Section 4

Subchapter 5B

Biogenic reefs and sandy, muddy and rocky shore substrates

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Key points

- Sandy, muddy and rocky shores, biogenic reefs and other coastal habitats are crucial for biodiversity and ecosystem services, supporting economic activities and protecting coastlines.
- Coastal habitats are interconnected by ocean currents that form part of a meta-ecosystem, in which energy and organisms can move across boundaries, enhancing ecosystem resilience. As such, integrated management approaches are needed.
- These habitats face intense pressures from climate change and human activity, with warming temperatures and heatwaves, rising sea levels, coastal hardening and pollution affecting biodiversity and ecosystem functions.
- The loss and degradation of coastal habitats pose a range of threats to human well-being, from increased flooding risks to loss of livelihoods in tourism and fisheries.
- Addressing these challenges demands robust governance, scientific innovation, strong partnerships and enhanced ocean literacy to promote and conserve resilient, sustainable coastal ecosystems.

1. Introduction and context

The present subchapter is focused on four critical coastal habitats (sandy, muddy and rocky shores and biogenic reefs), highlighting their ecological and economic importance. These environmental systems support diverse species that contribute to water filtration and nutrient cycling and play an important role in the coastal food chain. In addition, biogenic reefs, formed by such organisms as corals, oysters and mussels, provide natural barriers against coastal erosion. Home to invaluable natural resources, these coastal habitats are essential for tourism, fisheries and recreation, underscoring their economic, social, cultural and ecological significance.

Understanding these habitats requires recognizing the fact that they are interconnected through a “meta-ecosystem”, in which energy, materials and organisms move across habitats, shaping their resilience and health. This spatial connectivity necessitates collective management rather than isolated approaches in order to ensure the persistence and functionality of these habitats (Vozzo and others, 2023).

These coastal habitats face a multitude of stressors, however, driven primarily by local human activity and climate change. Urban expansion, pollution and climate-induced impacts, such as rising sea levels and heatwaves, are degrading biodiversity and ecosystem functions (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO),

2024). These cumulative stressors pose significant challenges to the resilience, conservation and sustainability of these ecosystems.

The present subchapter provides an updated assessment of biogenic reefs and sandy, muddy and rocky shores, with a focus on the changes observed since the second *World Ocean Assessment.* Emphasis is placed on the need for integrated coastal management to support biodiversity functions and the sustainable use of marine resources, which includes guaranteeing equitable access to coastal resources.

2. Changes in the state of biogenic reefs and sandy, muddy and rocky shore substrates

In the past decade, biogenic reefs and sandy, muddy and rocky shores have undergone increased landscape transformations due to a mix of environmental and anthropogenic pressures. Climate change and local anthropogenic impacts are driving transformations that threaten the stability and functionality of natural habitats (Hatje and others, 2024). Bivalve-based biogenic reefs illustrate this point; oyster reefs faced centuries of extraction, and estimates suggest that 85% have been lost globally, with impacts on socioecological systems (Beck and others, 2011; Thurstan and others, 2020). Mussel reefs have faced similar historical declines due to overharvesting, replacement by invasive species and, more recently, climate change, leading to scientific mussel reef restoration efforts (Petraitis and Dudgeon, 2020; Roberts and others, 2023; Buschbaum and others, 2024). These reefs play a vital role in coastal ecosystems by filtering water, attenuating waves, stabilizing sediments and providing habitats for a variety of species. Rising sea levels, increasing air and water temperatures, increased pollution and nutrient run-off, however, are leading to hypoxic conditions that weaken reef structures and reduce biodiversity. The harvesting of oysters and mussels, if unmanaged, further diminishes reef resilience, leading to long-term declines in water quality and biodiversity (Ponti and others, 2021; Gianni and others, 2023).

Urbanization stressors, including population density, tourism, nocturnal light, urban infrastructure, vegetation changes and certain beach nourishment practices, significantly reduce species richness and biomass on sandy and muddy shores (Orlando and others, 2020; Corte and others, 2022; De Schipper and others, 2024) and can also have impacts on the nesting areas of migratory animals, such as marine turtles. Artificial light at night disrupts key ecological processes, including circadian rhythms, feeding, reproduction and migration, affecting biodiversity, increasing the vulnerability of species and altering predator-prey dynamics (Marangoni and others, 2022). In addition, recent studies have shown that coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by the end of the century, compromising resilience to sea level rise (Vousdoukas and others, 2020; Nawarat and others, 2024). Combined pressures from sea level rise and urbanization are shrinking intertidal zones, affecting dependent species and reducing vital ecosystem services, such as coastal protection, recreation and habitats for shorebirds (Defeo and others, 2021; Lansu and others, 2024). Conserving natural areas and applying nature-based solutions can reduce infrastructure impacts by up to sevenfold (Lansu and others, 2024; Nawarat and others, 2024).

Muddy shores, which are found in estuaries, bays and other sheltered areas, are vital as nursery habitats for fishes, feeding grounds for migratory birds and sites of high nutrient cycling. They are, however, highly vulnerable to sedimentation changes caused by natural events, such as storms, and human activities, such as dredging and coastal construction. Increased sedimentation can smother benthic communities, disrupt nutrient dynamics and degrade habitat quality. Large-scale infrastructure, such as hydropower stations and reservoirs, reduces sediment and water flow, leading to seawater backflow,

salinization and declines in marine biodiversity (Yi and others, 2023). Pollution from agricultural run-off and urban waste introduces nutrients and toxins, creating hypoxic zones that further harm biodiversity (Daramola and others, 2022; Popoola, 2022). In addition, urban infrastructure, such as seawalls and breakwaters, replaces natural habitats with hard substrates, which can facilitate biological invasions and species range expansions (Airoldi and others, 2015; Dong and others, 2016; Wang and others, 2020).

Sea level rise has a significant impact on rocky shores and biogenic reefs by submerging intertidal areas, resulting in less biodiverse submerged communities and diminished ecosystem services, such as net production and biodiversity (Rilov and others, 2021). Changes in wave energy further affect these ecosystems; for example, high-energy environments reduce oyster density and surface area, decreasing species diversity (Vozzo and others, 2021). Climate change is also altering community composition on rocky shores, with warming waters affecting the range of intertidal and subtidal species (Sanford and others, 2019; Smale and others, 2019, Krumhansl and others, 2024). Heatwaves and other extreme events cause mortality in temperature-sensitive species, such as forest-forming kelps, transitioning communities to low-lying macroalgal turfs or filter feeders, and increasing the abundance of warm-tolerant species (Filbee-Dexter and Wernberg, 2018; Smith and others, 2021; Weitzman and others, 2021). Seasonal species loss can also occur in tropical monsoonal areas. These shifts reduce ecological resilience, increasing vulnerability to disturbances and facilitating the establishment of invasive species under heat stress (Diez and others, 2012; Rilov and others, 2021; Weitzman and others, 2021).

These soft- and hard-bottom interconnected habitats are influenced by the exchange of energy, nutrients and organisms across their boundaries, forming what is known as a meta-ecosystem (Loreau and others, 2003). It is still uncertain, however, how changes in one habitat type, such as a decline in biogenic reefs, can have cascading effects on adjacent habitats, such as sandy and muddy shores, altering nutrient flows and larval supply. This interdependence emphasizes the need for integrated management approaches in which the connectivity of natural habitats and the cumulative anthropogenic impacts on coastal ecosystems are taken into account, especially in the face of increasing global warming, since record air and ocean temperatures were reached in 2023 and 2024 (IOC-UNESCO, 2024).

3. Consequences of the changes for human populations, economies and well-being

The degradation of biogenic reefs and sandy, muddy and rocky shores has direct and indirect implications for human well-being. Natural habitats are crucial in providing multiple ecosystem services (such as coastal protection), supporting commercial fisheries and coastal livelihoods and offering opportunities to enhance local ecological knowledge and cultural values. As natural buffers, biogenic reefs protect coastal areas from wave action and storm surges, mitigate eutrophication through nitrogen removal and sequester significant amounts of carbon (Krause-Jensen and Duarte, 2016; Eger and others, 2023). The ecosystem services provided by kelp forests have been valued at $500 billion globally (Eger and others, 2023). With the weakening of these reefs due to human impacts and habitat fragmentation, communities face increased vulnerability to coastal hazards, resulting in higher costs for flood defence infrastructure and disaster recovery (Ponti and others, 2021; Giglio and others, 2024). Moreover, losses of kelp forests are associated with significant declines in fisheries revenues (Rogers-Bennett and others, 2019). Losses of macrophytes in soft-sediment and rocky habitats reduce their capacity to sequester carbon, and sediment disturbance causes carbon emissions.

Sandy beaches attract millions of visitors annually, generating substantial revenue for local economies. The uncontrolled development of tourism and urbanization, however, is having an increasing impact on habitats. For example, the impacts of artificial light on coastal habitats require immediate attention, as artificial light reduces biodiversity and associated ecosystem services, such as sustainable fisheries and coastal protection. Indirect economic impacts include decreased fishery productivity and the degradation of tourism habitats (Marangoni and others, 2022). The loss of beach areas due to coastal squeeze and erosion also reduces their appeal, leading to declines in tourism revenue and job losses in the service sector, such that total revenue loss could reach €140,400 per m² per year (Alexandrakis and others, 2015). Moreover, increased litter, pollution and habitat degradation on popular beaches lowers their recreational value, affecting both quality of life for residents and the appeal to tourists (Harris and Defeo, 2022; Bozzeda and others, 2023).

For traditional and Indigenous communities, muddy and rocky shores provide critical resources, such as shellfish and seaweed, and hold cultural and spiritual significance. The degradation of these habitats threatens not only food security, but also cultural and natural heritage. Threats to the recreational gathering of intertidal resources can also have an impact on well-being (Morris-Webb, 2021). In many coastal regions, these communities are at the front line of climate change impacts, experiencing increased flooding, loss of land and displacement. This loss of traditional livelihoods and connection to natural landscapes can lead to psychosocial stress and the loss of cultural identity, affecting overall community well-being (Biedenweg and others, 2016; Bennett and others, 2023).

Human health may also be affected, with coastal degradation leading to increased exposure to pollutants and pathogens, particularly in urbanized areas where urban infrastructure increases the presence of anthropogenic litter and synanthropic species (e.g. rats), which are vectors of various pathogens (Aguilera and others, 2023). For instance, the decline in oyster reefs reduces water filtration capacity, increasing the concentration of harmful bacteria and pollutants in coastal waters. This compromises water quality, which is essential for such activities as swimming, fishing and shellfish harvesting, posing health risks to local populations (Fanini and others, 2020; Vousdoukas and others, 2020).

4. Key region-specific changes and consequences

Climate change and anthropogenic impacts are influencing habitats worldwide through both global and local drivers. This part of the subchapter provides examples of such impacts with reference to their geographic, climatic and socioeconomic context and highlights recent updates for the period 2018–2024.

Increased wave energy and extreme weather in the North-West Atlantic and North Sea are intensifying erosion and sediment transport, reducing biodiversity and habitat resilience on sandy and rocky shores. Coastal urban expansion is worsening these impacts by increasing pollution and weakening natural defences. In the United Kingdom of Great Britain and Northern Ireland, marine heatwaves have significantly reduced cold-water species, while winter storms have resulted in damage to habitats, including mussel and algae loss. Despite some recovery, climate change has driven shifts towards warm-affinity species (Mieszkowska and others, 2021). In the Gulf of Maine and eastern Canada, warming temperatures and heatwaves, overfishing and interactions with invasive species are causing declines in kelp abundance and shifts from cold- to warm-tolerant species (Suskiewicz and others, 2024; Krumhansl and others, 2024). Similarly, the heatwave in the Gulf of Alaska between 2014 and 2017 transitioned rocky intertidal habitats from macroalgae to barnacle- and mussel-dominated communities, reducing

diversity and ecosystem complexity with lasting effects on productivity and trophic interactions (Weitzman and others, 2021).

Knowledge of the western region of the South Atlantic, in particular in Argentina and Brazil, has increased, but the east coast remains less studied. The western region faces significant coastal erosion, habitat alteration and ecological imbalances due to storms, cold fronts and disasters, such as oil spills and mine tailing discharges (Gutierrez and others, 2023; Escobar, 2019; Soares and others, 2020). These disturbances have an impact on tourism, fisheries and biogenic reefs with long-term socioeconomic effects. Key environmental drivers, such as ocean temperature, wave exposure and freshwater inputs, shape intertidal communities, altering species abundance and marine trophic chains – trends increasingly influenced by climate change (Pardal and others, 2021, 2022, 2023; Cordeiro and others, 2024). Excessive fishing of herbivores, such as fish and sea urchins, has caused biodiversity loss and macroalgal overgrowth, while urban pollution and eutrophication promote opportunistic species, further degrading benthic ecosystems (Martinez and Altvater, 2024).

In the Indian Ocean region, rapid coastal development, including the construction of artificial islands, is disrupting natural sediment flows, harming coastal habitats. In such regions as Maldives, these modifications have altered fish migration routes and reduced access to traditional fishing grounds, affecting food security and local economies. Plastic pollution and illegal waste dumping from these developments are further degrading water quality, affecting biodiversity and human health (Honorato-Zimmer and others, 2022; McCabe, 2023). Marine heatwaves, in addition to regional warming, are causing widespread tropicalization of kelp forests (Zarco-Perello and others, 2017). The Eastern and South-Eastern Pacific coasts are strongly influenced by climate-driven upwelling systems critical for nutrient supply to sandy and rocky shores (Thiel and others, 2007). Shifts in wind patterns affecting upwelling intensity are disrupting ecosystem productivity, affecting fisheries and biodiversity. The region is also vulnerable to oceanographic events, such as El Niño, which exacerbate coastal erosion, flooding, seawater encroachment and ecosystem changes, leading to long-term socioeconomic challenges (Xiu and others, 2018; Gelcich and others, 2019). During the El Niño event of 2015–2017, species turnover was significant, with some migrating southward due to temperature anomalies (i.e. changes in temperature relative to expected temperatures in the region), although latitudinal community structure remained largely stable (Valqui and others, 2021).

Arctic coastal erosion, driven by permafrost thaw and increased wave action from sea ice loss, is expected to accelerate significantly by the 22nd century, especially under high-emission scenarios (Nielsen and others, 2022). This process threatens sandy and muddy shores by displacing sediments, altering nutrient dynamics and degrading habitat quality. It also releases significant amounts of organic carbon, contributing to greenhouse gas emissions, while jeopardizing infrastructure, biodiversity and ecosystem services, with erosion rates doubling in some warming scenarios. The productivity of macroalgae on rocky shores in the Arctic may increase as the climate warms due to reduced ice cover and greater climate suitability for some species (Filbee-Dexter and others, 2019), though declines in some cold-adapted macroalgal species are expected at the southern extent of their range (Li and others, 2024) or where turbidity increases due to ice melt (Filbee-Dexter and others, 2019).

5. Outlook, key remaining knowledge and capacity gaps and new gaps

Biogenic reefs and sandy, muddy and rocky shores face increasing pressures from climate change, urbanization and human exploitation, threatening their biodiversity and ecosystem services. Coastal population growth, land reclamation and infrastructure development disrupt natural processes, accelerate biodiversity loss and alter sediment dynamics (Vousdoukas and others, 2020; Luijendijk and others, 2018). Emergent threats, such as plastic pollution and artificial light at night, place further strain on these environments, requiring targeted research and mitigation strategies (Marangoni and others, 2022; Ford and others, 2022).

Innovative approaches, such as blue engineering, whereby eco-friendly materials are used in coastal defences, show promise for sustainable urban development that respects ecological integrity (Bugnot and others, 2018; Pinardi and others, 2024). Further research is necessary, however, to understand the long-term impacts of these approaches on meta-ecosystems in terms of reducing biotic homogenization and improving the interconnectedness of natural coastal habitats, with consequences for ecosystem resilience and biodiversity (Firth and others, 2024).

Incorporating traditional and Indigenous ecological knowledge, which offers place-based insights for sustainable management and restoration, into governance frameworks is vital (Strain and others, 2018; Stori and others, 2019; Haugan and others, 2024). Significant knowledge gaps persist, however, particularly regarding the cumulative impacts of multiple stressors, including terrestrial influences, on marine ecosystems. Improved monitoring systems, capacity-building and interdisciplinary research are crucial, especially in underresearched biodiversity hotspots, such as the South Atlantic, the wider Caribbean and South-East Asia (Coleman and others, 2019; Cruz-Motta and others, 2020; Muller-Karger and others, 2024). A socio-ecological approach, integrating natural and social sciences, is essential for holistic coastal management and conservation (Arbic and others, 2024).

Promoting ocean literacy and raising public awareness of the socioeconomic importance of these coastal habitats through education, communication and cultural aspects, including all knowledge systems (Glithero and others, 2024), are key steps to enhance stakeholder engagement in conservation. Multilevel governance structures that include all national and community stakeholders can foster collaboration and ensure that policies reflect local realities. This participatory approach requires financial investment in capacity-building and technical training, enabling communities to actively manage and monitor their ecosystems.

For effective conservation and restoration, countries must develop equitable, inclusive and adaptive policies that prioritize the sustainable management of coastal habitats (Waltham and others, 2020) based on an understanding of their structural and functional connectivity. This includes securing long-term funding for the monitoring and restoration of natural habitats, the greening of artificial infrastructures to improve biodiversity and the use of nature-based solutions (Morris and others, 2018; Aguilera and others, 2020). Empowering communities and fostering resilience in these habitats allow countries to enhance the resilience of their coastal communities against climate change impacts, ensuring the protection of coastlines, the conservation of biodiversity and the sustainability of livelihoods (Sabine and others, 2024).

Safeguarding coastal habitats demands a robust form of governance that integrates diverse knowledge systems and encourages participatory decision-making. Innovative and extensive research is needed in tropical and subtropical regions, where data gaps persist; at the same time, it is important to address

disparities in coastal management between high- and middle-income countries (Nawarat and others, 2024). Coordinated, well-financed strategies aligned with global initiatives, such as the 2030 Agenda for Sustainable Development and the United Nations Decade of Ocean Science for Sustainable Development, are essential to ensuring the resilience and sustainability of these ecosystems for future generations. Continued monitoring, research, local management and international cooperation are essential in order to adapt to evolving challenges and safeguard these invaluable natural resources.

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