Section 4

Subchapter 5A

Intertidal zone

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Key points

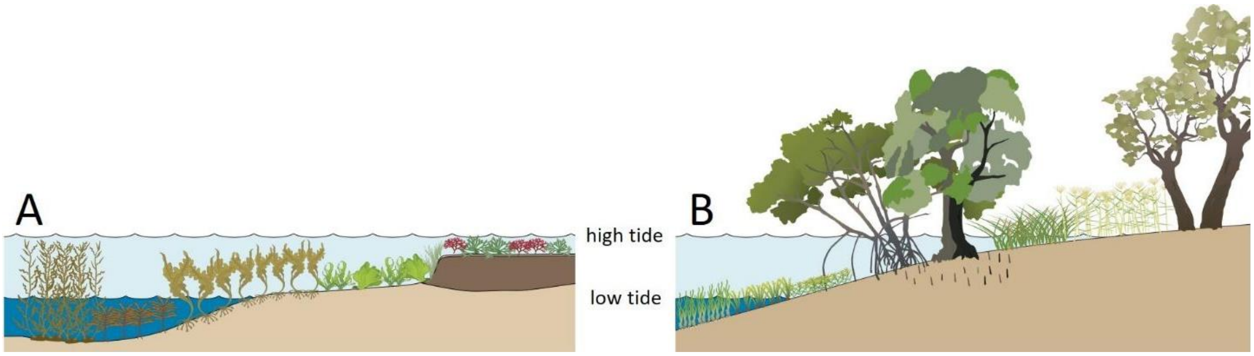
- The intertidal zone has undergone considerable transformations, driven primarily by climate change, pollution and coastal development. Sea level rise and coastal squeeze have led to habitat loss and reduced ecosystem services, such as the provision of natural resources and coastal protection. Rising temperatures and extreme weather events have exacerbated these effects.eEfforts to integrate intertidal ecosystems into climate change mitigation initiatives and increased aquaculture activities have affected i
- tertidal zones. Mangrove forests, salt marshes and seagrass beds are increasingly recognized for their role as blue carbon sinks, and there are initiatives to establish or re-establish and protect these habitats for their ecological and economic value.
- Regional differences in recent developments are becoming apparent, with each biogeographical region facing distinct challenges. Arctic areas are affected by sea ice retreat, while urbanization in such regions as the Mediterranean and the Caribbean is leading
- to eutrophication and habitat fragmentation. The vulnerability of intertidal ecosystems necessitates tailored conservation strategies that reflect regional socioeconomic and environmental contexts.
- Establishment and re-establishment efforts, such as introducing or restoring mangroves and seagrass and implementing green-grey infrastructure, are promising for mitigating habitat loss. The shift towards high-intervention approaches, such as ecosystem co-design, is aimed at creating resilient socioecological sy
- tems that adapt to climate change while providing essential ecosystem services.
- Rising carbon dioxide (CO_2) concentrations in seawater are resulting in ocean acidification that increasingly affects inhabitants of intertidal ecosystems, in particular molluscs, corals and other calcifying organisms.

1. Introduction

The intertidal zone is a dynamic interface between marine and terrestrial environments, characterized by large environmental variability due to regionally specific tidal regimes. This boundary includes diverse habitats (see figure below), such as rocky shores (with macroalgal forests), mudflats, seagrass beds, mangrove forests, salt marshes and sandy beaches, each providing essential services, such as shoreline stabilization, carbon sequestration (see subsect. 5B, chap. 1), and the provision of habitats for numerous species (Phang, Chou and Freiss, 2015).

Figure

Exemplary zonation of macrophytes in coastal and intertidal ecosystems



Source: Prepared by the writing team (symbols from ian.umces.edu/media-library).

Note: (A) temperate rocky shores: subtidal (e.g. *Macrocystis* spp., *Ecklonia* spp.), low-intertidal (e.g. *Laminaria* spp., *Lessonia* spp., *Ulva* spp.), mid-intertidal (e.g. *Chaetomorpha* spp.) and high-intertidal (e.g. *Chondrus* spp., *Codium* spp.) macroalgal beds (see sect. 4, subchap. 4I); (B) tropical and subtropical soft sediment shores: subtidal and intertidal seagrass beds (e.g. *Thalassia* spp., *Cymodocea* spp., *Halophila* spp.) (see sect. 4, subchap. 5G), mid- to high-intertidal mangrove forests (e.g. *Rhizophora* spp., *Avicennia* spp.) (see sect. 4, subchap. 5H), high-intertidal and low-supratidal salt marshes (e.g. *Spartina* spp., *Phragmites* spp.) (see sect. 4, subchap. 5I) and supratidal coastal forests (e.g. *Melaleuca* spp.).

The first *World Ocean Assessment* (United Nations, 2017) served to highlight the ecological significance of the intertidal zone, emphasizing its role as a unique interface between land and sea.

The second *World Ocean Assessment* (United Nations, 2021) contained details of substantial changes in intertidal ecosystems between 2010 and 2020, driven primarily by climate change, coastal development and invasion by non-native species. Key impacts included habitat degradation and biodiversity loss, notably in vegetated areas, such as mangrove forests, seagrass beds and salt marshes. These changes have affected the provision of ecosystem services and revealed the vulnerability of intertidal zones to anthropogenic pressures.

The present subchapter provides an updated assessment of the state of intertidal ecosystems between 2018 and 2023, detailing the effects of sea level rise, pollution, habitat fragmentation and socioeconomic shifts. The importance of regional trends is discussed, as are establishment and re-establishment efforts and adaptive strategies, such as nature-based solutions and green-grey infrastructure, to address these challenges. The aim is to provide a comprehensive overview that supports policymakers in devising targeted conservation, establishment and re-establishment strategies, while promoting resilience through such approaches as ecosystem co-design (Zimmer, 2018; Zimmer and others, 2022) and community-based management. This approach aligns with Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

2. Environmental changes since the second *World Ocean Assessment*

Changes in overall status

Climate change and its consequences have become increasingly prevalent, and the pace of change is faster than anticipated, posing imminent and rapidly growing threats to coastal ecosystems. In addition to warming, sea level rise has effected tangible change in intertidal habitats.

Between 2018 and 2023, sea level rise accelerated, averaging 3.2 mm per year globally (National Oceanic and Atmospheric Administration (NOAA), 2024) and now exceeds 6 mm per year in regions such as South-East Asia, where land subsidence and glacial melt are exacerbating the effects (Idris and Munadi, 2022). Depending on topography, this rise either shifts intertidal habitats landward or compresses them against developed coastlines, resulting in "coastal squeeze" (Rilov and others, 2021). This reduces the extent of intertidal habitats along the tidal gradient, in particular in urban areas, and affects biodiversity and key ecosystem services, such as shoreline stabilization and carbon sequestration. As the sea level rises, coastal areas become ever more vulnerable to coastal erosion (Evelpidou, Tzouxaniot and Liaskos, 2022); this is especially true of coastal areas undergoing additional, non-climatic rises in sea level due to tectonic subsidence or other factors (Cai and others, 2022).

Among direct anthropogenic drivers, agricultural run-off and urban and industrial wastewater discharges are major contributors to eutrophication, causing harmful algal blooms and reduced oxygen levels in coastal waters (Tuholske and others, 2021). Heavy metals and hydrocarbons (see sect. 4, subchap. 6E) from industries affect sediment characteristics and benthic species and reduce biodiversity (Rahmanpour, Ghorghani and Lotfi Ashtiyani, 2014; Moazampour and others, 2021). Urban expansion has increased pollutants, such as microplastics (Chen and others, 2023), which accumulate in many marine organisms (von Hellfeld and others, 2022), and pharmaceuticals, potentially affecting the endocrine system of many organisms (Arguello-Pérez and others, 2019) (see sect. 4, subchap. 6E).

Those pressures notwithstanding, there has been intertidal habitat expansion in some areas due to natural processes. Areas with minimal human interference have experienced sediment deposition, due in part to sea level rise and changed coastal hydrodynamics, leading to the formation of new mudflats and sandbanks (Wang and others, 2012). These new flats provide habitats for diverse species, enhancing local biodiversity. Such expansions are limited, however, to regions where natural sediment availability and transport are unaffected by human infrastructure (Braat and others, 2018).

Rising temperatures have affected, and continue to affect, the distribution of intertidal species and the species composition of intertidal communities. Warming has shifted thermally sensitive species poleward (Habary and others, 2017), and invasive species are often taking advantage of these conditions, outcompeting native species (Nguyen and others, 2020) (see sect. 4, subchap. 6A). The spread of invasive species is accelerated by global trade and travel (O'Shaughnessy and others, 2020). Along with rising temperatures, the frequency and severity of extreme weather events, such as storms and heatwaves, has increased (see subsect. 5B, chap. 4), contributing to ecosystem instability (Román and others, 2020).

Habitat fragmentation persists, especially in urbanizing regions of Asia and the Middle East, where natural intertidal areas are being replaced with artificial structures through land reclamation (Chee and others, 2017). This fragmentation reduces the ecological connectivity needed for species resilience (Aiken and others, 2021), leading to declining species richness, altered ecosystem processes and unequilibrated ecosystems (Sedano and others, 2021). There are some positive efforts to note, however. For example, green-grey hybrid infrastructure projects, in which mangroves and other natural elements are integrated into coastal defences, have mitigated erosion and created habitats that support intertidal species (Agardy and MacIntosh, 2023).

Significant socioeconomic changes can be attributed to environmental pressures, climate change (Mieszkowska and others, 2021), and conservation, establishment and re-establishment strategies (Katsanevakis and others, 2020) in the intertidal zone.

In response to declining shellfish populations, aquaculture (subsect. 5A, subchaps. 1C and 1D) has been focused increasingly on regional species better adapted to local environmental conditions (Carranza and zu Ermgassen, 2020). This reduces the impact of non-native species that often disrupt communities and ecosystems (Lima and others, 2018). Supporting native aquaculture improves sustainability and provides a stable income, contributing to food security and economic resilience (Engle and van Senten, 2022). Integrated and multi-trophic aquaculture has gained in popularity. It involves combining different species, ideally of different trophic levels, of commercial interest in order to optimize resource use and reduce environmental impacts (Barrington and others, 2008). For example, farming filter-feeding molluscs improves water quality (reduced nutrient load) and light conditions for primary producers (Du and others, 2023). Including mangroves in shrimp aquaculture also enhances coastal resilience by reducing erosion and improving water quality (Mahmudi and others, 2022), thereby combining some of the many services and benefits of mangroves with food production. This approach aligns with global sustainability goals and offers new economic opportunities for coastal communities (Hossain, Senff and Glaser, 2022).

The recognition of intertidal ecosystems, such as mangrove forests, salt marshes and seagrass beds, as important blue carbon sinks has led to efforts to protect, establish or re-establish these ecosystems (Heimhuber and others, 2023). Integrating blue carbon valuation into coastal management has created incentives for conservation projects, potentially generating funding through carbon credits and international programmes (Friess and others, 2022), provided that proper monitoring, reporting and verification (MRV) are assured (Van Dam and others, 2024).

The socioeconomic impacts of rising sea levels and increased storm frequency highlight the need for effective coastal resilience strategies (Hoggart and others, 2014). Nature-based solutions, such as mangrove forest establishment and re-establishment and salt marsh conservation, have been prioritized for their role in enhancing biodiversity and providing coastal defence (Van Coppenolle and others, 2018; Van der Meulen and others, 2023). These approaches can be complemented by engineering solutions, including sea walls, to improve infrastructure (Burcharth and others, 2015). Such green-grey hybrid infrastructure, combining natural elements with technical, architectural or engineering solutions, balances human needs with biodiversity conservation and the need for efficient coastal protection (Waryszak and others, 2021; Evelpidou and Spyrou, 2024).

Coastal tourism can have profound impacts on marine biodiversity (Alsaleh and others, 2023) and can cause the pollution of coastal sediments (Buzzi and others, 2022). Tourist activities on sandy beaches are often facilitated through the deliberate destruction of intertidal habitats (Evelpidou and others, 2022; Andriolo and Gonçalves, 2023) or the removal of beach wrack, gravel, boulders and beach rocks, resulting in changed coastal morphodynamics and increased erosion (Johnston and others, 2023; Saitis, 2022). Coastal tourism has, in turn, faced challenges due to beach erosion, pollution and biodiversity loss, reducing the natural appeal of intertidal and coastal areas (Thinh and others, 2019). This can lead to a decline in tourism revenue, pushing communities to adapt by promoting conservation-focused or ecotourism initiatives (Lukoseviciute and Panagopoulos, 2021). These adaptations provide new income opportunities and raise awareness of the importance of preserving intertidal ecosystems (Harahab and others, 2021) for both tourists and local actors.

Community-based management of coastal resources has gained emphasis, in recognition of the fact that Indigenous, traditional owner and local community knowledge and stakeholder engagement and involvement are key to sustainability (Tetelepta and others, 2023). Empowering communities to co-design measures to manage fisheries, establish or re-establish ecosystems and participate in conservation programmes has been effective in building coastal resilience. These participatory approaches foster a sense of ownership, leading to better stewardship (Galappaththi and others, 2022).

3. Region-specific changes

Intertidal zones across biogeographical regions have experienced distinct trends driven by changing climatic conditions, socioeconomic factors and human activities. The following paragraphs provide an overview of key trends in the seven major biogeographical regions.

Arctic Ocean

In the Arctic Ocean, the rapid retreat of sea ice due to increasing temperatures has had a significant impact on intertidal habitats (Assis and others, 2022). Rising sea levels and storm frequency have led to coastal erosion, altering sediment patterns and affecting species reliant on stable intertidal environments (Jones and others, 2009). The northward expansion of sub-Arctic species has displaced native Arctic organisms, challenging Indigenous Peoples and communities who depend on intertidal resources (Stafford and others, 2022). Increased commercial shipping traffic due to receding sea ice has led to higher pollution levels, including oil spills and noise pollution, disrupting intertidal ecosystems and wildlife (Ghosh and Rubly, 2015).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic, Baltic Sea, Black Sea, Mediterranean and North Sea regions have shown varied trends. The North Atlantic and North Sea face extreme weather events, floods of greater frequency and severity, and erosion (Mendez-Tejeda and others, 2020), while warming in the Mediterranean has facilitated invasive species, challenging native communities (Yeruham and others, 2020). Coastal urbanization in the Baltic (Vigouroux and others, 2021) and Black Seas (Akkoyunlu, 2018) has led to eutrophication, decreasing water quality.

South Atlantic Ocean and wider Caribbean

In the South Atlantic and wider Caribbean, coastal development (subsect. 5A, chap. 9), especially in urban areas, has fragmented mangrove and seagrass habitats (Blanco-Libreros and Ramírez-Ruiz, 2021). Tourism infrastructure expansion has further contributed to habitat loss (Tuholske and others, 2017).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf face intense socioeconomic and anthropogenic environmental pressures. Mangrove forests have been negatively affected by coastal squeeze (Milani, 2018), and increased temperatures have had an impact on intertidal ecosystems (Rajalakshmi and Achyuthan, 2021).

North Pacific Ocean

In the North Pacific, warming waters have shifted species distributions, facilitating invasive species (Liu and others, 2022). Coastal urbanization (Momota and Hosokawa, 2021), anthropogenic activities (Yap and others, 2020) and increased storm activity pose threats (Kuwano-Yoshida and others, 2022), leading to habitat fragmentation and highlighting the need for resilient construction practices (Bulleri and Chapman, 2010).

South Pacific Ocean

The South Pacific, which includes many island nations and small island developing States, has been affected by rising sea levels, leading to the loss of critical habitats and ecosystems, such as mangrove forests (Zhu and others, 2021), that are vital for communities dependent on small-scale fisheries (Flores-Verdugo and others, 2014). Pressures from urban expansion, pollution and habitat loss have caused the degradation of salt marshes and coastal wetlands, affecting both coastal biodiversity and the livelihoods of artisanal fishers (Gaete and others, 2017).

Southern Ocean

The Southern Ocean has seen less direct human influence (Murphy and others, 2021) than other regions, but climate change remains a major driver of environmental and ecological change and the degradation of intertidal habitats and ecosystems, as increased temperatures have altered species distributions in Antarctica (Chelchowski and others, 2021).

4. Key remaining knowledge and capacity gaps and new gaps

The ongoing trends in anthropogenic impacts, such as coastal development (see subsect. 5A, chap. 9), pollution (see sect. 4, subchap. 6E) and resource extraction, continue to degrade intertidal habitats (Stamp and others, 2022). At the same time, opportunities exist for the establishment and re-establishment of intertidal ecosystems in degraded and newly emerged habitats. Establishment and re-establishment efforts, however, must balance species richness, functional diversity and species distinctiveness in order to ensure that these ecosystems remain ecologically robust and contribute effectively to biodiversity, ecosystem processes and coastal resilience (Lester and others, 2020; Rahman and others, 2021, 2024).

Intertidal ecosystems exhibit a decline in native species richness (Cappelatti and others, 2020), and functional diversity and distinctiveness are being increasingly affected by the proliferation of invasive species (Pires-Teixeira and others, 2021) (see sect. 4, subchap. 6A). As species composition changes, the dynamic equilibrium of these ecosystems (Krohs and Zimmer, 2023) is at risk, potentially undermining their ability to provide essential services, such as shoreline stabilization, nutrient cycling and carbon sequestration (Pinto and others, 2014). The success of measures to combat the spread of invasive species will depend on increased awareness of the threats they pose and on adequate training of staff in the authorities responsible (Roussos and others, 2021).

Conventional restoration methods, which focus on returning ecosystems to their original state, may be insufficient in the face of accelerating climate change and ongoing anthropogenic pressures (Capon and

Pettit, 2018). High-intervention approaches, such as ecosystem co-design (Zimmer, 2018; Zimmer and others, 2022), are gaining traction. These methods are aimed at creating resilient socioecological systems that mitigate and adapt to the effects of climate change while serving human needs. Such strategies integrate natural and artificial components in order to bolster ecosystem services (Westphal and others, 2022).

The outlook for intertidal ecosystems ultimately depends on policy integration and effective management practices that combine conservation, establishment, re-establishment and adaptive approaches (Baskent, 2020). Engagement with stakeholders, in particular local actors and communities, and the incorporation of Indigenous knowledge, will be crucial for developing strategies that sustain these vulnerable, yet vital, ecosystems amid ongoing environmental challenges (Ndonye and others, 2021).

Key knowledge gaps with respect to the intertidal zone reflect the need for improved models and scenarios that can be used to project the future state of protected and established and re-established areas experiencing ongoing climate change effects (Garner and others, 2023). Such models must incorporate both physical and biological variables in order to predict how establishment and re-establishment actions will fare against accelerating sea level rise and shifting climatic conditions. Reliable projections are crucial for ensuring the long-term sustainability of intertidal conservation efforts and for informing adaptive management strategies (Judge and others, 2018).

A significant capacity gap is the lack of widespread, standardized monitoring of biodiversity loss and species distribution shifts. The implementation of advanced techniques, such as molecular taxonomy and environmental DNA approaches, is essential to fill this gap. These methods allow for non-invasive, accurate monitoring of species composition and help to detect changes, especially in response to climate-induced shifts in distribution, providing critical information for conservation planning (Thomsen and Willerslev, 2015). Actions against future coastal squeeze, such as strategic spatial planning for coastal vegetated ecosystems, require further research and implementation (Lester and others, 2020). Learning from such examples as New Orleans, United States of America, where proactive spatial planning has resulted in the designation of areas for future coastal vegetated ecosystems, can help to mitigate habitat compression (de Mutsert and others, 2021). Such strategies must be adapted to regional contexts in order to ensure the preservation and resilience of intertidal habitats (Chambers and others, 2019).

Addressing these gaps requires coordinated international and regional efforts (Cavallo and others, 2016), increased funding for technological advances and capacity-development initiatives (Clark and others, 2018) to empower local communities and stakeholders to use modern tools and approaches for effective intertidal ecosystem management (Goodspeed and others, 2016).

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