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Promises and perils of sand exploitation in Greenland

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Ice flow dynamics of the Greenland ice sheet control the production of sediment. Future acceleration in glacial flow and ice sheet melt will amplify Greenland's supply of sediment to the coastal zone. Globally, sand and gravel reserves are rapidly depleting while the demand is increasing, largely due to urban expansion, infrastructural improvements and the enhancement of coastal protection in response to climate change. Here, we show that an abundance of sand and gravel provides an opportunity for Greenland to become a global exporter of aggregates and relieve the increasing global demand. The changing Arctic conditions help pave a sustainable way for the country towards economic independence. This way, Greenland could benefit from the challenges brought by climate change. Such exploitation of sand requires careful assessment of the environmental impact and must be implemented in collaboration with the Greenlandic society.

In Greenland, natural resources provide a crucial livelihood for large parts of the population. Over the past century, Greenland has experienced a major transformation from a society based on hunting and fishing to a public sector and commercial fisheries economy. Greenland currently operates as a self-governing country under the Kingdom of Denmark. As approximately half of the national budget is subsidized by a block grant, Greenland has a great need to develop new sources of revenue to gain increased economic independence and to meet rising social costs associated with an aging population[1]. Fish and shellfish form the basis for 90% of Greenland's present revenue[1] and Greenland has sought to diversify its economy for decades, with a focus on mining, oil and gas exploitation and tourism. Simultaneously, one global grand challenge relates to resource scarcity of sediments and an urgent call to explore innovative methods and sustainable solutions for future resource supply and production. Sand and gravel are now the most-extracted materials in the world and sand shortages are becoming an issue for global conservation and sustainability, but the magnitude of this aggregate shortage and the impact thereof are not yet fully recognized or understood[2]. Here, we discuss recent progress in quantifying sediment delivery for Greenland and illustrate the potential of sand export from Greenland to meet increasing global demand. We provide a brief overview of the available evidence for the scope of sand exploitation in Greenland. We also assess the relative importance of this potential new income to the economy of Greenland. Lastly, we discuss the potential environmental and socio-economic impact of sand mining in Greenland.

Natural resources in Greenland

With the Self-Rule Act in 2009, Greenland was granted the right to manage all its natural resources including underground mineral resources[1]. Despite the self-rule status, Greenland continues to receive Danish subsidies, which will remain fixed at 2009 levels, adjusted for inflation[3]. Although Greenland is the twelfth largest country in the world, it has a small population of ~56,000 people. Almost 10% of the working age population is unemployed and 70% has only lower secondary education (equivalent to leaving school at ~15 years of age)[4]. The current business sector in Greenland is characterized by many small businesses with few employees, mostly within the construction and service industry and traditional trades[1]. Most of the workforce is involved in administration and the service industry. The primary economic industry is commercial fishing, while tourism continues to expand due to an increase in visits from cruise lines. A minor part of the workforce is involved in the hunting industry[1]. Greenland faces a growing gap between its national revenue and the cost associated with supporting infrastructure and social services to a small and geographically dispersed population with an aging demographic composition typical of other Western welfare states. To maintain the present-day welfare level into the 2030s, the Greenland economy is around US$160 million short every year[3]. Greenland must find new opportunities to diversify its industry, create a self-sustaining economy, increase revenues and ensure continued welfare.

Greenland holds a broad range of mineral resources and potential hydrocarbon reserves[1]. Mining of natural resources in the Arctic received more attention in the early 2000s due to economic up-turn and several plans for extraction of deposits in Greenland were developed[5]. Greenland scores in the upper half on the Investment Attractiveness Index[6] for mining companies, based on its geology, availability of geological and geophysical data, geographic size and policy climate[6]. Exploitation of the proven deposits of mineral resources, such as ores of rare-earth elements, uranium, gold, iron and zinc, has been seen as an immediate avenue for a new era of prosperity for Greenland[3,5,7], and it is believed that a warmer climate will facilitate exploitation of ores, oil and gas[1]. Greenland's economic development strategy sees promise in the emerging mining industry, but significant international investments have not yet been secured for any large-scale mining projects of proven resources[5]. Few of the known deposits can be seen as strategic resources, for global powers such as Europe, USA or China. Exploitation of

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classical geological resources in Greenland has not been competitive relative to other deposits in the world due to a lack of infrastructure, small population and high operating costs[3]. Concerns about the social and environmental impacts of exploitation of minerals, oil and gas, have prompted political attention in Greenland. For example, the community of Narssaq in southern Greenland, which comprises approximately 1,500 residents, is situated close to a large deposit of uranium and rare-earth elements. Planned mining of these deposits has sparked a debate about whether these types of mining activities should be pursued in the hope of economic prosperity[7]. The main concern relates to the risks associated with mining of radioactive materials and a citizen group against uranium mining activities was formed in 2014[3]. Furthermore, a projected large influx of foreign workers is a concern, both to the local community and to Greenland in general[1]. Concurrently, proponents of this mining project see an opportunity for new jobs that would replace those disappearing due to modernization of the fishing industry[3]. Altogether, like everywhere else, exploitation of these natural resources comes with both societal and environmental consequences.

Sand abundance in Greenland

Sediments have accumulated in front of the Greenland ice sheet (GrIS) and along the coast of Greenland since the onset of the current interglacial period some 11,700 years ago (start of the Holocene). These deposits consist of massive amounts of gravel, sand and silt often located along the fringes of fjords and in embayments, where deposits can be tens of metres in height and several kilometres in width[8]. These extensive deposits make up potential stocks for aggregate mining. However, a recent study has shown that, as the climate changes, significant additions to the existing sand deposits are delivered every year to the nearshore zone of Greenland[9].

Deltas constitute the transition zone between the catchment area on land and the receiving basin offshore, and act as natural traps of river sediment. Deltas consist of a delta plain, often with one or more distributary channels that form a subaerial delta platform near the riverine sediment source. Distal to this is the downward sloping delta front, which marks the transition into the marine domain[10]. Sediment grain sizes within Arctic deltas range from large cobbles and pebbles to fine-grained silt particles, with a typical decrease in grain size along the transect of transportation with gravel and sand dominating the delta plain and silt dominating the marine delta front[11,12] (Fig. 1c). Many deltas in Greenland are in fjords, where they are exposed to limited wave energy. Where meltwater input is high, deltas' extents are increasing due to deposition of newly added sediment[9].

The ongoing warming climate is particularly pronounced in the Arctic regions[13]. Consequently, the GrIS continues to lose mass[14] and, with the increasing rates of glacier calving and melting[15], an associated increase occurs in river runoff and transportation of sediment to the ocean[16]. With warming projected to continue, mass loss and associated river fluxes are very likely to increase the fluxes of sediment[17]. Ice margin retreat may lengthen river transport pathways in the future and could promote sediment trapping along the way. However, previous margin retreat has been limited[18] and so far increased meltwater has overprinted such trapping, with enormous amounts of material delivered to the coast and pronounced progradation of hundreds of deltas. Future glacier retreat and river morphology modelling can disentangle the balance between the lengthening of the transport pathway and the increased meltwater flux. Today, Greenland delivers ~7–9% of the global suspended river sediment input to the oceans (Fig. 1a). Moreover, only 15% of Greenland's rivers transport 80% of the total riverine sediment load of the ice sheet meaning that few river outlets are hotspots of sediment transport[16] (Fig. 1d). As an example, the Sermeq River delivers a quarter of the total suspended load in Greenland (Box 1). Of the total sediment load, the bedload, which is coarse sediment particles transported along the river bed, is particularly suitable material for construction. Bedload as a proportion of total sediment load, varies significantly for rivers of the world, including Arctic rivers. However, a conservative minimum estimate derived from data on selected Arctic rivers justifies the assumption that ~15% of the total sediment load is quartz sand, which can be of use for the global market[19]. The most dynamic deltas, with known high bedload deposition, are located at the western margin of the GrIS[14] (Fig. 1b), where massive meltwater fluxes cause delta progradation into the sea[9].

Global sand scarcity

Despite the global prevalence of sand, this natural resource is running low, largely due to exponentially increasing human appropriation[20]. Simultaneously, as climate changes, the world's population becomes increasingly vulnerable and faces great challenges in adapting infrastructure to changing climate, rising sea levels and more extreme weather events[21] (Fig. 2). These growing threats from climate change further strain global sand deposits[20]. The volume of aggregates used in buildings and transport infrastructure increased 23-fold between 1900 and 2010, and global market prices of sand are expected to continue to rise[22,23] (Fig. 3a,b). Today, the world's population is 7.6 billion and is projected to increase to 9.8 billion in 2050 and 11.2 billion by 2100. The current demand for sand (approximately 9.55 Gt yr^{-1} in 2017) has a market value of US$99.5 billion[23]. This estimate has been projected to reach US$481 billion in 2100 with a future increase in sand demand alongside sand shortages and the consequent increase in prices (Fig. 3a,b)[23].

On land, aggregates are used in road bases, sub-bases, railroad ballast and fill and normally account for 80–100% of the material volume used by the building and paving industry[24]. Aggregates are generally classified into two sizes: coarse and fine. Their shape characteristics are relevant, as the angular particles of river sand adhere better and strengthen road bases and asphaltic concrete[24]. Aggregates are essential to modern society for new construction as well as maintenance of existing infrastructure. Most countries now face a shortage of traditional aggregate resources, as these materials are the most used material worldwide, second only to water[25]. By far the most energy-efficient mode of transportation of this material is shipping[26]. Globally, coastal cities and settlements facing increasing pressure from urbanization, industrial practices, changing storm climate and sea-level rise require redesigned and reinforced constructed coastal zones. One type of management uses sand in nourishments[27]; as an example 'mega-nourishment' relies on one-time deposition of a large quantity of sand and then subsequently allows natural longshore and cross-shore sediment transport processes to redistribute sediment to adjacent beaches. Over a period of decades, the beaches evolve with changing coastal conditions to increase the resilience of the coastal zone, the infrastructure and the local communities[28].

Sand extraction in Greenland

The Greenland government holds that minerals can be exploited to the benefit of society[1] and, as the country holds enormous amounts of extractable sand, setting up a sand industry in Greenland could potentially act as a new way to diversify and strengthen the economy[29]. Sand extraction from the seafloor already exists in Greenland, though at a small and local scale[30]. Given the projected increase in global sand prices, sand resources in Greenland may indeed contribute significantly to the economy (Fig. 3c). Sand delivery from the ice sheet to the coast can at least be expected to continue at the current rate and is more likely to rise over the century to come[16]. Furthermore, diminishing sea ice extent increases open water periods[31] and lengthens the season during which sand extraction could take place. This type of natural resource exploitation offers an opportunity for Greenland to benefit from the consequences of climate change, which the country inevitably faces.

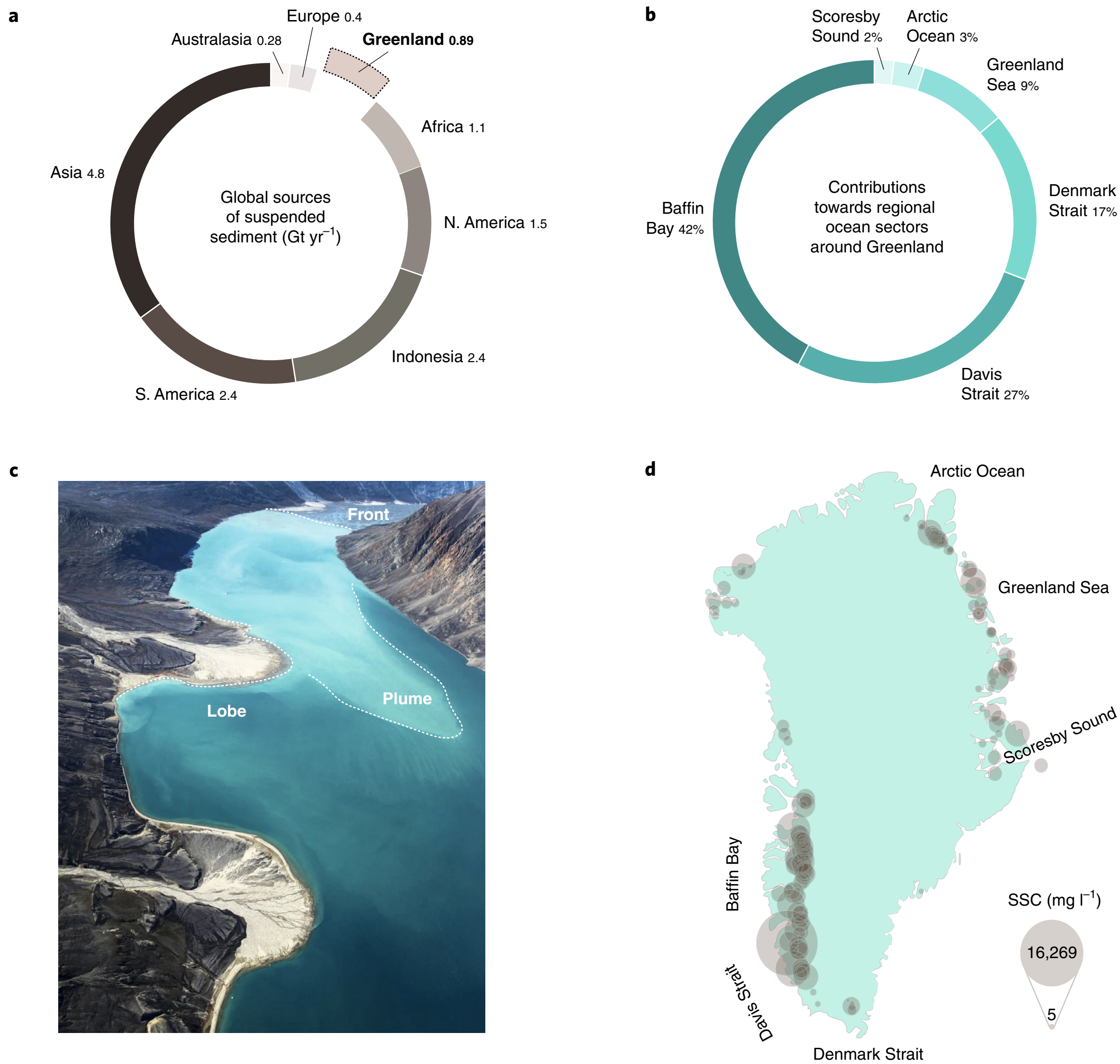

Fig. 1 | Suspended sediment loads delivered by the GrIS. a, Greenland's contribution of suspended sediment to the global budget. **b**, Proportional contribution of the total suspended sediment budget in Greenland to different ocean sectors around Greenland. **c**, Two deltas in the proximal part with clearly defined delta lobes and a delta front in the distal part with a clearly defined plume of fine suspended sediment in a Greenlandic fjord. **d**, Contribution of suspended sediment from rivers in Greenland to the various surrounding seas; a few sites deliver the majority of the material. Panel **c** is a photo by Anders Anker Bjørk; panel **d** is adapted from ref. [16], Springer Nature Ltd.

Relict Holocene outwash plains, 'sandur deposits', are formed by glacial meltwater and extraction of these would differ from those in the active deltas in terms of their sustainability. When extracted, they are being depleted and no new material is added, unlike the active dynamic deltas. Extracting these deposits would be equivalent to gravel pit mining, where sand and gravel are exploited until exhaustion. Extraction and exploitation of such aggregates in Greenland would require conveyor belts stretching from land to floating terminals, where sand could then be dumped into dry-bulk carriers. This means on one hand, that extraction of these land deposits will not interfere with an active system like a delta, on the other hand, extraction of on-land deposits would require a more developed infrastructure than present today. More sustainable is the constant supply of sand delivered by rivers draining the GrIS to the nearshore zone, providing continuous rapid delivery of aggregates to local hotspots (Fig. 1d). Extraction of aggregates on the delta front could avoid some of the traditionally controversial issues related to quarrying and transport of materials on land, such as noise and dust pollution as well as direct impact on terrestrial biodiversity. Extractions from the delta front would require suction dredgers to anchor offshore near a source of sand, pumping the material through a pipeline into large barges. The infrastructure required for this type of sand exploitation would be less complicated than terrestrial extract. It would however, require specific dredgers especially suited to the harsh Arctic environment.

The projected continuation of a warming climate will secure a delivery of sand to the nearshore zone in Greenland for centuries to come. Sand constitutes a more continuous resource in contrast to the mineral mining industry, where large scale mines have a limited lifecycle of ~10 years[1] and revenues are time-limited. We argue that economic profitability must be taken into account along with resource management and environmental impact on the physical and societal surroundings for sustainable natural resource exploitation.

Box 1 | The potential of sediment delivery from the Sermeq Outlet

An example of a rapidly prograding delta is the Sermeq Outlet in Sermilik Fjord, southwest Greenland. The outlet is located approximately 100 km south of Nuuk, the capital of Greenland, where one-third of the country's population resides, but this particular fjord has no permanent inhabitants. The outlet is protected from wave activity from the nearby Davis Strait as it is located in a narrow fjord and a diminishing Arctic sea ice cover[31] creates a longer open-water period, favourable for a longer mining season. The Sermeq outlet has experienced a marked decrease in sea ice cover since the 1980s, where the open water periods prevailed ~50% of the year. Whereas during the past decade, sea ice is only present ~20 days throughout the year[9] allowing nearly year-round direct shipping access. The outlet exports an estimated 25% of the total suspended load from the ice sheet margin to the coast in Greenland[16] and has prograded more than 2 km during the past three decades[9]. Assuming a usable amount is 15% of the total sediment load, 0.033 Gt yr^{-1} of new sand resources will be available for export from this single site. These contributions are so massive that they are relevant in a global context and could serve as potential sources for the global market.

Urban expansion in San Diego. A rising population in California creates an increasing demand for aggregates. The western San Diego County population is expected to increase ~25% within the next 50 years, causing the county to face a shortage of sand and gravel. For the next 50 years, the county's projected total aggregate demand is 0.76 Gt, ranging from 0.013–0.016 Gt yr^{-1}. The current reserves that are permitted to be mined are 0.271 Gt and are projected to last into 2035[60]. The rising demand for sand and gravel is largely due to sprawling development in rural areas, which hinders the establishment of quarry sites, as these often face fierce opposition from residents[24]. With a yearly sediment load of 0.33 Gt, the yearly amount of aggregates from the Sermeq Outlet covers twice the yearly need for San Diego County.

Beach recovery after Superstorm Sandy at Coney Island. Superstorm Sandy in 2012 was the second-costliest hurricane on record in the USA until surpassed by hurricanes Harvey and Maria in 2017, and coastal protection required significant revision hereafter[61]. The State of New York has the longest history of nourishment in the USA and coastal recovery after Hurricane Sandy along Coney Island cost US$48 million, paid through federal funding. The superstorm eroded more than 1.15 million m^3 of sand on an 8 km stretch at Coney Island, and 2.68 million m^3 of sand were then nourished here. The material was dredged from the seafloor 5 km offshore, pumped into a slurry and transported to the coast where bulldozers spread out the sand[62]. Within one year, the Sermeq Outlet could feed seven projects of the size of the Coney Island recovery project.

As climate changes, a larger part of the world's coast will need protection from rising storm surges, sea level rise, inundation and erosion. Soft coastal protection solutions are widely applied and are generally cheaper compared to hard constructions, and there will therefore be a higher demand for sediment for coastal protection implementations.

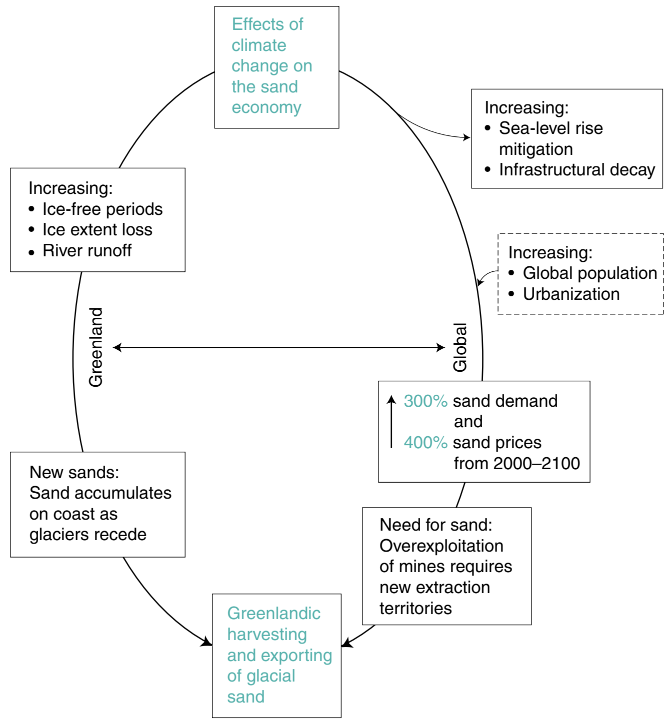

Fig. 2 | Drivers of global sand demand and local geomorphologic dynamics creating previously unknown sand resources in Greenland. Climate-induced coupling between the growing surplus of sand in Greenland and the increasing global demand for sand. With a changing climate and an increasing global population, Greenland will continue to have a surplus of sediment while the global demand for sand will increase.

Potential environmental impact of sand mining in Greenland

The natural delivery of material from the GrIS to the ocean affects the coastal zone and impacts ecosystem dynamics. Known consequences of increasing glacial sediments entering the Arctic ocean are homogenization of benthic habitats due to deposition[32], reduced light availability limiting primary productivity[33,34] or alternatively increasing bioavailable micronutrient inputs[35,36], which enhances biological productivity such as phytoplankton blooms[37,38]. These changes in local environmental conditions occur in tandem with a warming Arctic climate and cause systematic changes in ecological communities[39–41]. Sand extraction via dredging of marine sediments shares many of the same disturbance consequences for the local environment as those mentioned above. Excavation, transportation and disposal of fresh unconsolidated material enhance dispersal of sediments into the water, changes in seabed surface and turbidity from dredging plumes[42], ultimately affecting local ecosystems[42–44]. Thus, direct removal of bed sediments could locally enhance or even amplify the ongoing changes in ecosystem dynamics along the coast of Greenland.

Environmental impact assessments at potential extraction sites should include future climate scenarios and how sand extraction would affect these ecological communities (Box 2). A shift in species compositions under a warming climate will most likely occur along the coast of Greenland[39,40]. Vegetated coastal habitats are expected to expand their range in Greenland in a warmer climate[45]. These habitats support key ecosystem functions with the potential of mitigating effects of climate change[45,46]. However, macrophytes such as seagrasses that grow in soft-bottom sediments are highly vulnerable to sand dredging[43]. Colonization and establishment of seagrass meadows may be prevented if increase in turbidity and local sand removal from sand extraction significantly exceed the natural variation. Intensified human activities in the Arctic are expected to increase the likelihood of the establishment of new invasive species in the region[47]. Human activities that may impact the environment include ongoing commercial fishing and tourism, but also future expansion of shipping routes and port development[47]. Given that the establishment of sand extraction sites in Greenland would promote new infrastructure, special care should be taken to implement effective invasive species mitigation procedures[48].

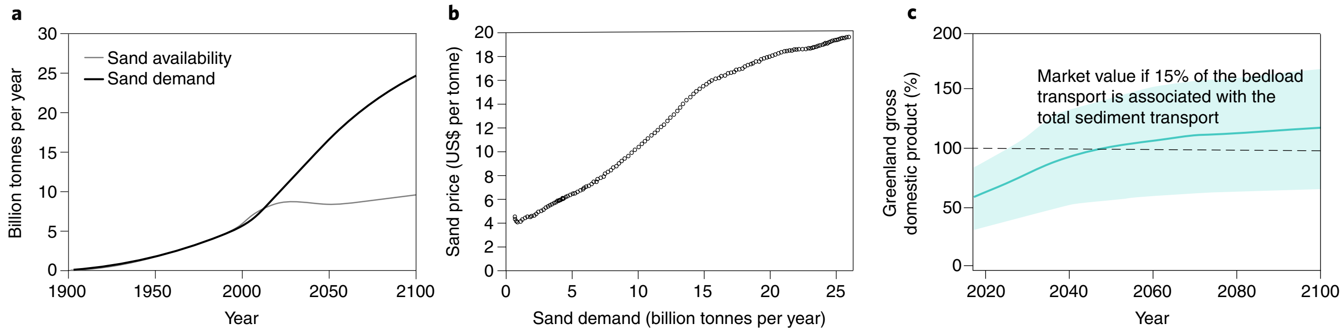

Fig. 3 | Global sand shortage and market prices. **a**, Observed and projected global changes in sand demand and availability. **b**, Modelled relationship between global sand demand and price. **c**, Projected market value of total sand deposits delivered annually at Greenland's coast. Solid lines represent the central estimate and the shaded areas ± the relative error of the central value (given a suspended sediment of 0.892 ± 0.374 Gt yr^{-1}). The dotted horizontal line marks the Greenland gross domestic product of US$2.22 billion (2015). Global sand data[23] reflecting a 'business-as-usual' scenario of sand resources where the demand is dependent on population size, maintenance and price. Suspended sediment estimates from ref. [16]. Figure adapted from ref. [23], Springer Nature Ltd.

Box 2 | Future research directions

- Determine the evolution of present sediment hot spots and detect future hotspots caused by continuous ice mass loss
- Understand sediment characteristics and their physical properties as aggregates to the global market
- Understand how fjord primary productivity depends on fluvial discharge and suspended sediment concentrations
- Demonstrate how projected site-specific disturbances from sand mining differ from current disturbance regime created by increasing freshwater discharge and ice-free periods
- Further develop legislative constructions optimizing and securing local gains from resource mining
- Develop dredging equipment and shipping vessels to meet the special requirements needed for this type of activity within the Arctic (look towards the fishing and commercial freight trading industries)
- Highlight the telecoupling patterns of sand to estimate the global effects of sand mining in Greenland and how these will change with changing shipping routes due to climate change
- Analyse the relative impacts and carbon footprint of Greenlandic sediment trade to the global market through cost–benefit analyses

Potential socio-economic impact of sand mining in Greenland

In this section, we discuss the potential industries that sand mining may interfere with and we address the actions that must be taken in the process of establishing such an industry.

Local policymakers have grappled for several decades with establishing the political processes to foster a Greenlandic mining sector. Several policies and a process of stakeholder involvement are in place and would offer an advantage to investors. The Greenlandic government has set a specific goal to minimize the share of foreign labour. The development of a sand mining industry in Greenland would require broad public and stakeholder support, as the changes caused by this exploitation would be significant and require an adjustment of today's society. Generations of experience and understanding of the fishing industry have given Greenlanders maritime knowledge, skill sets and equipment to offer the sand industry[1,49]. Many fishermen have decades of experience navigating ice filled waters and would be well equipped to support coastal mining operations by transporting equipment and workers. Additional expertise and support would include servicing and repair of maritime-related equipment used by the sand mining industry. A sand mining industry could benefit from the rising level of education among Greenlanders and the increase in number of people being trained within fields related to mining activities and the maritime sector[4]. These gains in expertise are highly relevant for a potential sand industry in Greenland. However, it would require skill-training initiatives and a close cooperation between businesses in need of workers, vocational schools and labour-market offices, as well as enhanced capabilities within the area of nature sustainability and environmental impact. Advancing current skills within the Greenlandic population will positively impact next-generation projects and provide a base for serving other industries in the future.

Fisheries and tourism are crucial for the Greenlandic economy and the natural environment provides the livelihood for large parts of the population, whether directly or indirectly. A sand mining industry must first and foremost take into account the fishing industry and ensure those industries can co-exist harmoniously. Generally, the fishing industry can be divided into two sectors: offshore fishing dominated by large companies and coastal fishing operated by local fishermen and small-scale companies. The offshore fishing industry is superior to the small-scale fishing when discussing value creation but is known to indirectly improve conditions for the minor companies, for example, through investments and experiments with new species as seen with the Marine Stewardship Council certification of shrimps[50]. Thus, well-coordinated management between large and small-scale fishing and the sand mining development is necessary in order for all industries to exist without mutual negative impacts.

Few areas in Greenland have a 'high' population density and the remaining part of the population is scattered among several small towns and settlements along the coast[1]. Growing global interest in the Arctic has led to an increase in tourism activities and Greenland is no exception to this trend[51]. In Greenland, adventure tourism, cultural tourism and ecotourism (ACE tourism)[52] operate throughout the coastal zone[53]. These activities include tourist cruises, guided sailing tours, glacier and whale watching, fishing and hunting. Since 2000, the number of guests staying in paid accommodations has tripled, with almost 110,000 paying guests in 2017[54]. Today, Greenland has three UNESCO World Heritage Sites: Ilulissat Icefjord in central west Greenland (a natural site), the Kujataa area in southern Greenland[55] and the newly approved Aasivissuit-Nipisat in central west Greenland (both cultural sites). In 2014, 30% of the total guests in paid accommodation stayed in the town of Illulissat and another 21% in the capital region of Nuuk — only 2% visited the eastern part of the country[53]. Setting up a sand mining industry could potentially interfere with the tourism industry, however, tourist activities are focused on relatively few sites throughout the country, while large parts of the country remain undisturbed and see very little human interference. Likewise, sediment deposition in Greenland is focused at a few, large outlets delivering a large proportion of the total amount of material from land to sea[16] (Fig. 1d). Therefore, the co-existence of these industries would require mining activities not to take place in important tourist areas, but coordinated management and zoning could prevent negative interferences between different industries.

The Arctic is projected to lose its summer sea-ice cover[31] and sea-ice will break up earlier and refreeze later in the season as temperatures continue to rise. These changes will allow for new shipping routes[56] and possibly open up Asian markets for Greenlandic sand. However, the hostile Arctic conditions and large seasonal variability may remain challenging for shipping, which relies on a stable time and route scheduling. Moreover, operating in the Arctic calls for increased safety measures for the crews and vessels[56]. So, the most immediate potential for Greenland may be to ship aggregates towards destinations in northern Europe and the eastern US. We argue that the development of a sand mining industry must benefit the Greenland society by establishing projects that specifically promote prosperity and employment opportunities with the greatest possible respect for the natural environment.

Summary and outlook

As the Arctic is rapidly changing, society needs to respond. Greenland's self-rule government needs to tackle future challenges of an increasingly volatile socio-ecological system to assure prosperity for the country[57]. However, historically, socio-ecologic processes have contributed to a continual change of Earth in stages of more or less smooth development with intermittent abrupt changes[49], and Greenlanders have shown high resilience and capability to adapt to changes. A sand mining industry in Greenland can in our opinion help to create prosperity for the country, if the establishment and implementation is managed with strict Greenlandic legislation safeguarding the natural environment and society from negative impacts.

The magnitude of sand delivery to the coastal zones by GrIS meltwater is significant and of potential value for the Greenlandic economy. However, a great deal of uncertainty exists around what impacts sand mining would have on the local environment and communities. Future research will be essential to document the persistence and quality of sand delivered to the coast and how sand mining impacts local ecosystems and associated ecosystem services. Profitability will be determined by the international market value of sand and the costs of extraction and transport, which may affect whether and when Greenland elects to develop this industry. Extraction costs are determined by the cost of labour, capital expenses and energy used during extraction. However, detailed market analyses focusing on extraction cost and shipping expenses must be carried out to ensure that the sand industry will be a competitive business with the global market.

The overarching aim in sustainable resource use should be to ensure both human and environmental wellbeing[58]. We propose that the challenges for the Greenlandic population related to adapting to a changing climate can be turned into opportunities for natural resource exploitation, if Greenland develops this industry within a framework of environmental and social assessments. We suggest that the main actors in establishing a sand mining industry aim to develop rigorous framework and guidelines that accommodate regional settings and characteristics to describe and explain the complex social-ecological systems related to the establishment of this industry[59]. Ideally, this would be done in close collaboration with environmental and scientific global institutions, and the involved partners should integrate local conservation initiatives to promote an inclusive approach and to sustain social-ecological systems.

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References

1. Rosing, M., Knudsen, R., Heinrich, J. & Rasmusen, L. *To the Benefit of Greenland* (University of Greenland Ilisimatusarfik, 2014).
2. Sutherland, W. J. et al. A 2017 Horizon scan of emerging issues for global conservation and biological diversity. *Trends Ecol. Evol.* **32**, 31–40 (2017).
3. Rosen, J. Cold truths at the top of the world. *Nature* **532**, 296–299 (2016).
4. *Number of Graduations, 2003–2017* UDXISC11D07 (Statbank Greenland, Statistics Greenland, 2012); http://bank.stat.gl/pxweb/en/Greenland/Greenland__UD__UD60__UD6010/UDXISC11D.PX/?rxid=UDXISC11D07-06-2018%2016:24:03
5. Zeuthen, J. W. & Raftopoulos, M. Promises of hope or threats of domination: Chinese mining in Greenland. *Extract. Ind. Soc.* **5**, 122–130 (2018).
6. Stedman, A. & Green, K. P. *Survey of Mining Companies* 1–72 (Fraser Insititute Annual, 2017).
7. Nuttall, M. Zero-tolerance, uranium and Greenland's mining future. *Polar J.* **3**, 368–383 (2013).
8. Bendixen, M. & Kroon, A. Conceptualizing delta forms and processes in Arctic coastal environments. *Earth Surf. Proc. Land.* **42**, 1227–1237 (2017).
9. Bendixen, M. et al. Delta progradation in Greenland driven by increasing glacial mass loss. *Nature* **550**, 101–104 (2017).
10. Galloway, W. E. & Hobday, D. K. *Terrigenous Clastic Depositional Systems: Applications to Fossil Fuel and Groundwater Resources* (Springer Science and Business Media, 2012).
11. Anthony, E. J. in *Coastal Environments and Global Change* (eds Masselink, G. & Gehrels, R.) Ch. 13, 299–237 (John Wiley and Sons, 2014).
12. Storms, J. E. A., de Winter, I. L., Overeem, I., Drijkoningen, G. G. & Lykke-Andersen, H. The Holocene sedimentary history of the Kangerlussuaq Fjord-valley fill, West Greenland. *Quaternary Sci. Rev.* **35**, 29–50 (2012).
13. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. et al.) (Cambridge Univ. Press, 2013).
14. Kjeldsen, K. K. et al. Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. *Nature* **528**, 396–400 (2015).
15. Khan, S. A. et al. Greenland ice sheet mass balance: a review. *Rep. Prog. Phys.* **78**, 046801 (2015).
16. Overeem, I. et al. Substantial export of suspended sediment to the global oceans from glacial erosion in Greenland. *Nat. Geosci.* **10**, 859–863 (2017).
17. Meyssignac, B., Fettweis, X., Chevrier, R. & Spada, G. Regional sea level changes for the twentieth and the twenty-first centuries induced by the regional variability in greenland ice sheet surface mass loss. *J. Clim.* **30**, 2011–2028 (2017).
18. Bjork, A. A. et al. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nat. Geosci.* **5**, 427–432 (2012).
19. Syvitski, J. P. & Saito, Y. Morphodynamics of deltas under the influence of humans. *Glob. Planet. Change* **57**, 261–282 (2007).
20. Torres, A., Brandt, J., Lear, K. & Liu, J. G. A looming tragedy of the sand commons. *Science* **357**, 970–971 (2017).
21. IPCC *Climate Change 2014: Impacts, Adaptation, and Vulnerability* Ch. 21–30 (eds Field, C. B. et al.) (Cambridge Univ. Press, 2014).
22. Krausmann, F. et al. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proc. Natl Acad. Sci. USA* **114**, 1880–1885 (2017).
23. Sverdrup, H. U., Koca, D. & Schlyter, P. 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. Res. Qual.* **2**, 8 (2017).
24. Kohler, S. *Aggregate Availability in California* (2012).
25. Danielsen, S. W., Kutznetzon, E. *Environmental Impact and Sustainability in Aggregate Production and Use* Vol. 7 (Springer, 2014).
26. Ascensão, F. et al. Environmental challenges for the Belt and Road Initiative. *Nat. Sustain.* **1**, 206–209 (2018).
27. Brown, J. M. et al. The effectiveness of beach mega-nourishment, assessed over three management epochs. *J. Environ. Manage.* **184**, 400–408 (2016).
28. de Schipper, M. A. et al. Initial spreading of a mega feeder nourishment: Observations of the Sand Engine pilot project. *Coast. Eng.* **111**, 23–38 (2016).
29. Bendixen, M., Iversen, L. L. & Overeem, I. Greenland: build an economy on sand. *Science* **358**, 879–879 (2017).
30. Boertmann, D. (ed.) *Miljoe og raastoffer i Groenland* (Aarhus Universitetsforlag, 2018).
31. Barnhart, K. R., Miller, C. R., Overeem, I. & Kay, J. E. Mapping the future expansion of Arctic open water. *Nat. Clim. Change* **6**, 280–285 (2015).

32. Węsławski, J. M. et al. Climate change effects on Arctic fjord and coastal macrobenthic diversity—observations and predictions. *Mar. Biodivers.* **41**, 71–85 (2011).
33. Slagstad, D., Ellingsen, I. & Wassmann, P. Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: an experimental simulation approach. *Prog. Oceanogr.* **90**, 117–131 (2011).
34. Middelbo, A. B., Sejr, M. K., Arendt, K. E. & Møller, E. F. Impact of glacial meltwater on spatiotemporal distribution of copepods and their grazing impact in Young Sound NE, Greenland. *Limnol. Oceanogr.* **63**, 322–336 (2018).
35. Hawkings, J. et al. The Greenland Ice Sheet as a hot spot of phosphorus weathering and export in the Arctic. *Glob. Biogeochem. Cycles* **30**, 191–210 (2016).
36. Hawkings, J. R. et al. Ice sheets as a missing source of silica to the polar oceans. *Nat. Commun.* **8**, 14198 (2017).
37. Kanna, N. et al. Upwelling of macronutrients and dissolved inorganic carbon by a subglacial freshwater driven plume in Bowdoin Fjord, northwestern Greenland. *J. Geophys. Res. Biogeosci.* **123**, 1666–1682 (2018).
38. Meire, L. et al. Marine-terminating glaciers sustain high productivity in Greenland fjords. *Glob. Change Biol.* **23**, 5344–5357 (2017).
39. Beaugrand, G., Edwards, M., Brander, K., Luczak, C. & Ibanez, F. Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. *Ecol. Lett.* **11**, 1157–1168 (2008).
40. Beaugrand, G., Reid, P. C., Ibanez, F., Lindley, J. A. & Edwards, M. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296**, 1692–1694 (2002).
41. Greene, C. H., Pershing, A. J., Cronin, T. M. & Ceci, N. Arctic climate change and its impacts on the ecology of the North Atlantic. *Ecology* **89**, S24–S38 (2008).
42. Manap, N. & Voulvoulis, N. Environmental management for dredging sediments: the requirement of developing nations. *J. Environ. Manage.* **147**, 338–348 (2015).
43. Erftemeijer, P. L. & Lewis, R. R. R. III Environmental impacts of dredging on seagrasses: a review. *Mar. Pollut. Bull.* **52**, 1553–1572 (2006).
44. Erftemeijer, P. L., Riegl, B., Hoeksema, B. W. & Todd, P. A. Environmental impacts of dredging and other sediment disturbances on corals: a review. *Mar. Pollut. Bull.* **64**, 1737–1765 (2012).
45. Krause-Jensen, D. & Duarte, C. M. Expansion of vegetated coastal ecosystems in the future Arctic. *Front. Mar. Sci.* **1**, 77 (2014).
46. Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I. & Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **3**, 961–968 (2013).
47. Ricciardi, A. et al. Invasion science: a horizon scan of emerging challenges and opportunities. *Trends Ecol. Evol.* **32**, 464–474 (2017).
48. Everett, R. A., Miller, A. W. & Ruiz, G. M. Shifting sands could bring invasive species. *Science* **359**, 878 (2018).
49. Jeppesen, E. et al. Living in an oasis: rapid transformations, resilience, and resistance in the North Water Area societies and ecosystems. *Ambio* **47**, 296–309 (2018).
50. Jervelund, C. & Fredslund, N. C. *Fiskeriets Økonomiske Fodaftryk i Grønland* (Copenhagen Economics, 2013); http://www.ga.gl/LinkClick.aspx?fileticket=HG%2F%2BIjJ2KK%20o%3D&tabid=36&language=da-DK
51. Ren, C. & Chimirri, D. Arctic tourism — More than an Industry? *The Arctic Institute* (3 April 2018).
52. Fennell, D. A. *Ecotourism* 4th edn (Routledge, 2014).
53. Weaver, D. B. & Lawton, L. J. in *Arctic Tourism Experiences: Production, Consumption and Sustainability* (eds Lee, Y.-S., Weaver, D. & Prebensen, N. K.) (CABI, 2017).
54. *Greenland Tourism Statistics* (Statistics Greenland, Visit Greenland, accessed 1 January 2019); http://www.tourismstat.gl/
55. *World Heritage List* (UNESCO, accessed 1 January 2019); https://whc.unesco.org/en/list/?search=Greenland&id_sites=&id_states=&id_search_region=&id_search_by_synergy_protection=&id_search_by_synergy_element=&search_yearinscribed=&themes=&criteria_restrication=&id_keywords=&type=&media=&order=country&description=
56. Hansen, C. O., Groensedt, P., Graversen, C. L. & Hendriksen, C. *Arctic Shipping: Commercial Opportunities and Challenges* (CBS Maritime, 2016).
57. Young, O. R. Arctic tipping points: governance in turbulent times. *Ambio* **41**, 75–84 (2012).
58. Rosa, I. M. D. et al. Multiscale scenarios for nature futures. *Nat. Ecol. Evol.* **1**, 1416–1419 (2017).
59. Ostrom, E. A General framework for analyzing sustainability of social-ecological systems. *Science* **325**, 419–422 (2009).
60. Gius, F., Busch, L. L. & Miller, R. V. *Update of Mineral Land Classification: Portland Cement Concrete-Grade Aggregate in the Western San Diego County Production Comsumption Region, California* (California Geological Survey, 2017).
61. FACT SHEET: Atlantic Coast of New York City, East Rockaway Inlet to Rockaway Inlet (Rockaway Beach) and Jamaica Bay. *US Army Corps of Engineers* (accessed 1 January 2019); http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487597/fact-sheet-atlantic-coast-of-new-york-city-east-rockaway-inlet-to-rockaway-inle/
62. Beach Nourishment at Coney Island *PBS* (29 October 2019); https://www.pbs.org/newshour/nation/beach-nourishment-at-coney-island

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M.B. and L.L.I. framed the Perspective and together with I.O. collected the data presented here. L.L.I. and A.G.Z. produced the graphics. M.B. and L.L.I. wrote the manuscript with contributions and inputs from all authors.

Competing interests

The authors declare no competing interests.

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