova, T., Garrett, R.D., Grove, J.M., Heinimann, A., Kuemmerle, T., et al. (2018). Middle-range theories of land system change. Glob. Environ. Change *53*, 52–67.
77. Brockway, P.E., Owen, A., Brand-Correa, L.I., and Hardt, L. (2019). Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nat. Energy *4*, 612–621.
78. Bendixen, M., Best, J., Hackney, C., and Iversen, L.L. (2019). Time is running out for sand. Nature *571*, 29.
79. Sverdrup, H.U., Koca, D., and Schlyter, P. (2017). A simple system dynamics model for the global production rate of sand, gravel, crushed

rock and stone, market prices and long-term supply embedded into the WORLD6 model. Biophys. Econ. Resour. Qual. *2*, 8.

80. Meinert, L.D., Robinson, G.R., and Nassar, N.T. (2016). Mineral resources: reserves, peak production and the future. Resources *5*, 14.
81. Börker, J., Hartmann, J., Amann, T., and Romero-Mujalli, G. (2018). Terrestrial sediments of the Earth: development of a global unconsolidated sediments map database (GUM). Geochem. Geophys. Geosystems *19*, 997–1024.
82. Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., Fattah, R.A., Doornenbal, J.C., and Hopper, J.R. (2019). GlobSed: updated total sediment thickness in the world's oceans. Geochem. Geophys. Geosystems *20*, 1756–1772.
83. Ioannidou, D., Sonnemann, G., and Suh, S. (2020). Do we have enough natural sand for low-carbon infrastructure? J. Ind. Ecol. *24*, 1004–1015.
84. Bendixen, M., Lønsmann Iversen, L., Anker Bjørk, A., Elberling, B., Westergaard-Nielsen, A., Overeem, I., Barnhart, K.R., Abbas Khan, S., Box, J.E., Abermann, J., et al. (2017). Delta progradation in Greenland driven by increasing glacial mass loss. Nature *550*, 101.
85. Minerals4EU (2020). Data for aggregates and related materials. In European Minerals Yearbook (Minerals Intelligence Network for Europe). http://minerals4eu.brgm-rec.fr/m4eu-yearbook/pages/bycommodity.jsp?commodity=Aggregates%20and%20related%20materials.
86. UN Comtrade (2020). United Nations Commodity Trade Database (United Nations Statistical Division).
87. Wriggers, P., and Moftah, S.O. (2006). Mesoscale models for concrete: Homogenisation and damage behaviour. Finite Elem. Anal. Des. *42*, 623–636.
88. Johansson, E., Miškovský, K., Bergknut, M., and Šachlová, Š. (2016). Petrographic characteristics of intrusive rocks as an evaluation tool of their technical properties. Geol. Soc. Lond. Spec. Publ. *416*, 217–227.
89. Schøning-Lyberth, S., and Jørgensen, D. (2020). Greenlandic Sand. Examining the Potential of Selling Sand from Greenland, MSc Thesis, Copenhagen Business School. https://research-api.cbs.dk/ws/portalfiles/portal/62178354/818905_Master_Thesis_Greenland.pdf.
90. CAFF (2019). Arctic Coastal Biodiversity Monitoring Plan (Conservation of Arctic Flora and Fauna International Secretariat).
91. Wenger, A.S., Harvey, E., Wilson, S., Rawson, C., Newman, S.J., Clarke, D., Saunders, B.J., Browne, N., Travers, M.J., Mcilwain, J.L., et al. (2017). A critical analysis of the direct effects of dredging on fish. Fish Fish *18*, 967–985.
92. Jägerbrand, A.K., Brutemark, A., Barthel Svedén, J., and Gren, I.-M. (2019). A review on the environmental impacts of shipping on aquatic and nearshore ecosystems. Sci. Total Environ. *695*, 133637.
93. ACP-EU (2018). Baseline Assessment of Development Minerals in Uganda (United Nations Development Programme).
94. UNEP and IRP. (2020). Global material flows database. https://www.resourcepanel.org/global-material-flows-database.
95. Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E., and Schellnhuber, H.J. (2020). Buildings as a global carbon sink. Nat. Sustain. 1–8.
96. USGS. (2017). Statement of the U.S. geological survey. https://www.usgs.gov/congressional-statement/statement-us-geological-survey.
97. Graedel, T.E. (2019). Material flow analysis from origin to evolution. Environ. Sci. Technol. *53*, 12188–12196.
98. van den Brink, S., Kleijn, R., Tukker, A., and Huisman, J. (2019). Approaches to responsible sourcing in mineral supply chains. Resour. Conserv. Recycl. *145*, 389–398.
99. UNEP (2021). Catalysing Science-Based Policy Action on Sustainable Consumption and Production: The Value-Chain Approach & its Application to Food, Construction and Textiles (UNEP). https://www.unep.org/resources/publication/catalysing-science-based-policy-action-sustainable-consumption-and-production.
100. IRP (2019). Mineral Resource Governance in the 21st Century. Gearing Extractive Industries towards Sustainable Development (United Nations Environment Programme).