Sand, gravel and UN sustainable development goals: conflicts, synergies and ways forward

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1. Abstract

Sand, gravel and crushed stone, collectively referred to herein as aggregates, are the most mined materials on Earth. Aggregates constitute the foundation for modern civilization and are essential for providing shelter (concrete-buildings), movement (transport infrastructure) and communication (silica-based electronic devices). With rapid population growth, climate change and anthropogenic pressures on the natural environment, sand and gravel are becoming scarce resources, such that global demand for aggregates is expected to exceed rates of natural renewal within the next 20 years. Here, we review the interconnections between the impacts of aggregate mining and the services they provide. Our assessment shows that societal benefits gained from aggregate resource mining arise from economic gains and the ability to improve livelihoods. However, the conflicting impacts on the environment and humankind disrupts the net positive effects of aggregate mining on sustainable development. With a focus on low- and middle- income countries, we link these interconnections to the United Nations Sustainable Development Goals and identify critical obstacles to a sustainable future for global aggregate resources. Our assessment identifies an urgent need to improve knowledge on: (1) direct and indirect impacts of extraction on human health, (2) system-level impacts on ecosystems and the services they provide, and (3) how to meet the projected trajectories of global aggregate demand. Without such knowledge, policies cannot be developed to help mitigate the negative effects of extraction, while at the same time maintaining the value of this critical commodity for communities and economies around the world.

Introduction

Sand, gravel and crushed stone (collectively referred to herein as aggregates) are the most in-demand materials on the planet in terms of volume[1,2]. Together, they are a central foundation of our economies, and integral to sectors such as construction, infrastructure, electronics, cosmetics and pharmaceuticals[3]. The growing need to protect the world's beaches in order to help mitigate climate change[4], additionally adds pressure on the world's sand resources. With increasing consumption, we are rapidly approaching the point at which the demand for natural sand and gravel will exceed the rate of natural renewal[5]. Alternative sourcing of aggregate from crushed stone and recycling, and a reduction in demand are urgently needed[6]. Rapidly rising demand is coupled with poor governance in many countries, resulting in inappropriate extraction practices that damage the natural environment[7–9]. In addition, since mining legislation in many countries was developed with a focus on metal commodities, and these products are often exported to markets in high income countries (HIC), management and governance do not take into account the central importance of these aggregate resources in the planning of future sustainable development within the country of origin. Yet aggregates play an increasingly important role for many economies, providing access to basic housing and public infrastructures and livelihoods for large numbers of informal miners in low-and middle-income countries (LMICs)[9].

Despite the central importance of aggregates, the impact of their mining on the natural environment and human society remains relatively unknown. The aggregate mining sector is largely hidden from view, leading to global ignorance of the role of aggregates in socioeconomic development and ecological change and, subsequently, poor oversight. To ensure the globally sustainable development of aggregates, an understanding of the conflicts and synergies between aggregates, societies and the environment is critical to drive policy recognition and change[6,10]. Here, we expose these links by reviewing the global importance of aggregates and the effect of their mining on human and planetary wellbeing. First we review the multifarious aspects of aggregate extraction on the environment and society, covering economic development, global trade and inequality as well as landscape changes, ecosystem implications and environmental health, while providing a broad variety of examples of its implications. Second we present the first, assessment of potential conflicts and synergies with the UN's Sustainable Development Goals, focussing on low- and middle- income countries. Third, we make recommendations on the resources, research and actions required to secure a sustainable future for the world's aggregate resources.

2. Industrialization increases aggregate-demand

In combination with a growing global population, unprecedented human pressures are confronting the Earth's system[11] Sand, gravel and crushed-stone play a significant role in the global economy, with concrete being a central pillar of urban development[12]. For cement alone, a proxy for aggregate usage, China's demand has increased exponentially by 438% over the past 20 years, compared to an increase of 60% in the rest of the world[8]. Concrete is made with cement, water, sand and gravel. For each tonne of cement, the building industry needs roughly 6-7 tonnes of sand and gravel, thus constituting a rough proxy for aggregate usage without taking into account the materials needed for land reclamation and infrastructure such as construction of roads, highways and pavements. These patterns mirror a rapid increase in sand and gravel production in Eastern Asia since 1970, compared to more stable production in Europe and North America[13]. A large proportion of aggregate consumption has occurred in BRICS (Brazil, Russia, India, China and South Africa) countries, though rapid growth of economies in the OECD-world (Organisation for Economic Co-operation and Development) continues to be economically reliant and interlinked with global growth in trade.

The quality of the aggregates depends on the sources from which they are mined from. Aggregates are used in a broad variety of industries and have different markets, with specific characteristics required by the consumer and different quality requirements depending on the industrial segment, such as construction and manufacturing[1,14]. For use in concrete production, aggregates from river-beds involve little processing to produce usable materials[15], whereas marine materials that contain salt must be washed before use[16]. In spite of its abundance, most desert sand is unsuitable for the construction industry due to wind-abraded grains being too rounded and of uniform grain size, preventing proper binding abilities[17,18].

While current global aggregate consumption of 32-50 billion tonnes per year[19,20] is dominated by high (per capita) production in North America and China (FIG. 1a), the greatest relative increase in production is projected to occur in low- and middle- income countries[21]. Here, large resource and extractive industries contribute significantly to developing economies[22]. As demand grows for new and renewed infrastructure and building construction, so does the volume of aggregates used (FIG. 1b)[5,23], with a close relationship between increasing aggregate demand and economic performance at the national level[24,25]. In contrast to the production of other minerals and metals, which often require technically complex operations, expertise and special equipment, sand and gravel production is less demanding[26,27]. Aggregate mining in low- and middle- income countries is often executed informally by artisanal small-scale miners[28,29], providing an essential source of livelihoods for many people worldwide. Since aggregates are predominantly mined, processed and used domestically, they are sometimes referred to as 'development minerals'. Development minerals have a low price per tonne, when compared to other mineral commodities, but a very high value for domestic development[9]. Yet the potential economic and societal benefits of aggregate mining are often overlooked[9,30,31]. A recent trend, to some extent led by the media, has disproportionately described informal sand, gravel and crushed stone miners as criminals using pejorative terms like 'illegal' and 'sand mafia'. Linking informal miners to criminal networks *per se* generalizes and simplifies the global situation of miners and also stigmatises very large numbers of people in poverty. However, there are indeed numerous examples of illegal aggregate extraction across the world[7,31,32] with associated conflicts related to ecological destruction, livelihood disruption and labour rights violations[33]. To ensure a respectful, balanced and productive discussion with different experiences and perspectives of the miners, focus should thus be on understanding the context of the activities in the aggregate industry.

3. Impact of aggregate mining on the environment

Quaternary deposits, mountainous regions with abundant precipitation and water runoff, and local bedrock geology create a heterogeneous global mosaic of areas with high concentrations of sand and gravel. Aggregate mining occurs in riverbeds and lakes, on floodplains, along beaches and in the marine environment as well as on land where the underlying geology is suitable (Box 1). In addition, other sources, such as in volcanic terrains[34], face issues of environmental governance in order to encourage sustainable development. The environmental consequences of aggregate mining activities in many landscapes are thus complex, with numerous geomorphic, ecological, societal and health implications[8,35].

3.1 A driver of landscape change

Aggregate extraction can alter local topography[15], creating incisional pits in river and lake beds[36–39], depressions on floodplains[40] and loss of beach elevation, coastal sand dunes[41,42] and shallow shelf environments[43]. In turn, mined aggregates are often used to infill depressions on floodplains and in nearshore areas to create land for construction, infrastructure projects and urban development. For example, over the past forty years, Singapore's land area has grown by 20% (130 km^2)[44]. This growth necessitated the import of a reported 517 million tonnes of sand, increasing past demand from across South-East Asia, notably Cambodia, Vietnam, Indonesia[44,45], Malaysia and India. Quarrying for aggregates can also leave visible scars on the landscape, although the restoration of disused quarries also affords an opportunity to repair damage, reintroduce biodiversity and promote ecosystem development[46], whilst creating new landscapes that can be used by society[47].

Major effects on hydrology can ensue as a result of aggregate mining, with open-cast pit mining potentially disrupting hydrological and hydrogeological regimes with far-reaching impacts on water quality and availability[48–50]. Aggregate mining of rivers can also cause major effects on the availability of, and access to, local water tables[51], as well as changing local flood regimes[52]. Increases in riverbed and riverbank slope angles, and subsequent slope instability, are also created by local topographic lowering. For example, along the Mekong River, Cambodia, individual mining pits on the river bed can reach up to 70 m in diameter and 10 – 17 m in depth[36,37]. Hundreds of individual pockmarks caused by mining have resulted in riverbank instability and, even at modest levels of bed scour (2 m), entire sections of the Mekong River banks are liable to fail when the banks become saturated during the monsoon flood[36]. River bed incision can also create problems in the scour of in-channel infrastructure, such as bridge piers and embankments[51,53,54]. When sediment is removed from riverbeds, water flow is altered. Flow over mining pits may create changes to the near-bed structure of turbulence[55], which promotes the downstream erosion of the mining pits, collapse of the flank walls, and longitudinal extension of the pit[56]. The removal of sediment may also cause the lowering of river and delta channel beds, which also directly affects the mixing of fresh and saline waters. In Vietnam, for example, ongoing deepening of the Mekong delta channels by 0.2 – 0.3 m per year has resulted in an increase in their water salinity of 0.2 – 0.5 PSU yr^{-1} (Practical Salinity Unit)[57]. As such, within approximately 10 years it is expected that salinities of 10 PSU will be observed an additional 10 km inland from the delta front, with some estimates forecasting a landward progression of the tidal limit by 56 km in the next two decades[58]. Such change will result in a reduced area for rice production, with ramifications for livelihoods across the delta[57,59].

Changes to sand dunes and sediments in marine environments can also be associated with aggregate mining. For example, the removal of sand and gravel in the nearshore zone has been identified as a driving force behind the enhanced erosion of sand dunes along Southern Monterey Bay during 1940 – 1990, compared to 1990 – 2004 when mining was prohibited[60]. If too close to the shore, offshore dredging limits the ability of coastal systems to transport sediment both offshore[61] and alongshore[62]. Nearshore dredging of sand shoals can also potentially change the hydrodynamics and processes of sediment suspension along coastlines[43].

3.2 Ecosystem impacts of aggregate mining

Aggregate mining can have severe effects on freshwater systems[35] and marine environments[16,63,64], with major ramifications for ecosystem function and biodiversity. Mining activities may impact local vegetation structure directly when mining destroys riparian vegetation on the floodplain[65], or change the abiotic conditions on the floodplain leading to a shift in vegetation structure[35]. In the Lower Eygues River, France, the creation of access roads and aggregate mining storage sites has fragmented riparian forests in the river valley[66]. Changes induced by aggregate mining to vegetation[67] and fish communities[68] have also been found to cause shifts in the rates of carbon and nitrogen cycling, ecosystem productivity and ecosystem structure[69].

During marine dredging, the ensuing disturbance of bed material and resuspension of fine sediments can result in reduced water quality around mining sites with compounding negative impacts on macroinvertebrate and fish communities[70,71]. This process impacts entire marine ecosystems through increasing water depth due to mining, together with increasing water turbidity, which can inhibit light penetration, thereby shifting the abiotic conditions that control benthic ecology[16,43]. Large scale continuous marine dredging has been shown to create a shift in local species pools towards a fauna dominated by pioneering species[72]. Increased turbidity produced by sand mining may also be detrimental to photosynthesis, and has been partly responsible for the decline in Indonesia's globally important seagrass meadows[73].

Another ecological consequence of sediment mining may be the introduction of non-native species into a region, as known from trade and transport of international shipping containers. This can take the form of altered habitats that may then favour the spread of non-native species[74], direct import of non-native species in the transported sediments[75], or the introduction of non-native species on ships used for transporting sediment[76], via ballast water and attachment to ships' hulls and propellers. Such non-native species may also include microorganisms, such as bacteria, fungi and viruses, due to global trade[77].

4. Implications for environmental health

Detrimental effects on human health caused by mining activities have been linked to the dispersal of contaminants, silicosis (a fibrotic lung disease) and increased risk of infectious and sanitation-related diseases.

4.1 A vector of contaminants

River, lacustrine and marine sediments are exposed to a wide range of inorganic and organic anthropogenic contaminants[78–81], such as pesticides, industrial metals, chemicals and plastics, which can be exported when aggregates are extracted[16]. Contaminants may also accumulate in sediments from mine tailings of active and relict metal mining activities[82]. Such tailing sources can contain toxic elements linked to both the extracted minerals and their processing, such as arsenic, lead and cyanide, in concentrations that may be hazardous to ecosystem and human health[83,84]. Dredged sediment has been shown to include contaminants that accumulate in marine oyster farms[85] and freshwater fish farms[86], and high copper concentrations in the Lagos harbor, Nigeria, have been attributed to sand dredging[87].

Besides sand-sized particles and larger grains, the sorption of some contaminants onto the surface of fine particles, such as clays and organic fragments, can possibly provide a route for contaminant spread within mined aggregates. The potential for contaminant spread depends on environmental conditions such as temperature, acidity, solubility and the speciation of the compound[78]. For example, the antibiotic ciprofloxacin and beta blocker propranolol have the potential for rapid sorption within the aquatic environment, and are an important example of the transport of microcontaminants[80]. In addition, other organic contaminants involve groups such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyl compounds (PCBs) that can persist and may accumulate in the organic sediment fractions[78].

Disease pathogens may also be present and exported within natural aggregates[78]. For example, snails act as the intermediate host for the liver fluke *Opisthorchis viverrini* in the Mekong River Basin, and *Schistosomas* (the causative agent of schistosomiasis or bilharzia) is widespread in many rivers and lakes across the tropics[88,89]. If these hosts can survive transport within mined aggregates, their lifespan of several years[90] suggests a potential source of spread of this disease.

To minimize the likelihood of contamination, the potential dangers presented by both natural and anthropogenic pollutants to human and ecosystem health must be understood. This has been achieved successfully in the remediation of polluted rivers and the implementation of procedures to enable safe dredging and removal of toxic sediments, such as those that have involved dioxins, PCBs and PAHs[78]. Procedures for the removal of such waste and its disposal are widely adopted in river basin restoration[79,91,92], but even in developed countries may pose long-term problems to safe environmental management[93,94]. Consequently, there is a need to assess the nature and magnitude of potential contaminants within mined fluvial aggregates before they are exported, and include such considerations within environmental impact assessments, from which they are currently absent[53].

4.2 Human wellbeing in the mining environment

In addition to the potential transport of contaminants, pathogens and disease vectors, other aspects of aggregate mining may affect human health. During mining activities, long-term inhalation of small crystalline particles of silica can lead to silicosis, lung cancer, chronic obstructive pulmonary disease, autoimmune disease and tuberculosis[95]. For example, the excavation and processing of aggregates has increased the prevalence of silicosis among workers processing crushed stone materials in Rajasthan, India[95,96]. Exposure of workers to new environments or disease vectors, as well as changes to the environment that increase disease transmission and socioeconomic changes, can also be risk factors for poor health. For example, workers in non-aggregate extractive industries have been found to have a greater exposure to infectious diseases such as diarrhoea, malaria, tuberculosis and sexually transmitted infections[22,97] This increased risk is due to the introduction of susceptible populations into disease endemic areas[98,99], inadequate housing, water and sanitation for mine workers[22], and changes to the environment that may provide aquatic habitats for disease vectors, such as mosquito vectors of malaria[100,101]. Violence can also increase alongside mining; in India, the mining of sand in particular has been associated with local conflict linked to water access and pollution[32]. Child labour is also common where the sector is informal, threatening the health and safety of children with limited or no access to schools or social services[1]. Paradoxically, income generated from aggregate mining activities can also be the factor that enables children to go to school[102], and the dispute that prohibition of child labour may harm the children is a well-known argument in the cobalt-industry[103]. Mining may also improve health through the provision of livelihoods[31,104] and ultimately the materials to build better houses, roads and other infrastructure[105,106].

5. Global inequality in the aggregate sector

Global patterns in aggregate supply chains and trade differ across high-, middle- and low- income countries. High-income countries are characterized by regulated extraction and higher rates of trade compared to low- and middle-income countries, in which mining is commonly an informal economic activity undertaken by artisanal and small-scale miners[28,29]. An increasing body of literature has claimed that in South Asia, these activities are often carried out as illegal activities with sand mafias controlling extraction practices and trade[32,33,107–109] However, in many growing economies such as the BRICS countries (Brazil, Russia, India, China and South Africa) as well as Indonesia, Malaysia, Thailand and Vietnam among others, aggregate mining is not only small-scale and livelihoods-driven, but mechanized extraction is driven by economic growth. Here, increased income levels and credit availability are resulting in major investments in infrastructure and housing and, subsequently, massive increases in aggregate demand.

5.1 Transitions in global trade patterns

Aggregate trade arises when local resources are limited relative to demand, or when land use policies prevent extraction of local resources[10,110–112]. Consequently, a combination of continued increase in demand for aggregates and depletion of local resources is shaping global patterns of aggregate trade[5,21]. While global trade of aggregate commodities has increased markedly in recent years (FIG. 2a), sand, gravel and crushed stone are predominantly produced and consumed domestically[1]. Of the 50 billion tonnes produced in 2017 (FIG. 1a), less than 1% (301 megatonnes, FIG. 2a) was legally traded transnationally.

The bulk nature of aggregates and high transportation costs result in the importation of large volumes of aggregate only being feasible for a small number of high income countries (HIC; FIG. 2b). Consequently, transnational trade is shaped by high importation rates in North America, North and Central Asia, Europe, and other HIC relative to Africa, Oceania and Central and South America (FIG. 2b,c), and the amount of aggregates traded has been rising for the last 15 years (FIG. 2a). In particular, the need for sand and gravel for construction is driving transnational trade wherever domestic aggregate demand cannot be met at a local level. For example, following a complete depletion of marine sand resources, prestigious construction and land reclamation projects in Dubai, UAE, were built largely with sand from distant sources, such as Australia[8]. Consequently, transnational export rates are expected to increase in many low-middle income countries (LMIC), despite the fact that these same countries have the largest deficit in future aggregate demands relative to their current national production[21].

The growing quantity of transnational trade (FIG. 2a) and concomitant increase in global aggregate prices are also extending the maximum transport distances for profitable exports. Exporting countries are thus expected to expand trade to new markets[21] and, as such, remote regions such as the Arctic, could potentially establish new global exports[113]. The sustainability of such emerging markets must be based on governance supporting local gains and minimizing potential effects on the environment[45,113].

5.2 Supply chains and livelihoods in HICs and LMICs

In high-income countries (HICs), the extraction of sand, gravel and crushed stone is largely regulated, mechanized, and practiced by formal quarrying companies, with sand and gravel extraction from natural waterways comprising a minority of aggregate production. In Europe, key aggregate sources are crushed rock from quarries (46%), terrestrial deposits and rivers (38%), recycled aggregate (12%) and manufactured sand (2%), whereas only 2% comes from the marine environment[114]. In low- and middle-income countries, however, sand, gravel and crushed-stone mining is commonly an informal economic activity undertaken by artisanal and small-scale miners, as well as small and medium sized enterprises[9]. Aggregate mining is present across a wide range of geological, social and environmental settings[115]. For example, in Fiji, river gravel extraction comprises 64% of aggregate production by volume and 76% of regulated extraction sites[116], whilst in Cameroon, artisanal sand miners dive to collect sand from river beds by hand[117]. In Kiribati, a shortage of aggregates has contributed to sand mining being practiced by communities along exposed beaches and reefs[118]. Beach sand mining could potentially impact tourism displacing or disrupting tourism-related activities impacting local economies. Although the sector is not well documented, artisanal and small-scale mining of aggregate is likely to be a major source of livelihoods across LMICs. For example, the World Bank[119] estimates that more than 12 million people are employed in the artisanal and small-scale quarrying sector in India, and there are at least 170,000 known sand and stone miners in Uganda[120]. As mining becomes more formal and mechanised, its contribution to livelihoods employment becomes more modest. Participation in artisanal and small-scale aggregate mining is generally poverty-driven, seasonal and a livelihood diversification strategy. Small-scale and informal mining can introduce precarious labour rights, contractual or sub contractual daily wage employment and occupational hazards[33]. For small-island developing states without adequate deposits of sand, gravel and crushed-rock, it is often necessary to import construction materials from neighbouring countries at significant expense[116,118]. In Uganda, three quarters of documented artisanal aggregate miners also practice farming, with average incomes from mining three to four times higher than smallholder farming[120]. The gendered aspect of aggregate mining differs from country to country with a varying proportion of women involved in the sector[121]. The general trend though is that men undertake the heavy jobs and women being responsible for the more labour-intensive jobs[121]. In places where criminal networks control the extraction, there is often a clear division of tasks including threats of labour unrests, forgery, threats and manipulations[107,108,121].

6. Conflicts and synergies with United Nations's SDGs At the core of the UN Sustainable Development Goals (SDG) is improvement of the lives and wellbeing of the world's poorest and most marginalized populations, via an international framework to tackle the most urgent economic, social and environmental challenges[122]. However, the SDG framework neglects the importance of sand and gravel as a natural resource[6,9], with no mention of aggregate mining nor any consideration of its environmental costs and social effects. This is a major oversight, since aggregates are a pillar of modern civilization and a major driver of environmental change, and their production and use is intricately linked to multiple SDGs.

To provide a first, critical step towards policy recognition and change, we assessed how aggregate mining (sand mining, gravel mining and crushed stone activities) and its use relates to the SDGs with a focus on low- and middle- income countries. Using a consensus-based expert elicitation method (for details of this approach see Supplementary Materials), we evaluated each SDG and sub-target for synergy or conflict with aggregate mining (Supplementary Table 1 and 2). This assessment included all aspects related to mining activities, from its use in infrastructure and urban development to its implications for human health and wellbeing. By estimating the impact of aggregate commodities and extraction on each of the 17 SDGs individual targets, we found major conflicts for nine SDGs, synergies for five SDGs and neutral associations for three SDGs (FIG. 3, Table 1).

The greatest conflicts were identified for goals linked to the future of the environment and human needs, in three critical areas. First, the combined effects of aggregate mining on the landscape and an underdeveloped implementation of climate mitigation and disaster planning in the aggregate mining sector, as well as disaster planning strategies, in the aggregate mining sector causes conflict with Goals 6 (Clean Water and Sanitation), 13 (Climate Action), 14 (Life below Water), and 15 (Life on Land). Second, the strong dependence of a low-income and uneducated workforce in the low- and middle-income countries on aggregate extraction is intertwined with inequalities among social and racial groups, conflicting with Goals 4 (Quality Education), 8 (Decent Work and Economic Growth) and 10 (Reduced Inequalities). Third, the lack of oversight and governance for the availability and use of aggregate resources negatively impacts the development of policies supporting peaceful, inclusive societies, targeted by Goal 16 (Peace, Justice and Strong Institutions).

In contrast, synergies were identified between aggregate development and five SDGs relating to socioeconomic development, specifically Goal 1 (No Poverty), Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation and Infrastructure), Goal 11 (Sustainable Cities and Communities) and Goal 17 (Partnerships for the Goals). Here, aggregate resources provide labour for millions of people, supply material for infrastructure projects, housing, and the renewable energy sector and drive economic development and diversification through direct and indirect economic benefits.
Finally, we identified three goals that are neither supported nor undermined by aggregate development, either due to lack of relevance of aggregate mining activities or due to synergistic effects counterbalancing conflicts within individual goals: Goals 2 (Zero Hunger), 3 (Good Health and Wellbeing) and 5 (Gender Equality) (FIG. 3). Overall, these results show that conflicting interests can be seen directly and indirectly between goals intended to safeguard the environment and those promoting economic development, improving health, eliminating poverty and reducing inequality.

7. Supporting the SDGs

The SDG-assessment of synergies and conflicts of aggregate mining presented herein clearly underlines the need to comprehensively understand the balance between the societal benefits gained from aggregate resource mining and the negative impacts aggregate extraction exerts on the environment and humankind. Many of the synergistic effects on the SDGs provided by aggregate mining activities arise from economic gain, and thus the ability to improve livelihoods with an overall positive impact of mining on low-income people. However, the physical impact that the scale of aggregate extraction and consumption has on the environment, conflicts with goals linked to the natural dynamics of terrestrial and aquatic ecosystems (Goals 14 and 15). In order to build effective management plans and policies that balance these pros and cons, a more complete understanding of the impact of aggregate mining is required. This need is especially acute for many countries in low- and middle- income countries that currently possess no overview of the extent of local mining activities, or how such activities are impacting ecosystem services and landscape dynamics[6,35]. Below, we highlight critical and urgent knowledge gaps and discuss six ways forward:

1. *Environmental threats*

Dredging and aggregate mining leave visible scars on the landscape and there is an urgent need to protect biodiversity from both direct habitat destruction at mining sites and indirect impacts from altered sedimentation rates in dynamic environments such as river channels, floodplains and coastal habitats. Historically, the impacts from aggregate mining have not been considered a high-level threat to aquatic diversity, with few protected areas designated to mitigate mining-related threats[123]. The discrepancy between mounting evidence for the negative effects of aggregate mining on the environment and the lack of conservation efforts related to these impacts, creates a major vulnerability for the protection of our global biodiversity resources (SDG 14 and 15). In regions where aggregate mining poses a threat to the environment, local conservation strategies and environmental impact assessments must include not only the direct, but also the indirect, effects of such mining activities. Upstream and neighboring resource mining have been shown to potentially disrupt conservation effects from protected areas in both marine and freshwater habitats[124,125]. Thus when evaluating how aggregate mining will impact a landscape, the effects from mining activities must be understood in the light of other existing human pressures. Compound stresses from several threats[126] can multiply the impact that aggregate mining has on the landscape, but current research on landscape change frequently fails to include such interactions, principally due to the lack of data and recognition of the spatial and temporal scales of the challenge. Such interactions could be present as: 1) Parallel, singular independent threats (e.g. an ecosystem stressed by climate change could be more sensitive to the impacts of aggregate mining, even though the two stressors largely affect the environment independently); 2) Parallel additive threats[127] such as river hydropower dams and aggregate mining both reducing downstream sediment delivery by trapping[126,128], or removing sand and gravel and thereby collectively impacting the riverine sediment balance; and 3) Crossed synergistic threats[127] such as dams that alter and homogenize stream flows[129,130] and that could reduce the ability of a river to recover from floodplain mining, thereby escalating the impacts caused by aggregate mining.

2. *Tracking contamination*

In the light of trade for aggregates, the nature and magnitude of potential contaminants within mined fluvial aggregates must be assessed *before* they are exported. Yet, assessment of potential local and global contamination from aggregate commodities is currently absent when evaluating environmental impacts from aggregate mining[53]. The pressing need to establish the origin, purity and sustainability of extracted aggregates also calls for a need to establish a 'Fair Trade' policy for aggregate mining that can aid progress specifically towards the goals linked to combating diseases and epidemics (SDG 3), ensuring the availability and sustainable management of drinking water (SDG 6) and sustainable consumption and production patterns (SDG 12). In addition to the environmental consequences of aggregate mining, sand and gravel possess a mineralogical and geochemical make-up that is unique to each geographical location. This composition may pose issues for environmental contamination and human health[81,131,132], but perhaps paradoxically also presents an opportunity to track the origin, and global dispersal, of aggregates. Some of these compositional characteristics are intrinsically linked to the geology of the contributing river basins, including elements that can be hazardous depending on their concentration (i.e., arsenic, lead, zinc, cadmium and chromium), whilst others may be specific to human-made components (such as plastics, pharmaceuticals and industrial contaminants). Thus, future research should focus on whether these natural and anthropogenic components of exported aggregates can provide a method by which to "*fingerprint*" the origin, or provenance, of the sediments[79,133].

3. *Overlooked human health implications*

Although aggregate mining provides livelihoods for many people in low- and middle- income countries, and health-related issues connected to aggregate resource extraction will disproportionately affect low-income populations, a comprehensive overview of direct health risks posed by mining is lacking for the aggregate sector. Yet, an increased focus would raise awareness of the implications, and allow development of policies by which to incorporate the importance of worker's health within sustainable extraction practices. These could help prevent, for example, known serious lung diseases, and more broadly improve the health conditions of workers. Regulations and strategies for controlling exposure to silica have helped reduce the incidence of silicosis in high-income countries, but such actions are currently lacking in low- and middle- income countries[134]. These issues may be exacerbated since aggregate extraction is often carried out illegally or informally by small-scale operators[31,109,135], who are unlikely to have access to adequate health care or who may avoid health services run by authorities[136], and who lack economic and physical security[137], increasing their vulnerability and overall feeling of lacking both a voice and power. An increased focus would specifically target SDG 3 'Good Health and Wellbeing' and contribute positively towards reducing substantially the number of deaths and illnesses from hazardous chemicals and air, water and soil contamination. Implementation of policies concerning labour conditions could help promote higher economic gains and improvements in livelihoods for miners, and would contribute simultaneously to achieving full and productive employment for women and men, including young people, relevant to SDG 8 (Decent Work and Economic Growth). The indirect threat to human health is exemplified in the apparent paradox between sand and gravel mining and disease prevention. It is known that shallow bodies of standing water are formed when sand and gravel are extracted on river floodplains, and that these pools constitute breeding-sites for malaria vectors[138]. Simultaneously, housing improvements, generated from aggregate mining products, can reduce risk from malaria and other vector-borne diseases, as well as improve other child health outcomes known to decrease child mortality[106]. An evident knowledge gap thus exists regarding the balance between the impact of sand and gravel mining on the prevalence of malaria, and to what extent mining generates novel breeding sites for mosquitoes or mitigates infections by improving local housing conditions. A better understanding of this interrelationship between aggregate extraction and its usage for housing and health improvement is needed to provide guidelines for best practices on extraction. If we fail to recognize the complex nexus of aggregates, housing and health, the consequences will further diminish the quality of life for millions of people who are already living in precarious circumstances.

4. *New technologies and alternatives*

Current trajectories of a steeply growing, and unsustainable, aggregate demand must be changed without undermining the livelihoods enabled and supported by the commodity. It has been highlighted that critical components in solving the challenge of sustainable aggregate resource extraction and consumption should prioritize new technologies and alternatives to aggregate extraction where they are a part of active ecological systems, by improving cooperation and enhancing knowledge sharing, specifically targeting Goal 17 (Partnerships for the Goals). These opportunities include development of methods to make use of desert sand in concrete production and recycling of materials, such as commodity plastic[139], benign by-products of mine tailings and mineral processing wastes, demolition waste[140], and new sources, such as in Greenland where the melting icesheet has been speculated to hold the promise of new sand and gravel sources[113] if environmental degradation could be avoided. Current debate on such speculation[10] shows that these developments in potential new sources, and their role in a global sand supply network, are worthy of fuller consideration.

5. *Circular economy approach*

Economies linked to aggregate commodities are increasingly tailored to a global market, dependent on transnational trade and resource availability. By ignoring the ideology of a resource efficient circular economy[10], such as a focus on increasing recycling, closed local supply chains and a lowering of the interconnectedness within the global trade market, the construction industry contributes to the fact that the world today is only 8.6% circular[141]. Furthermore, the construction and building industries jointly account for 39% of energy-related CO_2 emissions[142] Knowledge of circular initiatives, such as recycling in stock aggregates and integrating waste products into concrete production, would reduce dependency on global trade and thus limit carbon emissions, thus directly contributing to mitigating climate change (Goal 13: Climate Action). In light of the global lockdown during the Covid-19 pandemic and changes to economies as they emerge from the pandemic, now is the time to implement new ways of acknowledging, and acting upon this urgent need for setting new standards. When reopening economies after the pandemic, governments and policymakers have an unprecedented opportunity to structure a more balanced resource usage and create a new contemporary economic paradigm, and the construction industry has a unique chance to shift towards a more circular material usage helping to achieve Goal 9 (Industry, Innovation and Infrastructure).

6. *A pressing need for monitoring*

A critical component in achieving sustainable aggregate consumption is simply better monitoring of aggregate resources, aggregate usage and aggregate transport. Priorities for research should include information on the distribution of mining activities in the landscape[6], site specific measurements of sediment flow in aquatic systems[128], monitoring of how mining is changing such environments[35], quantitative data on local and transnational supply chains[5,7,10], and assessments compiling health data linked to mining activities[134]. Well-established techniques and methodologies are already in place, and such programs – on regional, national and international scales – are needed to address current data and knowledge gaps, and thus fully assess the magnitude of aggregate resource extraction. When monitoring initiatives go hand in hand with better global governance, national and regional governments can become better equipped to implement stricter environmental legislation that is directly related to the achievements of data, monitoring and accountability in Goal 17 (Partnerships for the Goals).

8. Conclusion

Aggregate resources, when managed appropriately, can create jobs, develop skills usable in other sectors of the economy and spur innovation and investment, whilst continuing to underpin the infrastructure upon which modern society is founded. Yet numerous conflicting interests with the UN SDGs are evident, thereby exacerbating many of the problems that these goals seek to address. The major challenge is to balance aspirations for economic growth with environmental sustainability, and thus planning a path forward requires a comprehensive understanding of the transdisciplinary interconnections between aggregate mining and the SDGs. Numerous targets within each SDG are intertwined, and the road towards achieving these goals will possess considerable bumps along the way, with costs and far-reaching effects for the environment and humans. However, the essential basis for the future management of aggregate resources must include human and environmental wellbeing in a holistic approach, where future frameworks and guidelines are flexible enough to address and achieve multiple interests and goals. Future assessments must be comprehensive in scope in order to fully understand the links between aggregate mining, poverty reduction, improvement of livelihoods and overall planetary health. At this pivotal time, it is imperative that local communities, governments, scientists and policymakers acknowledge the scale of the challenge. Focus must be on establishing tools and resources, and coordinating research and global action, in order to achieve a sustainable future for aggregates.

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Author contributions

M.B. initiated the study and framed the research questions together with J.B., C.R.H., and L.L.I. M.B., L.L.I., D.F., and L.T. linked the literature to the SDG indicator framework. L.L.I. organized the data and prepared the figures with inputs from all authors. All authors contributed to the writing of the manuscript. The initial author team was established on December 13, 2019 (M.B., J.B., C.R.H., and L.L.I.), including D.F. and E.L. on January 7, 2020 and L.T on July 6, 2020.

Competing interests

The authors declare no competing financial interests

BOX: The diversity of aggregate mining

Aggregates (sand, gravel and crushed-stone) are extracted from rivers, lakes and floodplains, along beaches and in the marine environment as well as on land. Extraction activities can depend on substantial investment and capital required for infrastructure (e.g. barges, trucks and pumps), but can also be highly labour intensive extraction practises executed by small-scale miners and quarry workers. Generally, where aggregate mining is informal, a large number of miners are involved in the extraction processes. While aggregates play an economically important role as a 'Development Mineral' for developing countries, employing millions of people, improving livelihoods and reducing poverty, the extraction has large complex consequences, with numerous geomorphic, ecological, societal and health effects and implications. **a)** Labourers offload buckets of sand from a dredge boat, Dhaleshwari River, Bangladesh. **b)** Aggregate quarry in Atlanta, United State (credit: Shane McLendon) **c)** A dredger pumping sediment for land reclamation in the Gulf of Dubai.

Figures

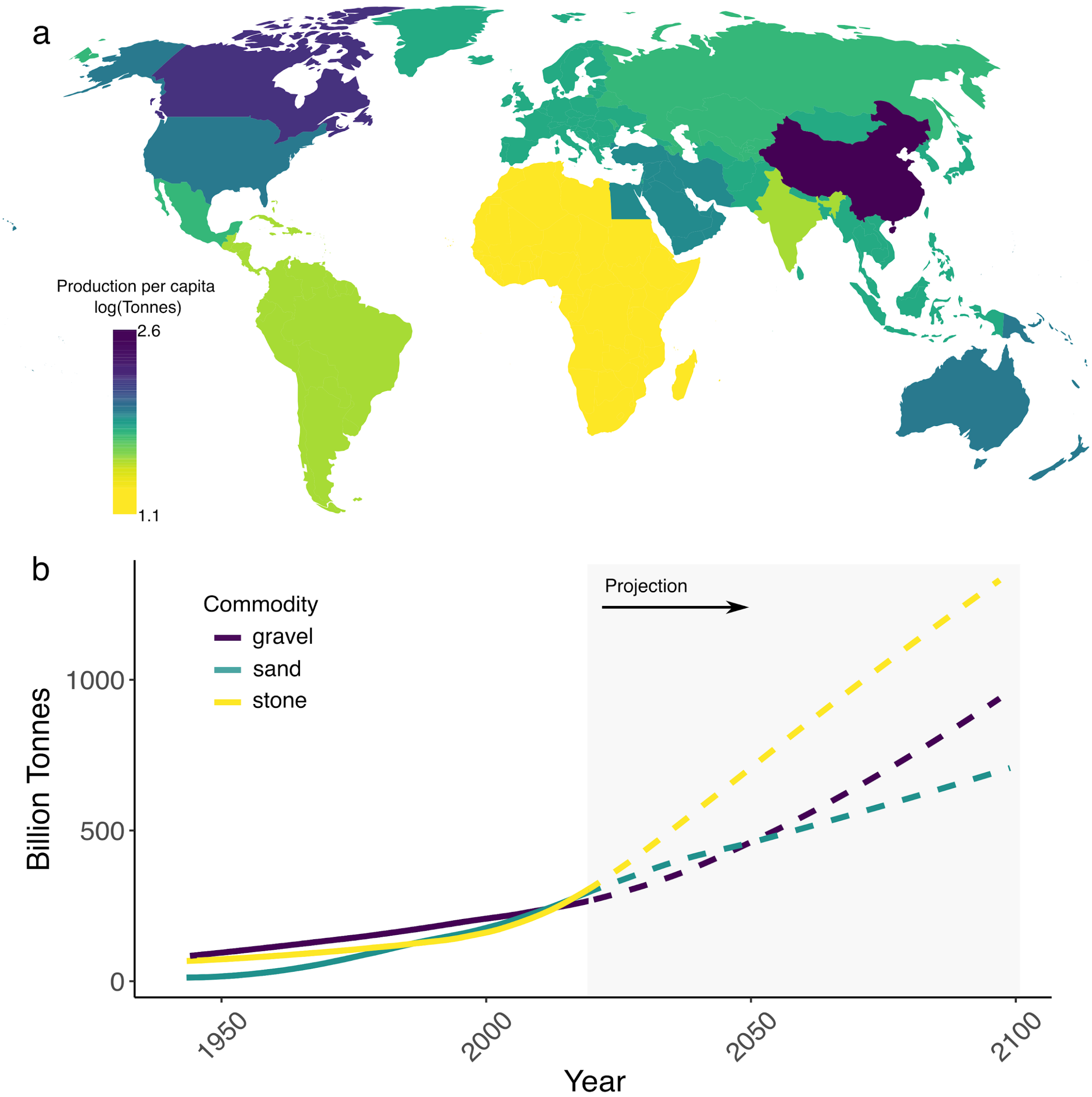

Figure 1: Global aggregate **production and in-stock usage. a.** Global per capita aggregate production in 2017, when thetotal global production was 50 billion tonnes (data from the Global Aggregates Information Network - gain.ie). **b.** The quantity of sand, gravel, and stone (stocks) in use by society. Solid lines represent current and historical values and dotted lines are projected estimates (data from Ref[5]).

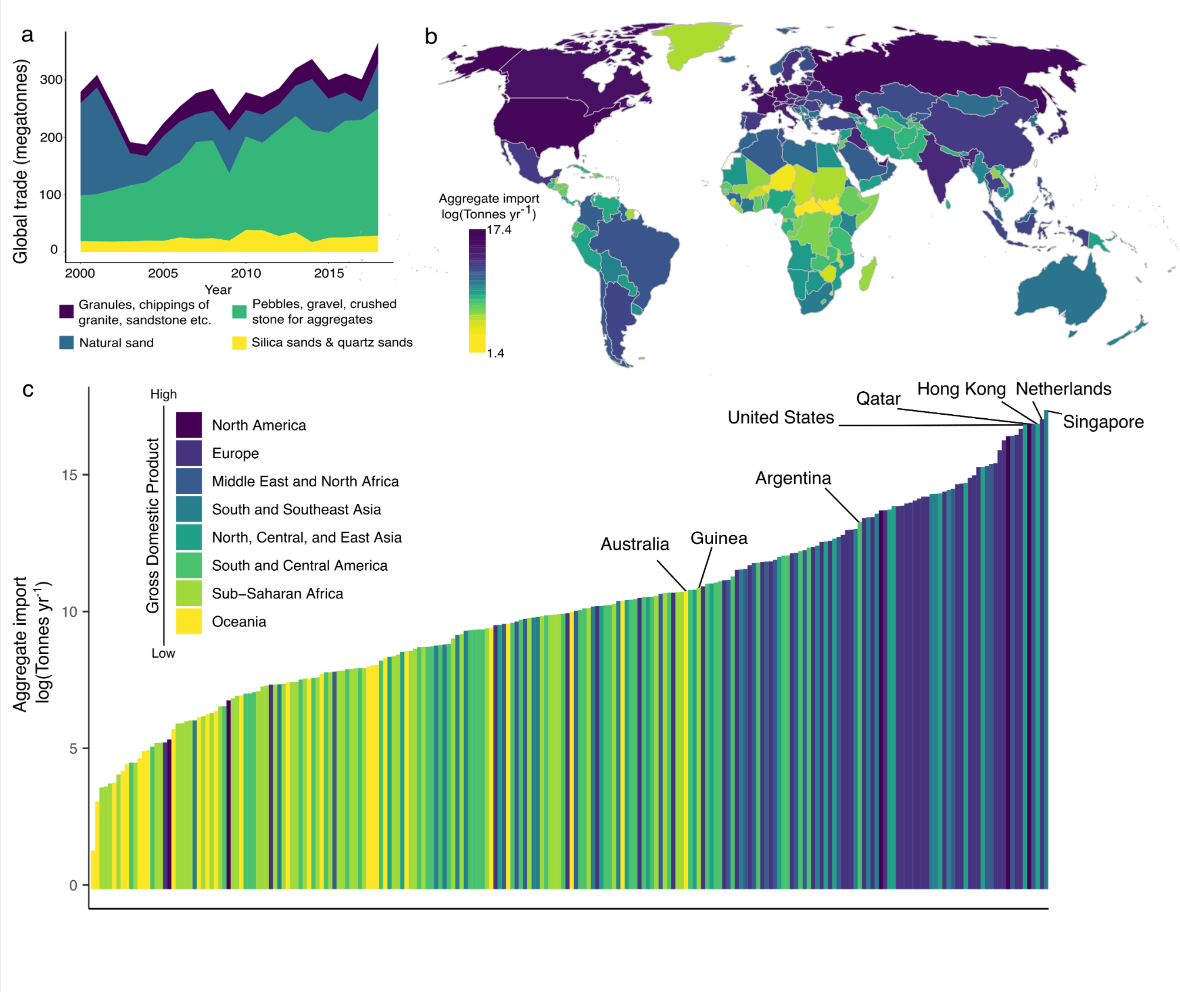

Figure 2: Global trade of aggregate **commodities. a.** Change in global trade of aggregate commodities between 2000-2018. **b.** Yearly amount of sand and gravel imported between 2010-2018. Industrial developed countries dominate the transnational import market. **c.** Countries ranked by their average aggregate import with the top importing countries in each region highlighted. Regions are colored according to their GDP (yellow - low median GDP, dark blue - high median GDP). (Trade data from comtrade.un.org)

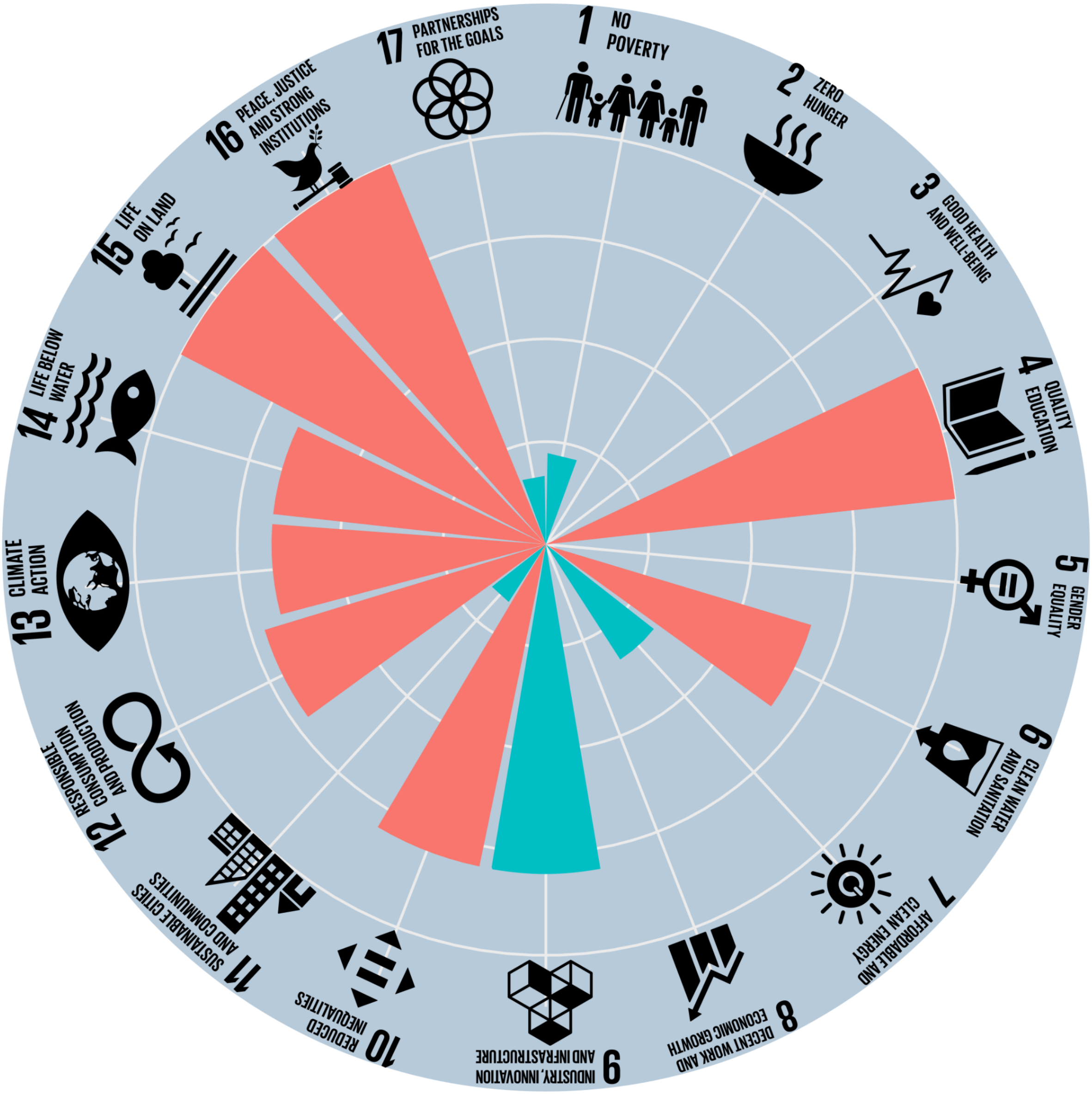

Figure 3: Conflicts and synergies between aggregate usage and the UN Sustainable Development Goals. Average target score of the 17 Sustainable Development Goals that are affected by aggregates and aggregate mining. Red colour indicates on average conflicts between aggregates and a given goal, whereas turquoise depicts synergistic effects, as assessed through a consensus-based expert elicitation method (see Supplementary Information). The size of the bar represents the average effect size (between 0 and 1) of the SDG targets with known link to aggregates and aggregate mining. The resulting scores reflect five goals (Goals 1, 7, 9, 11 and 17) with synergistic effects, three goals with neutral effects (Goals 2, 3 and 5), while a substantial number of inevitable conflicts exist between eight sustainable development goals (4, 6, 8, 10, 12, 13, 14, 15 and 16). Full data argumentation listed in Supplementary Data Table 1 and 2.

Table 1: Listed conflicts and synergies between aggregate resource usage and the UN Sustainable Development Goals (for full list see Supplementary Data Table 2).

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Goal	Synergy	Conflict
No Poverty	• Aggregates are used in constructing houses, and houses built with finished materials are considered more resilient to extreme events, shocks and disasters. • Infrastructure can promote social and economic development, for instance by increasing access to agricultural supplies and markets, facilitating transportation of people and goods, and decreasing production costs and crop losses. • Mining of aggregates provides labour for millions of people in low-income countries, supporting livelihoods and income for people living in poverty and mining has been shown to reduce poverty levels.	• Sand mining has been shown to increase the impacts of natural disasters and destruction of the natural environment. • Aggregate mining indirectly may increase poverty through population displacement caused by the destruction of the natural environment and/or livelihoods of the local populace. • A high proportion of artisanal and small-scale aggregate mining is informal and workers do not receive basic social protections or access to government services. • Informal and illegal mining activities are often driven by existing socioeconomic inequalities.
Zero Hunger	• New roads and other infrastructure at appropriate scales can promote social and economic development, for example by increasing access to agricultural supplies and markets, facilitating the transportation of people and goods, and decreasing production costs and crop losses.	• Aggregate mining activities can damage agricultural land and thus agricultural productivity, negatively impact ecosystems and water tables with implications for crop irrigation
Good Health and Wellbeing	• Aggregate enables the construction of roads and can improve access to health care. • Construction of well-built, modern housing using aggregates for concrete is associated with reductions in poor health outcomes such as malaria, diarrhoeal disease, anaemia and undernutrition. • Sand is commonly used in filters to purify water and reduce health effects of contaminated water.	• Quarrying and mining of aggregate is associated with elevated occupational health and safety hazards and a lack of health care around mine sites and little or no access to adequate health care. • Mining sand and crushing stone to produce aggregates are shown to damage human health and cause respiratory disease through the inhalation of small crystalline particles. • Environmental degradation caused by mining and building of urban environments can be associated with increasing air pollution, mental ill health and 'ecological grief. • Increasing the road network facilitated by aggregates will allow an increasing risk of the number of road traffic accidents.
Quality Education		• Mining of sand and crushing stone for sand production, especcially in artisanal small-scale mining in some cases involves child labour in some cases and can prevent children from participating in primary education from an early age on. • The aggregate industry and associated governance does not promote education or knowledge concerning sustainable development
Gender Equality	• Mining of 'development minerals' used in construction employs many people and especially women, although the proportion of women involved in the mining sector varies from country to country.	
Clean Water and Sanitation	• Housing constructed using finished building materials built from aggregates has increased the proportion of safely managed sanitation services and decreased the diseases associated with sanitation.	• Mining activities adjacent to, or in close proximity to water courses can impact ecosystems and landscape morphology through impact of natural processes.
Affordable and Clean Energy	• Sand (silica) is a vital material in the renewable energy transition.	
Decent Work and Economic Growth	• Aggregates are used in concrete-buildings and infrastructur projects, and are thus essential to improve development and economic growth. • If properly organized, aggregate mining activities can be used to initiate development-oriented policies. • Financial loans from high income countries support small scale mining businesses in low and middle-income countries that are enabled through partnerships.	• Mining of sand and gravel and crushed stone for aggregate production can involve child labour and comes with poor health and safety practices for the miners. • Aggregates mining can create an immediate conflict between economic growth and environmental degradation. • Small-scale miners are at risk of being criminalized due to complex legislation favouring political-economic interests.
Industry, Innovation and Infrastructure	• Minerals feed local industries with upstream value addition inside the country. • Mining can help drive economic development and diversification through direct and indirect economic benefits, spurring the construction of new infrastructure for transport. • Local cobblestone is used in the construction of rural	• The construction and building industries account for a significant proportion of the global energy-related CO_2 emissions.

	roads and is cheaper than importing asphalt.	
Reduced Inequalities	• Several modes of artisanal and small-scale mining (ASM) exist and can be a part of seasonal or more permanent livelihood strategies and can be pursued as a route out of poverty or an activity to complement insufficient income.	• Aggregate mining can obstruct the livelihoods of people dependent on agriculture, livestock and/or craftsmanship. • The lack of explicit policies structuring supply chains and extraction hinders inclusion. The aggregate mining industry has not developed antidiscrimination policies or other initiatives ensuring equal opportunities for all, prohibiting greater equality.
Sustainable Cities and Communities	• Aggregates provide a key ingredient in producing adequate shelter and are essential to building infrastructure advancing accessibility to transport. • Sand is a vital component in mitigation of storm flooding, such as beach nourishment and soft coastal protection solutions. • The need of the construction industry for aggregates ties it directly to energy budgets in buildings, which are designed with better energy performance than existing buildings, reducing the energy expenditure during operation.	• Sand mining has been shown to exacerbate the impacts of natural disasters and the construction and building industries account for a significant proportion of global energy-related CO_2 emission.s • The lack of overview of aggregate resources and extraction leads to an unsustainable urban development • Aggregate mining can lead to the destruction or threat of loss of cultural, traditional and religious sites.
Responsible Consumption and Production	• Reuse and recycling initiatives for demolition waste and concrete elements into the construction lessen the demand for aggregates. • New legislation, policies and development programming has been implemented in parts of the Global South.	• Transnational export rates, spearheaded by developed countries, are expected to increase in many developing countries despite the fact that these same countries have the largest deficit in future aggregate demands relative to their current national production. • Sustainable extraction of aggregate resources is not promoted by larger transnational companies nor is there access to data providing a clear overview of sustainability information in the aggregate industry. • In many countries, aggregate resources are extracted unsustainably. • Incentives and regulations for re-use of materials such as concrete are lacking. A general lack of a global overview concerningthe availability and use of aggregate resources prohibits a sustainable development • Contaminants accumulate in the sediment from mine tailings of active and historical relic mining activities.
Climate Action	• Sand is important in some climate change mitigations such as beach nourishment. • National mineral resource extractions (including aggregates) are not evaluated based on their resilience towards climate change.	• Sand mining can increase the negative impacts of climate change • Sand and gravel mining is further reducing the amount of sand transport in the Mekong River which is already being caused due to changes in climate and anthropogenic activities (such as upstream damming) • The potential negative impacts of commonly used climate change mitigation strategies is not implemented in national policies or planning. Mineral resource extraction policies are not actively exploring or educating the public concerning the role of aggregates and aggregate mining in relation to climate change.
Life Below Water		• Excavation, transportation and disposal of fresh unconsolidated aggregates in freshwater or marine systems negatively affects the systems. • The aggregate industry does not contribute to setting aside protected marine areas. • Although aggregate mining has the potential of generating local profit there is no evidence that this will happen for small island communities or developing countries
Life on Land		• Mining activities may negatively impact the marine and the freshwater environment. • Many artisanal and small-scale mining activities take place on forested lands, with transport to and from mining sites causing deforestation and a fragmentation of forest habitats. • Sand and gravel mining has been shown to promote the establishment and spread of non-native species, or through the introduction of non-native species on ships used for transporting sediment
Peace, Justice and Strong Institutions		• Aggregate mining can cause conflicts, harassment and violence. Aggregate mining activities are in some cases associated with, or controlled by criminal organizations, operating outside local and national laws. • Child labour is common where the sector is informal.
Partnerships for the Goals	• Transnational export rates are expected to increase in many developing countries. • The United Nations Environment Assembly has identified the sustainable development of aggregates as an area of cooperation, creating a platform for knowledge sharing by member states • Public-private partnerships build networks to encourage sustainable development practices, and	• Some aggregate extraction practices have not been executed in an environmentally sound way, in light of potential extraction methods and technologies. • There is currently lack of global overview of aggregate resource availability and use, prohibiting any coherence in policy. • There is no indication that the aggregate industry will promote an equitable trading system. Transnational export rates, pushed by the need of developed countries, are expected to increase in many

	outcomes from these will become more apparent over time.	developing countries despite the fact that these same countries have the largest deficit in future aggregate demands relative to their current national production

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