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Commentary

Reducing sand mining's growing toll on marine biodiversity

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Global demand for marine sand is on the rise, expanding dredging impacts on biodiversity and often encroaching on marine protected areas. Systems approaches like the metacoupling framework help uncover overlooked impacts and balance resource extraction with biodiversity conservation. This requires addressing knowledge gaps, enhancing accountability, and mainstreaming ecological restoration to reverse biodiversity loss.

Over the last century, global material extraction has shifted from primarily biomass-based resources to non-metallic ones, especially sand and gravel (hereafter referred to as "sand" for brevity). These are the world's most extracted solid materials by mass, with an annual extraction rate of 50 billion tonnes[1]—a 5-fold increase since the 1970s.[2] Such a demand has placed immense pressure on coastal and marine ecosystems, which are increasingly strained in balancing the extraction and protection of sand resources and associated biodiversity.[3,4]

Sand is fundamental to the structure and function of coastal and marine ecosystems. It supports biodiversity by creating different habitats, such as sandbanks, which in turn support biodiversity at multiple scales, from cyanobacteria to algae, fish, and rays; enhances resilience against sea-level rise and storms; and provides essential ecosystem services that support livelihoods.[3] As a material, it is also a key ingredient in climate change adaptation and mitigation strategies, including beach replenishment and *ex novo* construction, shoreline armoring, and nature-based solutions. To that end, sand is extracted from ecosystems by dredging vessels and deposited in beaches and dunes or used in construction and land reclamation projects.

With over 700 million people already living in coastal areas and projections exceeding one billion by 2050,[5] the demand for marine sand is driving a rapid expansion of dredging activities. Since 2000, 78% of coastal cities with more than one million inhabitants have engaged in land reclamation, adding 253,000 ha of land, 70% of which is in areas at high risk of sea-level rise.[6] Paradoxically, these dredging activities linked to coastal development can disrupt the natural flow of sediments, accelerating erosion and undermining their resilience to withstand climate change.[7] This further intensifies the demand for sand.[8] Here, we provide an overview of the scale and scope of dredging operations across the world and propose pathways for reducing the biodiversity impacts of sand extraction.

The expanding frontier of marine dredging

The Marine Sand Watch, launched in 2022 by the United Nations (UN) Environment Programme and the Global Resource Information Database - Geneva (GRID-Geneva), represents the first global effort to monitor the extraction of marine sand. The platform uses advanced algorithms combined with the vessels' automatic identification systems (AISs) to track large dredging vessels worldwide. According to Marine Sand Watch estimates, between 4 and 8 billion tonnes of sand and other sediments were dredged annually from 2012 to 2019.

While dredgers have long been operating in certain regions, the "dredging frontier" is expanding to new areas and intensifying in existing ones. Key global hotspots include the North and Baltic Seas, the US East Coast, the African West Coast, the Persian Gulf, and East Asia (Figure 1A). In the North Sea alone, annual sand extraction rose from a few hundred thousand to tens of millions of cubic meters over the past 50 years.[9] The Marine Sand Watch monitors about 60% of all dredging vessels equipped with AISs, but a significant proportion of activities remains untracked. Artisanal and small-scale dredging along shallow coastlines, or vessels intentionally turning off their AIS signals, operate beyond the platform's reach. Small island nations, where artisanal extraction is more prevalent than industrial dredging, remain a significant blind spot. Southeast Asia is also underrepresented despite well-documented conflicts over marine sand extraction that prompted intermittent export bans in countries like Indonesia, Malaysia, and Cambodia.[10]

The expansion and scale of dredging activities represent a growing challenge for biodiversity conservation. Monitored wildlife marine populations have shrunk by 56% from 1970 to 2020.[11] Mining and dredging are important local stressors

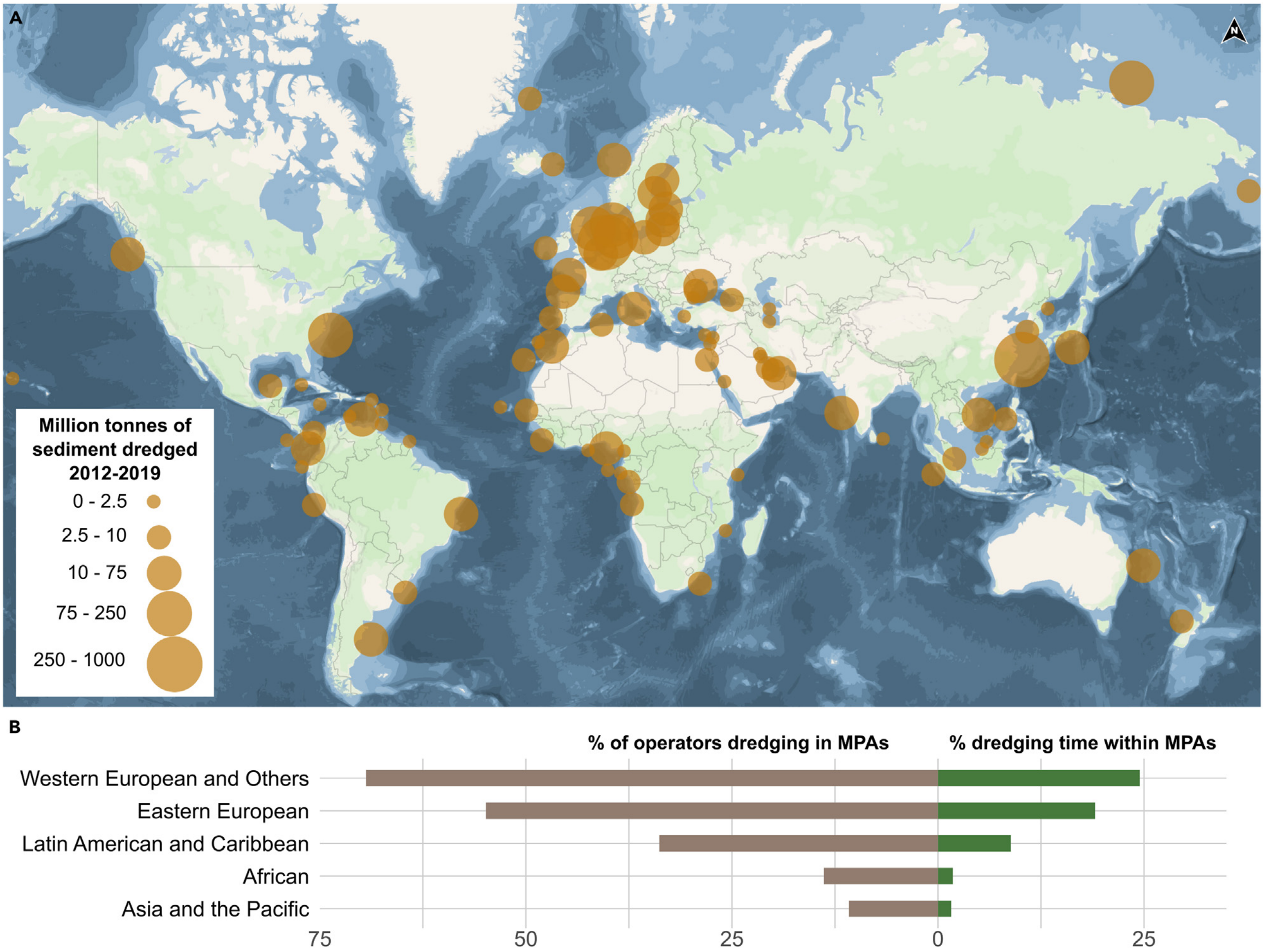

Figure 1. Dredging hotspots and level of overlap with MPAs

(A) Million tonnes of sand and other sediment dredged from 2012 to 2019 per 200 nautical mile zone, as estimated by the Marine Sand Watch.

(B) Percentages of operators dredging in MPAs and dredging time within MPAs by UN region.

The map was created using MapX (https://unepgrid.ch/en/mapx), an online platform developed by UNEP/GRID-Geneva for managing geospatial data on natural resources. International and administrative boundaries are from the UN map geodatabase (scale: 1:1 million, version: 2020).

that, alongside other global pressures, contribute to the loss and degradation of marine life, including sensitive habitats with acute declines such as mangroves, seagrass beds, coral reefs, maerl beds, and species such as sharks and rays. Alarmingly, dredging activities substantially overlap with areas of high conservation value. Between 2012 and 2022, almost half of the globally active operators (47%) dredged each year in marine protected areas (MPAs), accounting on average for 14.2% of total annual dredging time (Figure 1B). Western countries, with higher MPA coverage, show the greatest overlap, with nearly 25% of dredging occurring within these areas and 70% of operators engaging in dredging within MPAs. Efforts to expand the coverage of MPAs are underway with the "30×30" initiative of the Kunming-Montreal Global Biodiversity Framework (GBF), which aims to protect at least 30% of the world's oceans by 2030. The overlap between dredging and conservation areas underscores the need for effective management and enforcement to prevent MPAs from becoming the dredging areas of the future.

Complex impacts on biodiversity

Despite being among the most widespread human activities in coastal areas and shallow seas—second only to fishing—sand extraction and its impacts on biodiversity are often overlooked or underestimated.[3] The Sustainable Development Goal 14 ("Life Below Water") focuses mainly on fishing, aquaculture, and tourism, with no mention of dredging or sand mining. Likewise, while the GBF is more ambitious in scope, it lacks specific targets, actions, and outcomes regarding the reporting and monitoring of sand extraction.[12] However, momentum is rising, with recent resolutions from the UN Environmental Assembly and recommendations from the International Union for Conservation of Nature (IUCN) World Conservation Congress that highlighted the urgency of addressing the multifaceted environmental impacts of extracting sand from coastal and marine ecosystems (Figure 2).

Beyond direct mortality and habitat disturbance from dredging, the extraction of sand also causes indirect impacts,

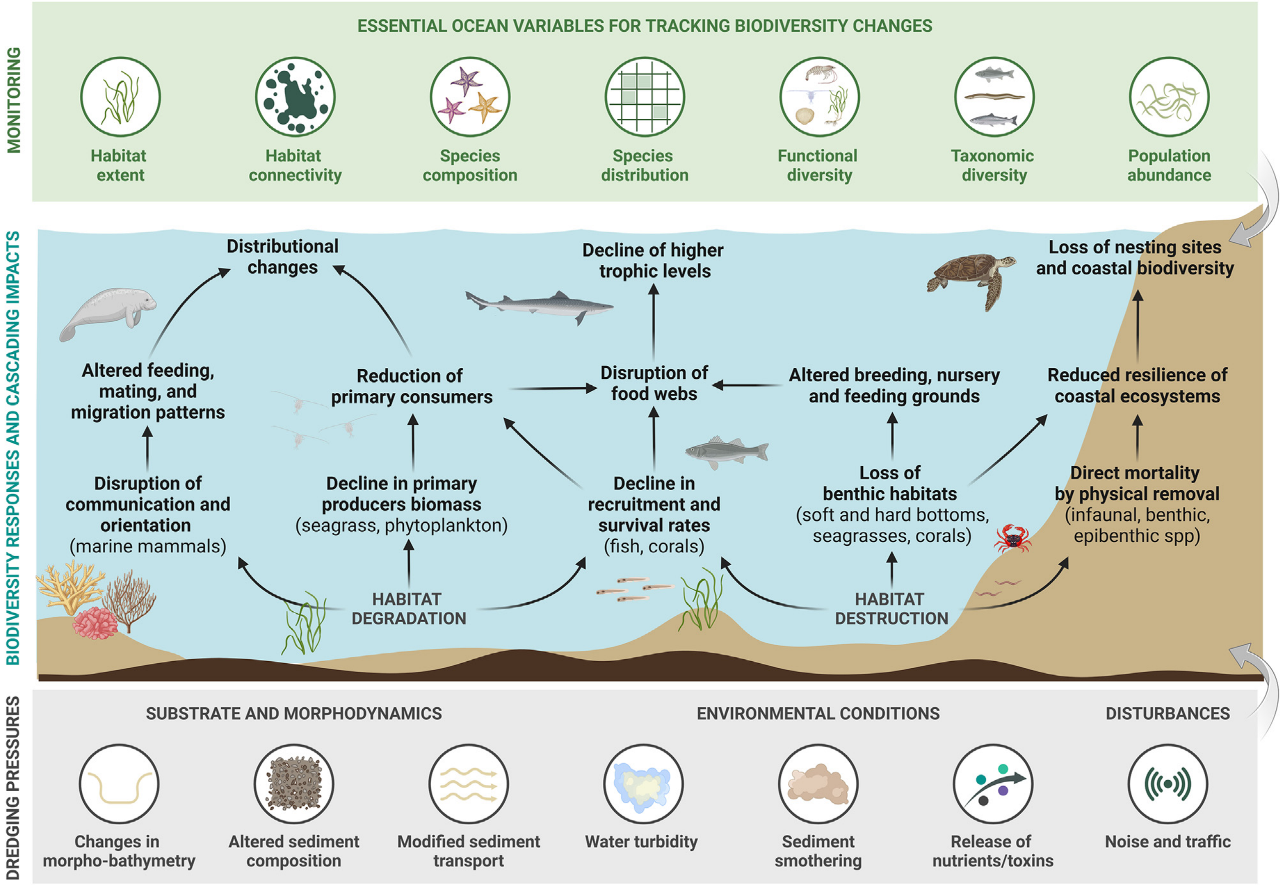

Figure 2. Mechanisms and biodiversity responses to marine sand extraction

Overview of dredging impact mechanisms (bottom), biodiversity responses (middle, as reviewed in Jouffray et al.,[3] Todd et al.,[13] and GESAMP[14]), and a set of essential variables for monitoring biodiversity changes (top). The figure highlights the complexity and interconnectivity of possible impact pathways (arrows), though it is not intended to be exhaustive. Created in BioRender https://BioRender.com/b70l063.

such as water turbidity and sediment smothering of seagrasses and corals, which can lead to synergistic effects. For example, during a 2016 bleaching event in the Maldives, coral mortality due to heat stress was nearly six times higher in dredged areas than in undisturbed sites.[15] Sand extraction can also have systemic impacts on the integrity and connectivity of ecosystems. A striking example is atoll islands, which are often seen as doomed to disappear due to rising sea levels. While these dynamic landforms can adjust through vertical accretion, a process reliant on sediment supply, sand extraction and dredging alter sediment fluxes, exacerbating the risk of erosion and hindering the island's natural ability to maintain elevation.[16] Distant regions may also be impacted by reduced ecological connectivity around dredged areas, as increased turbidity and disturbances can affect the dispersal and migration of species from mussels to marine mammals.[13]

Integrated frameworks are needed to help uncover overlooked or underestimated direct and indirect impacts of extraction on biodiversity within, near, and far from extraction sites. The framework of metacoupling (human-nature interactions within as well as between adjacent and distant systems)[17] offers a useful approach to disentangle these complex interactions across sand-supply networks[8] (Figure 3). It links sending systems (extraction sites) and receiving systems (consumption sites) while identifying spillover systems (e.g., transit routes) affected by the flows between them. For instance, beach replenishment typically involves extracting sand from "borrow" areas to mitigate erosion in receiving systems. However, this often disregards the biodiversity and ecosystem services lost at extraction sites, even when they overlap with threatened habitats or species. Spillover effects, such as sediment plumes along transit routes and changed wave regimes further compound these impacts (Figure 3). Moreover, regular beach replenishment leads to the compaction of beaches and the burial of beach fauna and flora.

Pathways for reducing and reversing biodiversity impacts

The proposed metacoupling framework for examining biodiversity impacts (Figure 3) also offers insights into addressing challenges and identifying pathways for better balancing societal material demand with biodiversity conservation amid growing human pressures on coastal and marine ecosystems. It outlines opportunities to minimize and

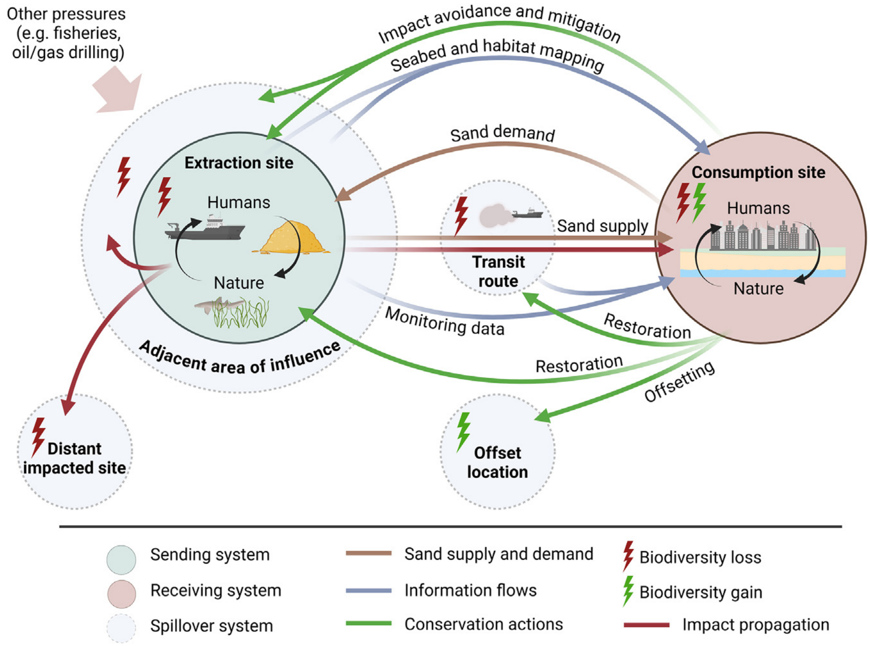

Figure 3. Application of the metacoupling framework to illustrate the impacts of marine sand extraction on biodiversity across space

Schematic representation of the impacts of marine sand extraction on biodiversity, organized around three types of coupled human-natural systems interconnected by the flow of sand resources: sending systems (extraction sites), receiving systems (consumption sites such as beach replenishment, land reclamation, wharves, or construction), and spillover systems (areas affected by the extraction site or by the transport of sand from sending to receiving systems). Spillover systems can be near or far from the sending and/or receiving systems, such as adjacent areas to the extraction site or distant ones affected by the long-distance propagation of impacts like reduced ecological connectivity. Other human pressures leading to cumulative effects on impact locations include, for example, fishing and energy sectors. Information flows from receiving and spillover systems may improve efforts to avoid, mitigate, and reverse impacts on damaged sites and offset impacts on new systems. Created in BioRender https://BioRender.com/e30h590.

reverse biodiversity impacts across sending, receiving, and spillover systems, from reducing sand demand and exploring alternatives[18] to managing marine sand resources and habitats more responsibly. Key challenges include (1) scarce knowledge on the extent and condition of sand deposits and marine habitats, (2) inadequate transparency and accountability in extraction practices, and (3) low engagement in ecological restoration. On the one hand, these challenges hinder the full operationalization of the metacoupling framework. For example, a lack of transparency and insufficient data prevent the framework's quantification and are contributing factors that mask the impacts of sand extraction on biodiversity. On the other hand, the framework can help address these challenges by identifying data and knowledge gaps, demonstrating the need for transparency and accountability and revealing priority areas for ecological restoration. Below, we provide concrete recommendations for addressing these challenges and reducing biodiversity impacts from marine sand extraction and subsequent activities.

Advancing seabed mapping and assessment for effective management

Reducing the impact of sand extraction starts with identifying the most suitable sending systems—where the quality and quantity of sand are most favorable, and environmental impacts are minimal. However, such knowledge of sand deposits remains sparse over vast areas.[17] The same holds true for the extent and condition of marine habitats. For example, the condition of 70% of marine habitats under the European Union (EU) Habitats Directive is unknown, according to the latest reporting period (2013–2018). Assessing the impact of sand extraction is complicated because of cumulative impacts through time and space, including the combination with other activities, such as fishing, aquaculture, wind farms, cables, navigational dredging and disposal, and traffic.[19] Proactively identifying and safeguarding valuable habitats is therefore ever more important, yet the knowledge and data scarcity hamper accurate evaluations of ecological damage and sustainable resource use. Strategic mapping of marine sand resources and habitats is critical for (1) securing a long-term, sustainable sand supply; (2) identifying "no-go" or "low-intensity" zones to safeguard sensitive and valuable habitats for both nature and people, which aligns with the 30×30 initiative; and (3) improving mitigation and restoration strategies to reverse habitat degradation.[17]

Assessing and managing habitat extent and condition is best achieved by combining metacoupled human and natural systems approaches, including spatially explicit biophysical methods, which clarify cause-effect relationships and inform intervention.[20] While impact monitoring should focus on project-level scales and their areas of influence near and far, broader seabed mapping is needed to identify vulnerable ecosystems under current and future warming scenarios. These efforts must be paired with transparent reporting, actionable strategies, and measurable targets to prevent and mitigate impacts within and beyond extraction sites.

States are the largest users and clients for marine sand and dredging works. Expanding the scope and resolution of dredging monitoring efforts is crucial for assessing the extent of ecological impacts and ensuring greater transparency and accountability in extractive initiatives.[3] Governments should leverage improved data and knowledge to promote effective marine spatial planning and sustainably manage their sand resources. However, few countries have assessed their critical sand needs for coastal resilience and development. To safeguard thriving coastal ecosystems for generations ahead, coastal countries should evaluate their sand resources so that their plans are environmentally sound and minimize the impact of potential sand extraction, even in case of a managed retreat from the shoreline. Multilateral collaboration, capacity building, and knowledge sharing are key to ensure that all countries can undertake these assessments and adopt sustainable management of sand resources. A pressing need remains for open debate, rationalization, and weighing of needs against impacts to inform balanced decisions.

Improving corporate transparency and accountability

Beyond governments, businesses and financial institutions related to sand extraction, transport, and consumption can play a key role in halting or reversing the environmental impacts of their activities and leverage their resources and expertise to be a driving force for sustainable practices within, near, and far from the extraction sites. In the dredging sector, transparency efforts should focus on systematically reporting the volume of sand extracted, transported, or consumed, alongside information on operators, activities, and locations. This aligns with Target 15 of the GBF, which emphasizes the need for enhanced corporate biodiversity reporting. Likewise, financial institutions must recognize and assess their exposure to environmental risks associated with sand extraction, such as large-scale land reclamation projects. Including these impacts within the scope of multilateral and private-finance environmental safeguard policies would influence tens of billions of dollars' worth of project financing annually.[12] Such measures could ultimately incentivize more sustainable practices and improve the governance of marine sand resources.

Severe knowledge gaps also persist regarding the biodiversity and carbon footprint of marine sand mining, transportation, and consumption. Public reporting of monitoring data collected before, during, and after dredging could strengthen the evidence base, assess the effectiveness of mitigation and restoration efforts, and identify scalable solutions.[12] Notably, the dredging industry has yet to fully account for its broader carbon emissions (e.g., beyond vessel fuel use), which in turn accelerate climate change and biodiversity loss not only in marine ecosystems but also in terrestrial ecosystems. Addressing uncertainties regarding the magnitude of dredging-induced CO_2 emissions from seabed disturbance and damage to ecosystems that act as carbon sinks represents an important research frontier for improving life cycle assessments and understanding the full environmental cost of sand extraction.

Boosting ecological restoration

While restoration requirements are central to land-based mining, the ecological restoration of dredged areas at sea is rarely addressed, let alone that of spillover systems. Few guidelines mention concepts like restoration and offsetting in the marine environment. Instead, the focus remains on reducing pressures and letting the habitats recover naturally, with minimal follow-up (passive restoration). This contrasts a strong consensus that restoration efforts are as important for marine ecosystems as for terrestrial ones,[5] supported by a backdrop of strategic policies that promote increased engagement in ecological restoration such as the EU Regulation on Nature Restoration (2024/1991), which set binding targets for EU Member States to restore 30% of degraded habitats by 2030 and 90% by 2050 through national restoration plans.

Under business-as-usual operations, biodiversity losses remain inadequately addressed, contributing to the continued decline of marine habitats and their services to people. New or expanding marine sand extraction operations should implement the mitigation hierarchy and allocate sufficient funds for restoration and monitoring.[7] We encourage a proactive approach to ecosystem recovery, moving beyond simply minimizing impacts. Active restoration can catalyze natural recovery processes by improving habitat suitability through actions such as assisting the establishment of foundational species, using state-of-the-art planting techniques, or mimicking natural bedforms to enhance habitat heterogeneity.[21,22] If passive restoration is deemed more suitable, it should be pursued within the scope of an ecological restoration project and follow restoration standards with measurable targets and long-term monitoring.

Restoration initiatives should be supported by robust data collection and applied research to understand the time and conditions needed to restore biodiversity and carbon stocks equivalent to natural ecosystems. On a larger scale, national restoration plans should consider areas degraded by sand dredging, transport, and consumption, aligning with and elevating the goals of the UN Decade 2021–2030 to reverse degradation and promote sustainable recovery. Importantly, restoration must be coupled with effective protection to be truly successful and avoid further degradation during or after the recovery process.

Conclusion

The growing demand for sand threatens biodiversity, ecosystem services, and coastal resilience. Without long-term planning of construction material supply chains, integrated marine spatial planning, effective governance, and transparent monitoring, the potential of MPAs to halt and reverse the sector's impacts on biodiversity remains limited. The metacoupling framework offers an integrated approach to marine sand research and management. It is needed to uncover overlooked and underestimated impacts while balancing extractive industries and infrastructure development with biodiversity conservation within and beyond extraction sites. This requires mapping sand resources and habitats, avoiding extraction in the most sensitive areas, improving transparency and accountability of dredging initiatives, and adopting solid restoration approaches across sending, receiving, and spillover systems. Closing these gaps can align the dredging sector with global biodiversity goals, ensuring a more resilient and sustainable future.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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