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Coastal Development: Resilience, Restoration and Infrastructure Requirements

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Abbreviations

ADB	Asian Development Bank
CBD	Convention on Biological Diversity
CO_2	Carbon dioxide
EEZ	Exclusive economic zone
GSLR	Global mean sea level rise
ICM	Integrated coastal management
ICZM	Integrated coastal zone management
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LMMA	Locally managed marine area
MPA	Marine protected area
NbS	Nature-based Solutions
NDC	Nationally determined contribution
NGO	Non-governmental organisation
OECM	Other effective conservation measure
PES	Payments for ecosystems services
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SEEA	System of Environmental-Economic Accounting
TURF	Territorial use right for fisheries
SIDS	Small island developing states
UNFCCC	United Nations Framework Convention on Climate Change

Highlights

- Resilient coastal ecosystems are central to the realisation of a sustainable, inclusive, prosperous, and equitable ocean economy, as coastal areas are home to more than 40% of the world's population and host most of the transport, commercial, residential and national defence infrastructure of more than 200 nations and territories.
- Coastal ecosystems are undergoing profound changes, as they are challenged by climate change, threatened by urbanisation and poor upstream agriculture and extractive industry practices, increasing sprawl of coastal infrastructure, and over-exploitation of resources.
- Failure to properly manage our coastal ecosystems will result in continued environmental damage, compromised development of established and emerging ocean sectors, disadvantaged nations and peoples, as well as inadequate infrastructure to meet the demands of changing demographics and climate change impacts.
- To ensure the environmental, economic and social sustainability of our space-constrained coastal ecosystems, ongoing development of our coasts must be balanced across multiple competing uses.
- The full range of economic, social, cultural and environmental values of coastal ecosystems must be balanced through enduring partnerships and active stewardship from government, industry and communities, and supported through innovation and research.

Originally published in:
Steven, A.D.L., Appeaning Addo, K., Llewellyn, G., Vu, T.C. et al. 2020. *Coastal Development: Resilience, Restoration and Infrastructure Requirements*. Washington, DC: World Resources Institute. www.ocean-panel.org/blue-papers/coastal-development-resilience-restoration-and-infrastructure-requirements.
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J. Lubchenco, P. M. Haugan (eds.), *The Blue Compendium*, https://doi.org/10.1007/978-3-031-16277-0_7

- This Blue Paper focuses on how to enhance coastal ecosystem resilience and enable sustainable pathways for economic, infrastructure and social development, without compromising the integrity and benefits of coastal ecosystems, or disadvantaging the people who rely upon them.
- This paper identifies opportunities for nations to cooperate by building upon past success to realise a sustainable ocean economy through championing the following four coastal opportunities for action: build ecosystem resilience; mitigate impacts of terrestrial and extractive activities on coastal ecosystems; advance sustainable, future-proofed blue infrastructure; and enhance community resilience, equity and access.
- With COVID-19 creating an imperative for stimulating economic activity, there is a unique window of opportunity to ensure that relevant policy and investment decisions address the challenges faced by coastal ecosystems and communities, as well as foster sustainable economic pathways. This involves supporting the recovery and development of impacted communities, building the resilience of coastal ecosystems and safeguarding the services they provide and future-ready built infrastructure.

1 Introduction

More than 200 countries have a coastline, and this forms the basis for their claims to territorial waters and exclusive economic zones (EEZs). Globally, about 40% of the world's population live within the "near coastal zone"—the area below an elevation of 100 metres (m) and closer than 100 kilometres (km) from the coast (Kummu et al. 2016). The vast majority of resources for current and emerging sectors that comprise the "ocean— or blue—economy" are concentrated along coastal areas within these EEZs and must operate within a complex, multiple-use and often space-constrained context. The near coastal zone is also where the majority of many coastal nations' commercial, residential, transport and national defence infrastructure is situated, and it is the backbone to domestic and international supply chains that deliver the marine goods and services upon which we increasingly rely.

Coasts sustain livelihoods for hundreds of millions of people in work that ranges from artisanal small-scale fisheries and aquaculture to transnational fishing, shipping, energy and tourism industries. Our increasingly urbanised societies are highly dependent upon coastal resources for food, energy, minerals and pharmaceuticals. Consequently, the coastal economy—which is much broader in its accounting than the ocean economy because it includes not only the sum of outputs from ocean resources but also employment on or near the coast—makes a disproportionately high contribution to the economies of many countries, and to the global ocean economy (He et al. 2014; Mohanty et al. 2015; NOEP 2016; Voyer et al. 2018). A significant, but mostly unquantified, informal or grey economy also occurs within coastal settings and underpins the livelihoods of some of the most disadvantaged populations. In addition to providing these important provisioning goods, the biodiversity and natural functions of intact coastal ecosystems provide regulating, supporting and cultural services that also underpin the ocean economy. These services are recognised as nature's contributions to people (NCP), as they are central to links between nature and people and their culture knowledge systems (Pascual et al. 2017; Diaz et al. 2018; IPBES 2019).

Coastal environments occur where the land and the ocean meet, and they are the place where, historically, people have concentrated and prospered. These environments are intrinsically dynamic—shaped as they are by the interaction of marine, terrestrial and atmospheric processes. However, they are also profoundly changing across human timescales, as they are challenged by extreme climate events that are escalating in frequency and severity, and threatened by increasing population growth and urbanisation, poor upstream land practices, conversion of coastal habitats, and environmental impacts from industry, pollutants and over-exploitation of resources. These changes are direct and physical through the loss, fragmentation and alteration of many ecosystems, but also functional, through a loss of resilience that diminishes the capability of coastal environments to resist and recover from such perturbations. Poorly designed and operated infrastructure can also create harmful environmental and social impacts, increase vulnerability to natural disasters and can sometimes leave an unserviceable burden of debt.

Future projections over the coming decades of our accelerating use and dependence on the coastal zone for living space and resources highlight that, unless we change the way we manage and adapt our use of coastal environments, there will be profound consequences for the resilience of coastal environments and the communities that rely upon them. To avoid the realisation of these projections requires innovative approaches to increase the resilience of coastal environments, and to ensure that the services they provide are sustained. Nature-based solutions are increasingly being adopted as complementary approaches to bridging this adaptation gap, to make infrastructure more resilient to climate change effects and add longer-term value to infrastructure assets.

They are also critical to our aspirations for achieving a sustainable ocean economy and many of the Sustainable Development Goals (SDGs). To realise a sustainable ocean economy that protects, produces and prospers, fundamental issues of equity, inclusion and access must be addressed by developing better governance, participatory, finance and capability-enhancing mechanisms. While COVID-19 has had a profound impact on the economies and social fabric of many nations, under the banner of "build back better", there are significant opportunities to address many of the challenges confronting coastal environments, by adopting approaches that support both a sustainable ocean economy and associated livelihoods to create win-win outcomes for governments and coastal communities. For example, promoting natural infrastructure and grey-green infrastructure nation-building projects provides jobs and builds coastal resilience, while establishing local supply chains for fisheries supports community resilience in low-income countries.

This Blue Paper reviews the major human activities that have increased pressure on coastal ecosystems and reduced their resilience. Our focus is principally on reviewing and identifying practicable solutions that can be implemented to enhance coastal ecosystem resilience and enable sustainable pathways for economic and infrastructure development, without compromising the integrity and benefits of coastal ecosystems or disadvantaging the people who rely upon them. Thus, we use the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) conceptual framework, which rationalises inclusive valuation of nature's contributions to people in decision-making, and we consider resilience not only in physical and ecological contexts but also in terms of social, institutional and financial resilience (see Table 7.1).

We have drawn upon a number of recent intergovernmental reports, notably the Intergovernmental Panel on Climate Change (IPCC) *Special Report on the Ocean and Cryosphere* (IPCC 2019) and the IPBES *Global Assessment Report* (2019), which provide comprehensive global assessments of current and projected conditions of coastal environments.

Likewise, there are a number of other excellent reports that develop solutions spanning a number of fields: innovation, finance, engineering and material science, and behavioural psychology. Many of the coastal issues and their potential solutions can only be briefly considered here, and several companion Blue Papers provide more detailed analysis.

Table 7.1 Coastal resilience definitions adopted for this report

Type of resilience	Characteristics
Physical resilience	Resilience of existing and planned infrastructure, including through risk-sensitive land-use planning, incorporation of structural resilient measures into infrastructure projects, investments in structural risk reduction measures, and improved operation and maintenance of infrastructure as pathways to building physical resilience
Financial resilience	Improved financial management and timely provision of adequate flows through contingency financing, increased availability and coverage of insurance and capital market risk transfer solutions. Comprehensive risk financing solutions and enhanced capabilities to use financing effectively
Social and institutional resilience	Governance and the promotion of poverty reduction and social protection programmes that build community resilience and channel support to affected poor households. In particular, building women's resilience through greater access to technologies and finance, diversification of livelihoods, and increased participation in women-led solutions
Ecological resilience	Natural ecosystems play multiple roles in conferring resilience. Examples of this type of resilience are enhancing support for nature-based climate and disaster solutions, including upper watershed restoration, wetlands restoration, mangrove rehabilitation, and installation of detention basins and retention ponds to reduce flooding, storm surges and coastal erosion

Source: Adapted from ADB (2019)

2 Coastal Changes and Challenges

For millennia, coastal environments have been the location of many civilisations, providing resources and materials for local use, as well as trade along sea routes with other nations (Paine 2014). Today, however, the scale of coastal use and resource demand, driven by rapid population growth and increasing urbanisation, is unprecedented and has been referred to as the *blue acceleration*—a race among diverse and often competing interests for ocean food, material and space (Jouffray et al. 2020). Concurrently, coastal environments, which have always been shaped by climate processes, are now the frontline of anthropogenic climate change, with these environments and their dependent human communities already experiencing the impacts of both extreme climate events and slow-onset changes, such as sea level rise. Together, these climate-induced changes and the accelerating demand for coastal space and resources, as well as the forms of pollution that result (e.g. litter, wastewater), are threatening the extent, condition and biodiversity of many coastal ecosystems, and the goods and services we derive from them. Below, we briefly summarise global patterns of change in climate conditions and human demand for coastal resources and space over the last 50 or so years, and projections for the coming three decades that will profoundly shape and alter our coastal environments.

2.1 Climate Changes and Coasts

Rising carbon dioxide (CO_2) and greenhouse gas emissions have led to well-documented global increases in sea level and sea temperatures, which have resulted in stormier and more extreme sea conditions. The IPCC *Special Report on the Ocean and Cryosphere* (IPCC 2019; and key chapters: Bindoff et al. 2019; Magnan et al. 2019; Oppenheimer et al. 2019) provides the most current and authoritative analysis of recent (1950–present) observed changes in the climate system, and future projections (to 2100) based on low and high Representative Concentration Pathway (RCP) emission scenarios (RCP2.6 and RCP8.5, respectively). Table 7.2

Table 7.2 Summary of key observation and trends in climate change

Parameter	Observed trends	Near-term (2030–2080) and end-of-century projections	Physical effects on coastal ecosystems and settlements	Key references
Global mean sea level	Rate change from 1.38 mm/year during 1901–1990 to 3.16 mm/year during 1993–2015	Up to 2050, global mean sea level will rise between 0.24 m and 0.32 m In 2100, the numbers are 0.59 m and 1.10 m, respectively	Permanent submergence, flood damage, erosion, saltwater intrusion, rising water tables/impeded drainage, ecosystem loss (and change)	Storlazzi et al. (2018), Vitousek et al. (2017), Donnelson Wright et al. (2019a, b), Becker et al. (2020), Oppenheimer et al. (2019)
Regional mean sea level	Rising and accelerating	Increased regional relative sea level nearly everywhere (RCP8.5)	Coastal flooding, submergence, erosion, salinisation	Oppenheimer et al. (2019), Minderhoud et al. (2020)
Extreme sea levels	Increase due to increase in storm intensity	More frequent extreme sea level events as a consequence of sea level rise at many locations by the end of the century (RCP8.5)	Coastal flooding, erosion, saltwater intrusion	Mentaschi et al. (2018)
Waves	Small increases in significant wave height with larger increases in extreme conditions and largest increase in the Southern Ocean	Low confidence for projections overall but medium confidence for Southern Ocean increases in wave height	Coastal erosion, overtopping and coastal flooding	Young and Ribal (2019), Reguero et al. (2019a), Camus et al. (2017)
Winds	Small increases in wind velocity with larger increases in extreme conditions and largest increase in the Southern Ocean	General trend of reduction in wind velocity in summer, autumn and spring, but increase in winter in Northern and Central Europe. General increase in extreme conditions	Wind waves, storm surges, coastal currents, land coastal infrastructure damage	Young and Ribal (2019), Zheng et al. (2019)
Storms, tropical cyclones, extra-tropical cyclones	Regionally variable but increase in annual global proportion of tropical cyclones reaching Category 4 or 5 intensity	Decrease in global tropical cyclone frequenc but proportion of cyclones that reach Category 4 or 5 intensity will increase by 1–10% (RCP8.5)	Higher storm surge levels and storm waves, coastal flooding, erosion, saltwater intrusion, rising water tables/impeded drainage, wetland loss (and change). Coastal infrastructure damage and flood defence failure	Kossin et al. (2020)
Sea surface temperature	SST warming rates highest near the ocean surface (>0.1 °C per decade in the upper 75 m from 1971 to 2010) decreasing with depth	0–2000 m layer of the ocean projected to warm by 900 zettajoules (ZJ) (RCP2.6) and 2150 ZJ (RCP8.5)	Increase in number of coral bleaching events, number of coastal bottom dead zones due to density stratification, harmful algal bloom events, altered ecosystem structure, increased stress to coastal ecosystems	Bindoff et al. (2019)
Marine heatwaves	Doubled since 1980s	Projected to increase (high confidence)	Changes to stratification and circulation, reduced incidence of sea ice at higher latitudes, increased coral bleaching and mortality, increased poleward species migration, decrease in the abundance of kelp forests, massive sea bird die-off and harmful algal bloom	Bindoff et al. (2019), Oliver et al. (2019)
Freshwater input	Declining trend in annual volume of freshwater input	Increase in high latitude and wet tropics and decrease in other tropical regions	Altered flood risk in coastal lowlands, water quality, salinity, fluvial sediment supply, circulation and nutrient supply	Wang et al. (2019), Llovel et al. (2019)
Sea ice and perma-frost thaw	A loss of soil carbon of 5.4% per year across the site Arctic sea ice loss of over 40% over the last last 40 years	By 2100, thaw-affected carbon increase 3-fold (RCP4.5) to 12-fold (RCP8.5)	More storm surges, increasing ocean swells, coastal erosion and land loss in the Arctic and Antarctica regions	Nitzbon et al. (2020), Plaza et al. (2019), Rignot et al. 2019
Ocean acidification	Ocean surface water pH is declining by a very likely range of 0.017–0.027 pH units per decade, since 1980	pH drops of between 0.1 (RCP2.6) and 0.3 (RCP8.5) pH units by 2100, with regional and local variability, exacerbated in polar regions	Increased CO_2 fertilisation, decreased seawater pH and carbonate ion concentration. Enhancing coral reef dissolution and bioerosion, affecting coral species distribution and community	Bindoff et al. (2019), Agostini et al. (2018), Gao et al. (2019)

summarises the historical changes and future projections for climate drivers and ocean and coastal conditions, while below, we focus on the consequences and implications of rising sea levels, warmer and more acidic water, and a greater frequency of extreme climate events, for coastal environments.

Changes in the observation record—which extends back to the early 1900s for tide gauges and more recently for measurements from satellites—from the ocean around the world are clear: sea surface temperatures, wave energy, storminess and acidity have all risen, in many cases doubled, and have continued to accelerate, particularly in the last 30 years (Table 7.2). Near-term and end-of-century model projections all predict, with a high degree of certainty, that these trends will continue to increase and to accelerate. What is unclear is the magnitude, extent and timing of slow-onset climate drivers, such as global mean sea level rise (GSLR), and the frequency of occurrence and magnitude of extreme climate events, including inundation and marine heatwaves.

These changes in ocean state result from both changes occurring directly within the ocean, such as the changes in heat content, density stratification and circulation patterns, and cryosphere changes that include the melting of glaciers, particularly in Greenland and the Antarctic, and sea ice. Both of these factors can act to dilute the salinity of seawater, leading to changes in density and circulation patterns, but only glacial melt will increase the volume of the ocean.

Changes in ocean condition and state are magnified in shallow coastal environments, where tidal and wave energy have their greatest impact on shorelines, and extend across the regional tidal range, and can result in: increased frequency of inundation and subsidence, changes in wetlands, increased erosion of beaches and soft cliffs, and the salinisation of surface and groundwater. Here, the local or relative sea level is complicated and compounded by activities occurring within the coastal zone that affect land elevation, such as subsidence, as well as prevailing winds and water circulation.

While there are significant regional variations, GSLR over the coming century (to 2100) could increase by between 0.43 m (c.4 millimetres (mm)/year) under RCP2.6, and 0.84 m (c.15 mm/year) under RCP8.5. Locally high sea levels, which historically only occurred once per century (historical centennial events or HCE), are projected by 2050 to occur at least annually in many locations, inundating many low-lying areas, including deltaic regions (e.g. Bangladesh and the Mekong Delta), coastal megacities (e.g. Jakarta and Manila) and small islands (e.g. Oceania), impacting their coastal ecosystems, economic development and habitability (Vitousek et al. 2017; Storlazzi et al. 2018; Minderhoud et al. 2019; Oppenheimer et al. 2019; Donnelson Wright et al. 2019a, b; Becker et al. 2020).

In conjunction with sea level rise, greater wave action (wave height, period) and changes in direction and intensity, and more frequent and intense storm surges will affect many coastal areas that were previously never, or infrequently, exposed to such events. These changes can result in cascading impacts on coastal infrastructure and communities living in coastal areas, which are considered further in Sect. 3.3. Projected changes in sea level and wave action, and storm surges will be important considerations for how we build future climate-ready coastal infrastructure (Bhatia et al. 2018; Morss et al. 2018; Abram et al. 2019; Bindoff et al. 2019; Fernández-Montblanc et al. 2019; Kim et al. 2019; Marcos et al. 2019; Magnan et al. 2019; Morim et al. 2019; Oppenheimer et al. 2019; Reguero et al. 2019b).

Coastal shelf waters, from polar regions to the tropics, are also undergoing profound changes as a result of changes in patterns of water circulation and stratification, warmer sea surface temperatures, deoxygenation and more acidic conditions. Rising sea surface temperatures have led to well-documented and rapid changes in the distributions of many marine taxa, including fish, birds and mammals, while changes in circulation and upwelling events have affected the productivity of many eastern boundary systems of the Pacific and Atlantic (Bakun et al. 2015; Champion et al. 2018).

Prolonged extreme ocean warming events—also known as marine heatwaves—over the period 1982–2016 have doubled in frequency and have become longer lasting, more intense and more extensive. Climate models project further increases in the frequency of marine heatwaves, notably in the Arctic Ocean and tropical oceans. Marine heatwaves can severely impact marine ecosystems, resulting in losses of species and habitats from ecosystems as varied as coral reefs, kelp forests, seagrass meadows and mangrove forests, and indirect effects like disruption to sediment-nutrient dynamics and carbon storage (Hughes et al. 2017, 2018; Arias-Ortiz et al. 2018; Hoegh-Guldberg et al. 2018; Oliver et al. 2019; Smale et al. 2018, 2019; Babcock et al. 2019; Garcias-Bonet et al. 2019; Hebbeln et al. 2019; Holbrook et al. 2019, 2020; Sanford et al. 2019; Thomsen et al. 2019; Wernberg et al. 2019).

Deoxygenation in coastal regions results not only from rising sea temperatures but also over-fertilisation and associated runoff from agriculture and from sewage outputs into coastal waters, which leads to algal blooms that consume oxygen once they die and decay. Since the mid-twentieth century, over 700 coastal sites have reported new or worsening low-oxygen conditions. Such oxygen minimum zones can cause widespread changes to marine ecosystems, including loss of invertebrate and fish species and changes in biogeochemical cycling.

Climate models confirm this decline and predict continuing and accelerating ocean deoxygenation (Breitburg et al.

2018; Laffoley and Baxter 2018; Oschlies et al. 2018; Limburg et al. 2020; Rodríguez-Martínez et al. 2020).

Over the last 25 years, the pH in the surface waters of the ocean has reduced as they have absorbed more CO_2, and it is projected to decline further during this century, leading to under-saturation of the carbonate system in the Arctic Ocean, major parts of the Southern, North Pacific and Northwestern Atlantic Oceans (Orr et al. 2005; Hauri et al. 2015; Sasse et al. 2015; Bindoff et al. 2019). As a result, primary productivity of calcifying and non-calcifying plankton species are projected to decrease, while the calcification of corals and bivalves can be impeded, making them more brittle and susceptible to damage, which causes higher mortality, reduced recruitment, increased vulnerability to disease and increasing sensitivity to warming (Fabricius et al. 2011; Doropoulos et al. 2012; Nagelkerken and Connell 2015; Mollica et al. 2018; Gao et al. 2019; Hall-Spencer and Harvey 2019; Liao et al. 2019). In coastal waters, carbonate chemistry is also affected by freshwater runoff which lowers pH due to leachate from acid sulphate soils and humic acids from groundwaters. The extent of coastal acidification can be exacerbated by sea level rise, catchment driven flooding and land runoff, and has had significant impacts on the shellfish industry—a US $19 billion global industry—and can lead to intermittent fish-kills (Salisbury et al. 2008; Barton et al. 2015; Gledhill et al. 2015; Fitzer et al. 2018).

2.2 Changes to Coastal Environments and Ecosystems

Coastal ecosystems are diverse, forming a mosaic of interconnected seascapes, which vary latitudinally from the tropics to the poles, across intertidal and cross-shelf gradients from land to ocean, and in relation to the amount of tidal and wave energy. These coastal ecosystems are most often classified by their geomorphic landform (e.g. estuaries, sandy beaches and rocky shores) or by their foundation species, which can be wetland vegetation (e.g. saltmarshes, seagrass meadows, mangrove forests) or biogenic structures such as coral and shellfish reefs. Many of these ecosystems, particularly over the last 50 years, have undergone massive worldwide reductions in their extent and in their functional resilience, which are the combined consequence of various human activities (clearing and fragmentation of vegetation, hydrological alterations, decreased coastal sediment supply, pollution and emplacement of coastal infrastructure) as well as climate change. Combined with other coastal pressures, such as pollution, most countries are experiencing increased cumulative impacts in their coastal areas, with islands in the Caribbean and mid-latitudes of the Indian Ocean experiencing the greatest impacts (Halpern et al. 2015, 2019). In this section, we summarise observed global changes to these ecosystems, while Fig. 7.1 represents the global extent of these

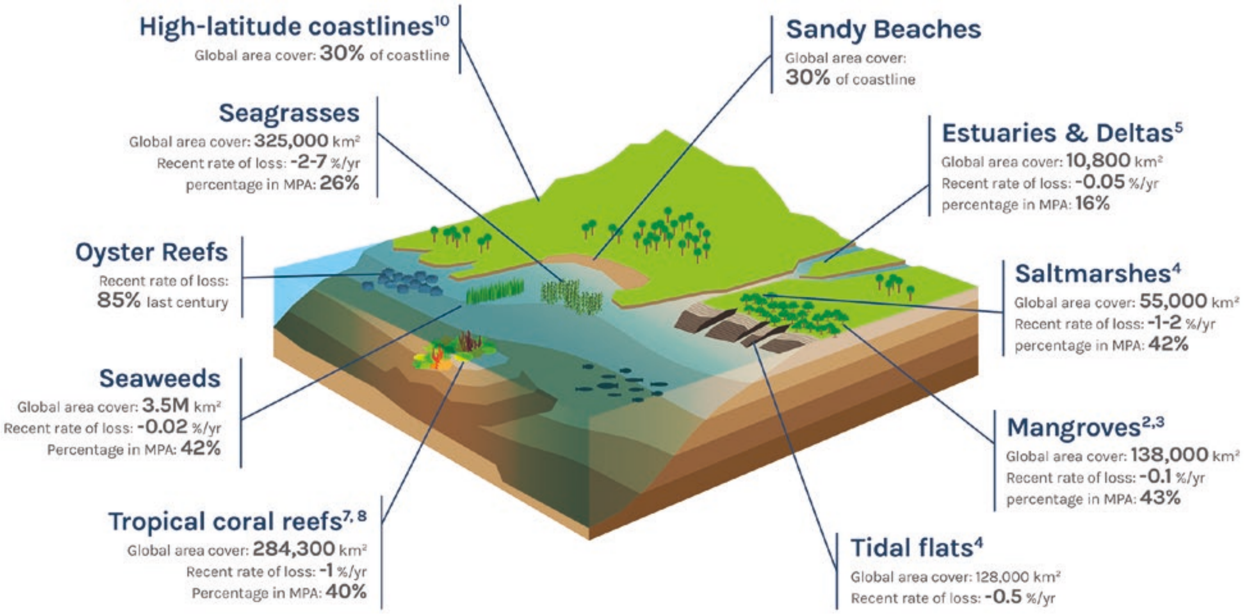

Fig. 7.1 Areal extent and historical and projected losses of major coastal ecosystems. (Source: CSIRO. (1) Beck et al. (2011); (2) Bunting et al. (2018); (3) Goldberg et al. (2020); (4) Mcowen et al. (2017); (5) Murray et al. (2018); (6) Nienhuis et al. (2020); (7) Rogers et al. (2020); (8) UNEP (2020); (9) Vousdoukas et al. (2020); (10) Wernberg et al. (2019))

changes. The companion Blue Paper *Critical Habitats and Biodiversity* (Rogers et al. 2020) provides comprehensive analyses of these changes in habitats and biodiversity.

2.2.1 Coastal Landforms

Coastlines comprise a variety of coastal landforms—beaches, dunes, cliffs, reefs, estuaries, rias, fjords, bays and headlands—that have developed at the dynamic interface of land and sea and have evolved over multiple timescales from quasi-cyclical patterns of erosion and accretion that occur under varying climatic, oceanographic and geological conditions.

Along exposed open coasts erosion is the dominant process weathering these environments. About 50% of the world's coastlines are rocky and sandy beaches. Rocky coasts form where harder more stable substrates predominate, forming reefs that are often covered subtidally by seaweeds and shellfish beds, which in turn support biodiverse communities. Intertidal areas are exposed to strong environmental gradients and these ecosystems are highly sensitive to ocean warming, acidification and extreme heat exposure during low tide emersion. While rocky coastlines form a physical barrier between the land and the sea, softer lithologies are more susceptible to both physical and biological erosion, with significant morphological changes often following extreme events such as storms or tropical cyclones (Hawkins et al. 2016; Ciavola and Coco 2017; Young and Carilli 2019).

Muddy depositional environments, such as estuaries, deltas and tidal flats, are highly dynamic as they are affected by natural and/or human-induced processes originating from both the land and the sea. In addition to GSLR, changes occurring in adjacent catchments that affect sediment supply can result in land subsidence or coastal erosion, or introduce pollution. This in turn can lead to flooding, land loss, salination of coastal aquifers and river reaches, with consequences for properties, agricultural production and food security, especially in agriculture-dependent coastal countries (Khanom 2016).

Shoreline erosion leads to loss of coastal habitats and can, together with sea level rise, contribute to "coastal squeeze" when the intertidal region is constrained by infrastructure built above high water. Shoreline erosion increases the risk of increased flooding and damage to coastal infrastructure and anthropogenic activities, such as upstream dam construction, and river and coastal sand mining, while coastal infrastructure development can significantly alter depositional processes that lead to increased erosion and subsequently diminish the resilience of coastal habitats and increase risks to infrastructure (Naylor et al. 2010; Brooks and Spencer 2012; Pontee 2014; Koehnken and Rintoul 2018).

Satellite-based observational records, from the 1980s to the present, demonstrate changes in the global extent of coastal landforms and show strong regional patterns—with some areas eroding and others accreting—that reflect a dynamic balance between prevailing sea conditions and the extent of catchment and hydrological modification. When globally aggregated, these patterns can be less discernible, which belies the significance of regional changes. Over the last 40 years:

- The loss of *permanent land* in coastal areas is almost 28,000 km^2, which is almost twice as large as land gained within the same period; more than 50% of this net loss of 14,000 km^2 occurred along Asian and Caspian coasts (Mentaschi et al. 2018).
- Twenty-four percent of the world's *sandy beaches* have eroded at rates exceeding 0.5 m/year, but other areas either accreted (28%) or were stable. It is projected that by 2050 13–15% of the world's sandy beaches could face severe erosion, but in low-elevation coastal zones the figure is more than 30%. A number of countries, including the Democratic Republic of the Congo, Gambia, Jersey, Suriname, Comoros, Guinea-Bissau, Pakistan, could face extensive sandy beach erosion issues by the end of the twenty-first century (Luijendijk et al. 2018; Vousdoukas et al. 2020). Worldwide, sandy beaches show vegetation transformations caused by erosion following locally severe wave events with the original dense vegetation being replaced by sparser vegetation and often resulting in a regime shift in the beach morphology and shifts in the associated fauna composition. Coastal dunes are extensive along the world's sandy shorelines and back the majority of beaches forming a linked system. Human disturbances, especially tourism and recreation that have increased foot and vehicular traffic, have increased erosion rates on sandy beaches and dunes, while coastal squeeze has constrained sediment supply and accretion capacity. Paradoxically, vegetation cover on sand-dunes has increased substantially on multiple, geographically dispersed, coastal dune fields on all continents in the period 1984–2017 and points to enhanced dune stability and storm buffering effects (Jackson et al. 2019; Nayak and Byrne 2019).
- *Tidal flats* are intertidal, muddy, sedimentary habitats, often flanking estuaries, and are widely distributed, with a present global extent of 128,000 km^2, of which 70% occur in three continents (Asia 44%; North America 15.5%; South America 11%). Since 1984, it is estimated that 16% of tidal flats have been lost, principally from coastal development and coastal erosion due to reduced sediment delivery from major rivers and sinking of riverine deltas. In China, massive losses of tidal flats have resulted from reclamation, or conversion to other activities, principally aquaculture (Murray et al. 2018).
- *Deltas* account for less than 1% of global land area, yet are home to more than half a billion people and some of

the largest cities. Deltas have a dynamic and evolving geomorphology, formed by the accumulation of unconsolidated river-borne fine sediments (mud, silt and clay) and so are particularly sensitive to anthropogenic activities which influence the mobilisation, delivery, deposition and erosion of sediment to and from a delta. Over the past 30 years, despite sea level rise, deltas globally have experienced a net land gain of 54 km^2/year with deltas being responsible for 30% of all net land area gains that result principally from deforestation-induced increases in fluvial sediment supply. Yet, for nearly 1000 deltas, river damming has resulted in a severe (more than 50%) reduction in anthropogenic sediment flux, resulting in global deltaic land loss of 12 km^2/year. In many of the major deltas (e.g. Mekong, Irrawaddy, Ganges-Brahmaputra), this decline of sediment supply due to upstream dam construction, combined with land-use changes, river sand mining and over-abstraction of groundwater, has led to deltaic subsidence rates at least twice the concurrent rate of GMSL rise (3 mm/year). As a consequence, flooding now routinely occurs in many deltas around the world, with an estimated 260,000 km^2 of delta temporarily submerged in the 1990s/2000s, and leads to saline or brackish water intrusion that increases residual salinity of potable and irrigated water. Intensive human activities around estuaries and river deltas have also substantially increased nutrient and organic matter inputs since the 1970s resulting in eutrophication (Ericson et al. 2006; Nicholls et al. 2020; Nienhuis et al. 2020).

- Some of the most significant effects of climate change are occurring along *high latitude* (polar) coastlines that occur to the north and south of 60º (IPCC 2019). Whereas Arctic coastlines represent about one-third of the world's coastlines and occur over a range of geological and oceanographic settings, Antarctic coastlines are often permanently covered in ice. Rapid and accelerated Arctic sea ice loss, which has averaged 10% per decade over the last 40 years, is attributed to the impacts of land–ocean warming and the northward heat advection into the Arctic Ocean. The possibility of a nearly ice-free Arctic summer within the next 15 years has led to speculation as to whether this will create new shipping channels between Asia and Europe. With longer open-water periods during summer, extra wave activity is expected to result in higher erosion rates along many high-latitude shorelines, while warmer temperatures and increased frequencies of extreme storms may trigger landscape instability, increase sediment and nutrient supply, change carbon fluxes, affect the structure and composition of pelagic communities and benthic habitats and the well-being of dependent human populations. Given the rapidity of these changes, adequate governance frameworks need to be urgently implemented (Moline et al. 2008; Krause-Jensen and Duarte 2014; Kroon et al. 2014; Bull et al. 2019; Gardner et al. 2018; Bendixen et al. 2019b; Oppenheimer et al. 2019; Rignot et al. 2019; Ouyang et al. 2020; Kumar et al. 2020; Hugelius et al. 2020; Peng et al. 2020).

2.2.2 Vegetated Coastal Ecosystems

Vegetated coastal ecosystems, including saltmarshes, mangroves, seagrasses, and kelp and other seaweed, are wetland systems that form important interconnected habitats which support high biodiversity and provide valuable ecosystem services, such as fisheries production, sediment and nutrient trapping, storm protections and carbon storage. Mangroves typically grow between the low and high tide, and reach their highest abundance and diversity in the tropics, predominantly in the Indo-Pacific region. Saltmarshes occur particularly in middle to high latitudes but often overlap with mangrove distributions, resulting in dynamic transitions between these two communities. Seagrasses rooted in unconsolidated sediments grow in shallow coastal waters to 60 m depth and have a global distribution. Seaweeds attach to solid reef substrates, with some species such as kelp—a brown algae—forming large canopies present in more than 40% of the world's marine ecoregions.

However, these ecosystems have been extensively modified by human activities and must also adapt to accelerating rates of climate change. For example, it is estimated that eustatic sea level rise could result in the loss of 22% of the world's coastal wetlands by 2080, and in the Indo-Pacific region, where sediment delivery has declined due to damming of rivers, existing mangrove forests at sites with low tidal range and low sediment supply could be submerged as early as 2070 (Waycott et al. 2009; Duarte et al. 2013; Blankespoor et al. 2014; Copertino et al. 2016; Lovelock et al. 2016; Kelleway et al. 2017; van Oosterzee and Duke 2017; Besset et al. 2019; Serrano et al. 2019a, b).

The current extent and historical loss of these ecosystems are summarised in Fig. 7.1, and below.

- Globally more than 6000 km^2 of mangroves were cleared between 1996 (142,795 km^2) and the present (137,000 km^2). Contemporary (2000–present) global losses (0.2–0.6%/year) of mangroves are an order of magnitude less than losses during the late twentieth century, and have resulted primarily from land-use change, usually through conversion but also fragmentation. In Southeast Asia, mangrove loss has been recorded at twice the global rate, where conversion of mangroves to shrimp aquaculture accounted for more than 50% of losses, while more recently oil palm plantations and coastal erosion are leading to further losses. In Brazil, Puerto Rico, Cameroon, China and Singapore, large areas of mangroves have been lost to urban development. Significant declines in the delivery of upstream sediment supply have further diminished the ability of mangroves to expand and to keep pace with rising sea levels (Richards and Friess 2016; Woodroffe et al. 2016; Hamilton and Casey 2016; Bunting et al. 2018; Romañach et al. 2018; Worthington and Spalding 2018; Agarwal et al. 2019; Friess et al. 2019; Goldberg et al. 2020; Richards et al. 2020; Turschwell et al. 2020a).

- Saltmarshes, with a present global extent of c.56,000 km^2, are declining around the world, having lost between 25 and 50% of their global historical coverage through conversion to agriculture, urban and industrial land uses. Many saltmarshes are also being squeezed between an eroding seaward edge and fixed flood defence walls, and agricultural grazing has a marked effect on the structure and composition of saltmarsh vegetation, reducing its height and the diversity of plant and invertebrate species (Bromberg Gedan et al. 2009; Crooks et al. 2011; Mcowen et al. 2017; Thomas et al. 2017).
- Seagrass meadows, with a present global distribution of about 300,000 km^2, are estimated to have been lost at rates of 110 km^2 per annum between 1980 and 2006. Current losses are particularly high in East and Southeast Asia, principally as the consequence of coastal development: poor water quality resulting from watershed siltation, physical disturbance such as dredging and coastal reclamation, and the degradation of food webs from aquaculture and fisheries (Waycott et al. 2009; Short et al. 2011; Erftemeijer and Shuail 2012; McKenzie et al. 2020).
- Loss of macroalgal forests over the last half-century has been significant, although spatially variable; kelps have declined by 38% in some ecoregions, but have either grown or remained stable in other regions such as southern South America. Temperature is a key determinant of the biogeographic distribution of many seaweeds, so increases in sea temperatures have led to changes in range and abundance. Kelp die-off from marine heatwaves has been reported along the coasts of Europe, South Africa and Australia, and the kelp is replaced by a less diverse turf-dominated ecosystem (Ling et al. 2015; Krumhansl et al. 2016; Vergés et al. 2016; Wernberg et al. 2016; Piñeiro-Corbeira et al. 2018; Filbee-Dexter and Wernberg 2018; Smale et al. 2019; Wernberg et al. 2019; Wernberg and Filbee-Dexter 2019; Friedlander et al. 2020).

2.2.3 Coral and Shellfish Reefs

Coral reefs occur throughout tropical latitudes and are one of the most diverse and productive ecosystems, providing services that support almost 30% of the world's marine fish species fisheries, and 500 million people who depend on them for work, food and coastal protection in more than 100 countries across Australasia, Southeast Asia, the Indo-Pacific, the Middle East, the Caribbean and the tropical Americas. Coral reefs throughout the world are today one of the most endangered habitats, threatened by a combination of climate change and human activities that weaken the natural resilience of coral reefs.

Activities such as over-exploitation and destructive fishing, watershed and marine-based pollution, and coastal infrastructure development have had an impact on reef population structure and biodiversity by reducing coral recruitment, survival and growth, and hindering community recovery (Fabricius 2005; Roff et al. 2012; Otaño-Cruz et al. 2017; Lam et al. 2018; MacNeil et al. 2019; Vo et al. 2019).

Since 1998, marine heatwaves have bleached, or killed, corals on many reefs across the Indo-Pacific, Atlantic and Caribbean. In 2016 and 2017, heat stress associated with consecutive El Niño events triggered the third major global coral bleaching event, resulting in severe coral bleaching of around 70% of the world's reefs throughout all three tropical ocean basins; in the Great Barrier Reef, the world's largest reef system, half of the corals died. Further projected increase in sea level, storm intensity, marine heatwaves, turbidity, nutrient concentration due to floods may contribute to the degradation trend of a majority of coral reefs worldwide and require comprehensive management and intervention responses (Hoegh-Guldberg and Bruno 2010; Hughes et al. 2017, 2018; Magel et al. 2019; Morrison et al. 2019, 2020).

Shellfish reef ecosystems have, until recent times, been overlooked as an important estuary habitat. Historically, dense aggregations of bivalves, their shells, associated species and accumulated sediments were a dominant habitat in temperate and subtropical estuaries around the world. Oyster reefs provide numerous ecosystem services, such as improvements to water quality through filtration, shoreline stabilisation and fisheries productivity. Dredging, habitat degradation, including poor water quality and altered species interactions, disease outbreaks and habitat loss, have contributed to the drastic decline in bivalve habitats with an estimated 85% of oyster reefs lost over the last century, as well as largely unquantified losses of other habitat-forming bivalves, such as the formerly widespread green-lipped mussel (*Perna canaliculus*) beds in New Zealand, which now occur at less than 1% of historical levels (Lenihan and Peterson 1998; Newell and Koch 2004; Piehler and Smyth 2011; Scyphers et al. 2011; Beck et al. 2011; Grabowski et al. 2012; Paul 2012).

2.3 Coastal Development Changes

The key global economic trends relevant to maritime sectors are increasing energy demand, increasing food and water demand, and increasing population growth and urbanisation, all of which depend on coastal infrastructure. Factors such as adaptation to climate change, developing economies seeking an increasing share of global growth, growing expectations around health and safety and human rights, and technological innovations are also relevant to maritime and coastal development trends and coastal infrastructure. Energy production, food production and water demand, as well as urbanisation and population growth, represent over a third of the global economy and provide up to two-thirds of jobs. While natural resources make human development possible and underpin economic growth, our accelerating demand for coastal space and resources, as well as the forms of pollution that result (e.g. litter, wastewater), threatens the extent, condition and biodiversity of many coastal ecosystems (IPBES 2019; WEF 2020a). Below, we summarise the major trends in coastal development and discuss the potential consequences.

2.3.1 Population Growth and Urbanisation

About 40% of the world's population lives within 100 km of the coast and 11% live in low-lying coastal areas that are less than 10 m above sea level. While the majority of these populations are based on continental coastal areas, small island developing states (SIDS) are home to 65 million people, while 4 million people live within the Arctic region. Coastal population growth has been increasing at around twice the rate of national growth and is the result of population and demographic changes, as well as migration from rural areas to cities, and displacement of some indigenous and other disaffected communities. Over the next decade, population growth will occur most significantly in Africa (380 million) and Asia (373 million), where the urban population is expected to grow by 2.5 billion over the next 30 years (Creel 2003; McGranahan et al. 2007; Ford et al. 2015; Neumann et al. 2015; Kummu et al. 2016; Jones and O'Neill 2016; Merkens et al. 2016).

Population growth has been accompanied by rapid urbanisation, and today 55% of the global urban population lives in coastal settlements, and 16 of the world's 31 megacities—those with over 10 million inhabitants—are coastal, including New York City, Tokyo, Jakarta, Mumbai, Shanghai and Lagos. Asia has the greatest intensification of coastal population, property and infrastructure, with 10 of the world's megacities, and 20 of the top 30 most populated coastal cities. Even in many SIDS, urbanisation is a growing concern, where 38 million (59%) already live in urban settlements. Globally, from 1985 to 2015, urbanisation expanded on average by 9687 km^2/year, with nearly 70% of this development occurring in Asia and North America (Small and Nicholls 2003; Jongman et al. 2012; UN-Habitat 2015; Liu et al. 2020).

2.3.2 Infrastructure Development

Coastal infrastructure systems form the backbone of every society, providing essential services that include coastal defence, trade, tourism, fisheries and aquaculture, energy, water, waste management, transport, telecommunications and other industries. Urbanisation is, however, not only a land-based problem, and coastal development has led to a proliferation of coastal infrastructure, commonly referred to as "ocean sprawl", that is occurring worldwide along coastlines and in near-shore waters, and is more recently expanding offshore as industries seek to utilise new resources and access space to operate. Along and adjacent to coastal foreshores, infrastructure for defence, residential and commercial developments, transport and tourism/ recreation are common, while moving further offshore infrastructure for aquaculture, oil and gas, offshore renewable energy, mineral extraction and desalination occur.

Although this proliferation of structures provides a suite of economic, social and even ecological benefits, it also replaces natural habitats and can modify environmental conditions critical to habitat persistence at regional scales. Catchment-based infrastructure, such as dams, that affect the natural patterns of hydrological discharge and sediment transport to the coast, can also affect downstream coastal ecosystems.

As of 2018, the physical footprint of built structures was at least 32,000 km^2 worldwide, and is expected to increase by at least 23% (7300 km^2) to cover 39,400 km^2 by 2028. The global area of seascape that is modified around these structures is estimated to be in the order of 1.0–3.4 million km^2 globally, an area comparable to the global extent of urban land (Bugnot et al. 2020). This concentration of structures close to the shore means that many coastal habitats are affected by multiple structures.

There are also substantial regional differences in the amount of different types of marine infrastructure. Proportionally, China, Democratic People's Republic of Korea and the Philippines have the largest marine infrastructure footprints; nearly half of all oil and gas rigs are located in the US Gulf of Mexico, while wind and tidal farms are spread along the coasts of North America, India, the United Kingdom, Germany and in the Asian North Pacific (Bugnot et al. 2020).

Table 7.3 represents the current extent and projected growth of various infrastructure and activities occurring in, and adjacent to, coastal environments. There is also a growing number of regional-scale transnational infrastructure projects under way that will fundamentally change the use of the coastal zone and marine water offshore and in areas beyond national jurisdictions and, unless carefully managed, these present serious threats to biodiversity (see Box 7.1).

Table 7.3 Crowded coasts: global growth of major coastal infrastructure

Category	Type	Footprint	Category	Type	Footprint
Reclamation	Coastal reclaimed land[2]	Area: 3370 km^2	Water Infrastructure	Large dams[8]	Number: 58,000
	Artificial islands[1]	Number: 480		Desalination plants[3]	Number: 16,000
		Area: 1267 km^2			Growth rate: 10.5%/year
	Artificial reefs[1]	Area: 36,000 km^2	Ports and Shipping	Commercial harbours	Number: 4700
	Cemented shorelines	Length: >14,000 km			Area: 4500 km^2
Coastal Defence	Cemented shorelines	Length: >14,000 km		Marinas[1]	Number: 9628
	Breakwaters[1]	Number: 268			Area: 776 km^2
		Area: 577 km^2		Commercial vessels[7]	Number: 95,402
	Coastal canals[4]	Area: 4000 km			Growth rate: 2.6%/year
Energy Infrastructure	Oil rigs[1]	Number: 5179		Cruise ships[5]	Number: 272
		Area: 89,964 km^2			Growth rate: 6%/year
		Growth rate: 1.2%/year		Fishing vessels[6]	Number: 4,600,000
	Oil pipelines[1]	Length: 136,000 km		Motor vessels[6]	Number: 67,800
		Growth rate: 1.2%/year	Miscellaneous	Coastal aquaculture and mariculture[1]	Number: 78,240
	Offshore wind energy[1]	Number: 6000			Area: 22,927 km^2
		Area: 30%/year			Growth rate: 3%/year
	Offshore wave and tidal energy[1]	Growth rate: 208%/year		Telecom cables[1]	Number: 428
					Length: 39,304 km
					Growth rate: 8.2%/year

Source: CSIRO. (1) Bugnot et al. (2020); (2) Donchyts et al. (2016); (3) Jones et al. (2019); (4) Waltham and Connolly (2011); (5) CLIA (2019); (6) FAO (2020a); (7) UNCTAD (2020b); (8) Mulligan et al. (2020)

Since investment in infrastructure is at an all-time high globally, an ever-increasing number of decisions are being made now that will lock in patterns of development for future generations (Bromberg Gedan et al. 2009; Aerts et al. 2011; Sekovski et al. 2012; Jennerjahn and Mitchell 2013). Such infrastructure, unless carefully planned to account for future climate conditions, constructed using environmentally sensitive methods, and operated with appropriate regulations, can pose significant environmental risks to coastal environments, including: changes in coastal morphology from disruption to natural sedimentary processes, destruction and fragmentation of coastal habitat, and impacts on resident and migratory wildlife through disruption to established connectivity pathways or from "accidents" with infrastructure (Dafforn et al. 2015; Firth et al. 2016; Hughes 2019; Hughes et al. 2020). Below, the major forms of infrastructure, their extent and projected growth, and known impacts on coastal ecosystems are summarised.

Coastal defence structures: With increased urbanisation, rising sea levels and stormier seas, shorelines worldwide have dramatically changed as they become increasingly "hardened" with a proliferation of coastal armouring infrastructure, constructed to protect coastal populations and their property, transport infrastructure, industry and commerce, and amenity and recreational areas. Seawalls, breakwaters, jetties, piers and related infrastructure have replaced once natural shorelines by more than 50% in some cities and countries; for example, wetlands along China's 34,000-km coastline have been replaced with 13,830 km of hard engineering structures (Luo et al. 2015). Such coastal defence structures can have a variety of negative effects on adjacent coastal ecosystems. These structures are typically designed to reflect waves and reduce coastal flooding and erosion; consequently, they can alter wave exposure, interfere with the spatial dynamics of sediment transport, and impede animal movement and connectivity between habitats. Over the longer term, this can cause changes in sediment, current and wave dynamics that accelerate erosion, leading to the loss of beaches and other coastal habitats they were intended to protect. Artificial structures may also produce larger-scale impacts through their alteration of ecological connectivity, which restricts the movement or dispersal of organisms, and which may in turn, influence the genetic structure and size of populations, the distribution of species, community structure and ecological functioning (Bulleri and Chapman 2010; Nordstrom 2014; Bishop et al. 2017; Leo et al. 2019).

Box 7.1. Regional Coastal Infrastructure Projects

Belt and Road Initiative and the Maritime Silk Road: The Belt and Road Initiative is a long-term Chinese government vision for improved global connectivity, expanded production and trade chains, and closer overall cooperation. Potentially spanning 72 countries, the Belt and Road Initiative is the largest infrastructure project of all time (valued at over $8 trillion by 2049) and seeks to create connections between core cities and key ports across Eurasia, Asia and parts of the African continent through infrastructure development in the transport, energy, mining, IT and communications sectors. First announced in 2013, the twenty-first Century Maritime Silk Road is the maritime/coastal component of the Belt and Road Initiative, and focuses on creating a network (string of pearls) of ports, through construction, expansion or operation, and the development of portside industrial parks and special economic zones that link China's coastal ports through the South China Sea to the Indian Ocean, extending to Africa and Europe; and potentially to the Pacific Ocean (Fig. 7.2). To date, deep-water ports projects have been initiated in Africa (Tunisia, Senegal, Tanzania, Djibouti, Gabon, Mozambique, Ghana), Asia (Pakistan, Sri Lanka, Myanmar, Indonesia) the Middle East (Oman, Israel) and Europe (Greece). Studies looking at the potential environmental impact of the Belt and Road Initiative have identified that over 400 threatened marine species, including mammals, could be affected by port infrastructure, while over 200 threatened species are at risk from an increase in shipping traffic and noise pollution (Huang 2016; Hughes 2019; Hughes et al. 2020; Narain et al. 2020; Turschwell et al. 2020b).

LAPSSET Corridor, Africa: The LAPSSET Corridor Program is a regional project intended to provide transport and logistics infrastructure aimed at creating seamless connectivity between the eastern African countries of Kenya, Ethiopia and South Sudan. The project connects a population of 160 million people in the three countries and is part of the larger land bridge that will connect the East African coast (at Lamu Port) to the West African coast (at Douala Port). The LAPSSET Corridor is intended to operate as an Economic Corridor with the objective of providing multiple eastern African nations access to a large-scale economic trade system, thereby promoting socioeconomic development in the region. The LAPSSET Corridor Program consists of several subsidiary projects, including the development of deep-water ports, railway lines and highways connecting cities in Kenya, South Sudan and Ethiopia, oil refineries and pipelines, and international airports and resort cities (LAPSSET Corridor Development Authority 2016; Okafor-Yarwood et al. 2020).

Bangladesh Delta Plan 2100: The Bangladesh Delta Plan 2100 is the combination of long-term strategies and subsequent interventions for ensuring long-term water and food security, economic growth and environmental sustainability. It aims to effectively reduce vulnerability to natural disasters and build resilience to climate change and other delta challenges through robust, adaptive and integrated strategies, and equitable water governance. Six hotspot areas were identified: coastal zone; Barind and drought-prone areas; Haor region (flash-flood areas); Chittagong hill tracts and coast; major rivers and estuaries, and urban areas (Bangladesh Planning Commission 2018).

The Red Sea Project: The Red Sea Project is a large-scale luxury tourism development that will extend over 28,000 km^2 along the shores of the Kingdom of Saudi Arabia. The area includes the Al-Wajh lagoon, a large lagoon area with 92 islands, valuable ecosystems and rich biodiversity, including species of global conservation importance. The Red Sea Development Company, responsible for the execution of the Red Sea Project, has committed to achieving a net-positive impact on biodiversity. To grow tourism, which currently represents only 3% of the economy, it will create a special economic zone that is expected to attract 1 million people every year, create 70,000 new jobs and add $5.9 billion to the Saudi GDP (Chalastani et al. 2020).

Ports and harbours: Seaports are nodal hubs in the maritime transportation network, enabling more than 90% of world trade. A growing reliance on marine transport for international trade has led to the construction of more ports and harbours, and the expansion and deepening of existing facilities to accommodate larger vessels. Today, there are more than 4700 commercially active ports worldwide, which are used by more than 50,000 international merchant ships, manned by over a million seafarers, and carry more than 90% (>10 billion tonnes in 2015) of global trade by weight. The development and operation of ports and harbours have been associated with a number of negative environmental and social impacts on coasts, including principally altering regional coastal processes which disturb the sediment balance and exposing downdrift areas to increased erosion. Oil, sewage and noise pollution can result from port operations and can seriously impact surrounding marine life and disrupt social amenity (Zanuttigh 2014; Lee et al. 2015; Johnston et al. 2015; IAPH 2016; IMO 2017; Camus et al. 2019; Leo et al. 2019; Santana-Ceballos et al. 2019; Vaughan 2019; Valdor et al. 2020).

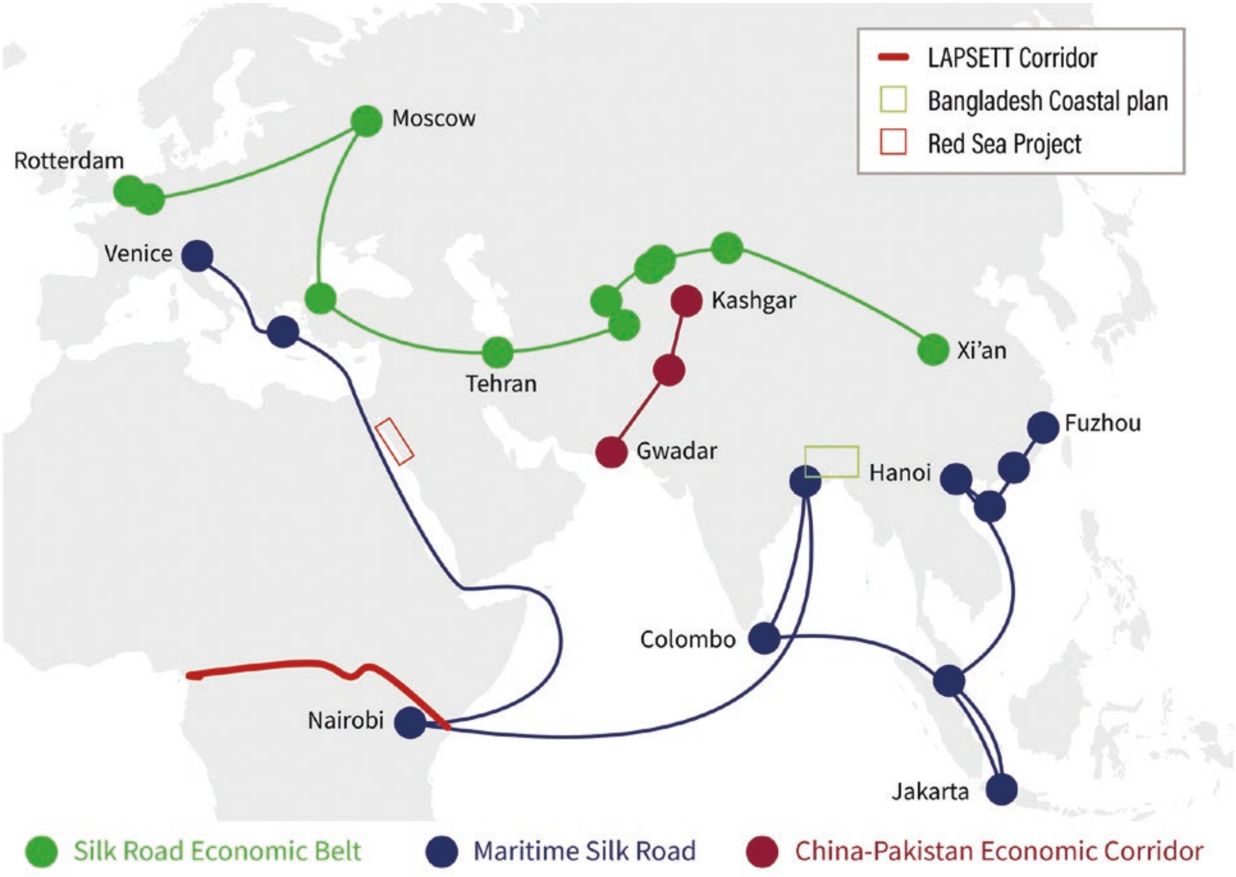

Fig. 7.2 Map of belt and road initiative and twenty-first-century maritime silk road

Energy infrastructure: Conventional oil and gas platforms and associated pipelines, and increasingly offshore renewable energy technologies, including wind farms and tidal power, are common infrastructure in coastal and offshore environments. Tidal farms are located closest to the shoreline, with 41% closer than 2 km in 2018, while nearly half (47%) of all wind farms were located within 10–50 km of the coast, and half of all oil and gas fields were located within 40 km of the shoreline.

Catchment infrastructure: Infrastructure such as dams and weirs for the impoundment of water, irrigation, hydroelectric power generation and flood protection results in hydrologic alteration of the quantity and timing of river flow. Decreased fluvial sediment transfer to coastal regions can lead to sand-starved beaches, and accelerated coastal erosion of deltas and loss of mangrove forests. Construction of embankments and navigation structures can result in rivers becoming disconnected from their floodplains, disrupting natural sediment fluxes, reducing marine and ecological connectivity. Coastal aquifers are more vulnerable to groundwater extraction than to predicted sea level rise under a wide range of hydrogeologic conditions, and over-pumping has led to saltwater intrusion, subsidence and loss of the water supply for future use. Lack of appropriate sewage processing facilities in coastal areas can increase the nutrient pollution and consequent degradation of coastal ecological systems (Poulos and Collins 2002; Giannico and Souder 2005; Al-Bahry et al. 2009; Dafforn et al. 2015; Reopanichkul et al. 2009; Ferguson and Gleeson 2012; Martínez et al. 2014; Rovira et al. 2014; Firth et al. 2016; Chee et al. 2017; Smith et al. 2017; Appeaning Addo et al. 2018; Tessler et al. 2018; Silva et al. 2019; Luijendijk et al. 2020).

2.3.3 Competition for Coastal Space

Today, coasts are an increasingly crowded space, where various sectors of the economy vie for access to areas within territorial and EEZ waters, not only for food and materials, but for a number of other activities, including tourism and leisure, transport and telecommunications. Other activities, such as aquaculture and renewable energies, seek to produce rather than extract seafood and energy, but require coastal space with environmental conditions conducive to their operation. The growth and success of these emerging industries are central to the predicted growth and significance of the ocean economy over the next few decades (see Box 7.2) and will place further demands on access to coastal space.

The allocation of space and the management of associated resources is the responsibility of various government entities, often with overlapping jurisdictions and sometime incompatible mandates, which results in a struggle to balance conservation and sustainable use, to set appropriate operational limits for individual sectors, to resolve conflicts between overlapping incompatible uses and to properly assess the cumulative impact of activities.

Competition and conflict over access to coastal space and resources have often led to allegations of "ocean grabbing" by powerful actors to secure exclusivity or dominance over a resource, and have often disadvantaged other groups, particularly livelihood-dependent local communities, indigenous and artisanal peoples, or those seeking to undertake recreational and cultural activities. In many nations today, coastal developments and industries face greater scrutiny of their environmental and social performance than in the past, and many businesses now seek "social licence" through local environmental and social responsibility programmes that create benefits for the local community, but this is sometimes viewed negatively as nothing more than "green-washing".

To accommodate increasing urban and industrial development, agriculture, silviculture (notably oil palm) and aquaculture (notably shrimp), coastal space has been created by both the clearing of existing coastal vegetation, including mangroves, saltmarshes, coastal dunes and tidal flats, and the reclamation of intertidal and subtidal areas. Urban land expansion rates are significantly higher in coastal areas than in adjacent hinterland, and it is estimated that by 2030, global urban land cover will increase to 1,527,000 km^2 (Brown et al. 2013; Seto et al. 2011; Liu et al. 2020).

Coastal infilling, dredging and reclamation have been the primary means of expanding the coastal foreshore or creating artificial islands, and produce direct loss of marine habitat. While reclamation of coastal wetlands and tidal flats has been practised for millennia, the current scale to meet increasing demands for land is unprecedented. Globally, it is estimated that 33,700 km^2 of land has been added to coastal areas over the last 30 years, with more than 1250 km^2 of land being reclaimed from 16 megacities between the mid-1980s and 2017. Further ambitious land reclamation projects are under way in many regions of the world (see Box 7.1). China, in particular, is leading the world in large-scale reclamation projects, extending its coastline by hundreds of square kilometres every year, while the Netherlands and India have reclaimed areas of 7000 and 1500 km^2, respectively. As well as removing valuable habitat, reclamation of coastal areas contributes to land subsidence in coastal areas. Many of the world's coastal cities—built in low-lying areas where soft sediments can compress under the weight of infrastructure as cities grow—are now sinking (see Box 7.5). This results in increased risk of flooding, with consequences including structural damage and high maintenance costs for urban infrastructure and risk to human livelihood (Waltham and Connolly 2011; Wang et al. 2014; Donchyts et al. 2016; Reyna et al. 2016; Tian et al. 2016; Sengupta et al. 2017).

Box 7.2. Key Coastal Growth Sectors of the Ocean Economy

Coastal (beach-based) and maritime (water-based) tourism is the second largest employer in the ocean economy, providing 1 in 11 jobs worldwide and generating more than $1.5 trillion in trade income or 9.2% of global GDP, and it is the dominant sector in an increasing number of national economies. For some island states, tourism can comprise 25% of national GDP. Globally, over 350 million people annually travel to the coral reef coast, and the coral reef tourism sector has an estimated annual value of $36 billion globally, with over 70 countries and territories having "million dollar reefs"—reefs that generate over $1 million in tourism spending. Cruise-ship tourism has been growing (at least until the COVID-19 pandemic, see Box 7.3) at 7.7%, and can account for more than 90% of international visitors to some destinations. By 2030, coastal and maritime tourism is expected to comprise 26% of the total ocean industry value-added, and will employ c.1.5 million more people than it does at present. Coastal and maritime tourism generates indirect land activities linked to infrastructure construction that are responsible for pollution and destruction of natural habitats, as well as for pressure on natural resources, such as water, but also sand, limestone and wood (OECD 2016; Spalding et al. 2017; Tonazzini et al. 2019; WTTC 2019; UNWTO 2020a, 2020b).

Aquaculture, the farming of aquatic animals (e.g. finfish, molluscs and crustaceans) and seaweeds, is the fastest-growing food production sector in the world, with an average annual growth rate of 5.8% during the period 2000–2016. In 2016, global aquaculture production reached 80 million tonnes of food fish, with coastal aquaculture and mariculture (i.e. aquaculture in a marine environment) producing 28.7 million tonnes or 36% of this production. Aquaculture is mainly practised in tropical and subtropical regions and globally more than 60,000 km^2 of coastal areas is used for aquaculture. Asia accounted for 89% of global aquaculture production in 2016, much of which is produced in areas of former tidal flats and near-shore areas; China ranked first, followed by India, Indonesia, Viet Nam, Bangladesh, Egypt, Norway, Chile and Myanmar. Comparatively, Africa contributes the least of any continent to total global aquaculture production, yet the continent's aquaculture sector is growing faster than anywhere in the world, and accounts for 8% of the 12.3 million Africans employed in the fisheries sector.

Globally, the potential for onshore and offshore mariculture is large, and seafood production is expected to be predominantly sourced through mariculture by 2050. Significant areas of coast have been identified as areas that are suitable for further aquaculture development, including environmentally sensitive areas such as southern Patagonian coastal waters. The environmental impacts of aquaculture are well recognised and include the clearance of mangroves for shrimp ponds, eutrophication leading to disruptions to the surrounding benthic communities and increased phytoplankton and harmful algal blooms and disease (Kapetsky et al. 2013; Waite et al. 2014; Tenório et al. 2015; FAO 2018, 2020a; Obiero et al. 2019; Agarwal et al. 2019; Ahmed and Thompson 2019).

Offshore renewable energy, particularly offshore wind, is projected to grow significantly over the next decades. Under the International Energy Agency's (IEA) Stated Policies Scenario, installed capacity of global offshore wind is set to expand by at least 13%/year, increasing more than 15-fold over the 2018 installed capacity of 23 GW by 2040 (IEA 2019). Further extension of policy targets and falling technology costs may drive even greater uptake with over 560 GW installed capacity, accounting for 5% of global electricity supply, by 2040 in the Sustainable Development Scenario (IEA 2019). The UK Government 2020 levelised costs update shows continual reduction of offshore wind costs, being now lower than new gas and other fossil fuel generation, and projected to be less than onshore wind by the mid-2030s, owing to the relative strength and consistency of resource, and the large-size turbines able to be deployed offshore (BEIS 2020). Technical resource potential in shallow (<60 m) water depths, accessible to current fixed-bottom foundation wind technologies, is more than 87,000 terawatt-hours (TWh)/year. The emergence of floating foundation wind technologies removes depth constraints, and could provide access to another 330,000 TWh/year; 70% of the most accessible wind resource (20–60 km from shore) is located in water depths greater than 60 m (IEA 2019), which reflects the size of the opportunity to floating technologies. Other ocean-based renewable energy sources, including tidal, wave, floating solar and others, are less developed than offshore wind but also have significant potential for many regions where other drivers or advantages occur (see Haugan et al. 2020).

Over the coming decades, a number of industries are seeking to move further from the coasts in search of space to operate, or additional or more stable energy resources. Aquaculture, common in many inshore areas, will be much more prevalent offshore where larger, more complex, infrastructure designed to withstand the rigours of these environments will be required. Likewise, marine renewable energy infrastructures to harness wind waves and tidal power will become much more common.

2.3.4 Resource Extraction

The demand for food and materials—some traditional and others novel—from coastal environments has expanded rapidly in the last 50 years and will continue to do so over the coming decades, as growing coastal populations and a rising middle class seek greater protein in their diets, increased fresh water and more materials to build infrastructure. Box 7.2 briefly summarises three sectors—aquaculture, tourism and offshore renewable energy—that will see significant growth in coastal regions throughout the world over the coming decade.

The growing demand for global seafood still relies predominantly on coastal fisheries—those that occur less than 50 km from inhabited coastlines, or in waters less than 200 m deep. Despite significant declines over the last 60 years in a large number of exploited fish and invertebrate populations, coastal fisheries (see Gaines et al. 2019) still accounted for 55% (50–60 million tonnes/year) of global marine fisheries in the period 2010–2014. About 36% of this catch is from small-scale fisheries, undertaken mainly in developing countries and engaging more than 47 million people, nearly 50% of whom are women. These statistics not only highlight the global importance of coastal fisheries, but also the prominent role of small-scale fisheries in supporting coastal livelihoods, food security, nutrition and human well-being (World Bank et al. 2012; Monfort 2015; FAO 2020a, b; Palomares and Pauly 2019; Palomares et al. 2020).

Demand for fresh water for human consumption and agricultural and industrial use has rapidly increased and led to greater impoundment and extraction from coastal rivers and aquifers in drier areas, or where there is no longer sufficient water, the use of desalination plants has become commonplace. In 2000, there were c.45,000 reservoirs installed, and, as of 2014, at least 3700 major dams, each with a capacity of more than 1 megawatt (MW), were either planned or under construction, primarily in countries with emerging economies in Southeast Asia, South America and Africa.

While this construction will increase the present global hydroelectricity capacity by 73% to about 1700 gigawatts (GW), these impoundments will reduce the number of free-flowing large rivers by about 21% and trap 25–30% of the total global sediment load—and all of the bed load—that might otherwise be delivered to the coasts. Desalination facilities worldwide include about 16,000 operational plants with a global capacity of more than 95 million m^3 per day and the majority of these are from seawater or brackish water (21%). New ocean-water desalination projects are on the rise, including floating desalination plants constructed on ships and offshore structures, which have the advantage of being mobile (Vörösmarty et al. 2003; Syvitski et al. 2009; Grill et al. 2019).

Over the next 30 years, greater areas of irrigated agricultural land will be required, which, unless carefully managed, will have negative consequences for downstream coastal ecosystems. While today c.70% of irrigated areas are in Asia, under business-as-usual scenarios, by 2030 the total harvested irrigated area is expected to increase by at least 12%, to 394 million hectares (ha) (and perhaps as high as 1.8 billion ha), with approximately 9% of this growth expected to be in developing countries, especially those in Sub-Saharan Africa, but also South Asia and Latin America and the Caribbean. Irrigation is responsible for significant groundwater depletion in many regions, with about 11% of this resource embedded in the international food trade (Dalin et al. 2017; Ringler 2017; Puy et al. 2020).

Aggregates, such as sand—a key ingredient of concrete, asphalt, glass and electronics—and gravel, are the largest proportion of primary material inputs used in building and transport infrastructure (79% or 28.6 gigatonnes/year in 2010) and are the most extracted group of materials worldwide, exceeding fossil fuels and biomass. In most regions, sand is a common-pool resource, and even when sand mining is regulated, it is often subject to illegal extraction and trade. As a result, sand scarcity is an emerging issue with major sociopolitical, economic and environmental implications. Continued urban expansion and large infrastructure projects, as well as increasing trade and consumption, are pressuring sand deposits, causing conflicts, and compromising environmental and human systems. Activities such as unregulated sand mining of riverbeds, particularly in developing countries, can accelerate erosion and destabilise riverbanks and shorelines, and can harm benthic habitats, either through direct removal during dredging operations or from sedimentation. Transport of sand may also lead to increased biosecurity risks (Torres et al. 2017; Schandl et al. 2018; Koehnken and Rintoul 2018; Bendixen et al. 2019a; UNEP 2019).

More than 30% of current global energy demands are met by marine oil and gas reserves, and collectively the oil and gas sector accounts for one-third of the total value of the ocean economy. There are currently more than 6000 offshore and a few coastal (<200) platforms in service worldwide. As shallow-water fields become depleted and novel technologies emerge, production is moving towards greater depths and new territories. Other unconventional forms of gas, such as shale and natural hydrates, are also being increasingly exploited, as the technology to cost-effectively extract these reserves develops (Arthur and Cole 2014; US Department of Energy 2015; OECD 2016).

Despite the rhetoric of a sustainable ocean economy, there is growing scepticism that a business-as-usual scenario, favouring industrial and economic expansion of established and emerging industries, is being progressed without adequately addressing the equity, inclusion, access and benefit-sharing rights of those who also hold rights to the same resource (Selig et al. 2019; Bennett et al. 2019; Cisneros-Montemayor et al. 2019; Cinner and Barnes 2019; Hodgson et al. 2019; Cohen et al. 2019; Lau et al. 2019).

2.4 Summary

Large-scale declines in the extent of coastal landforms, vegetated ecosystems and biogenic structures over the last 40 years have occurred in many regions, and these declines have diminished coastal ecosystems' natural resilience to recover from a range of climate and anthropogenic threats, and to the biodiversity and services they support. The primary agents occurring on local to regional scales are the direct consequences of land-clearing and fragmentation, the degradation of these ecosystems from pollution, and imbalance in natural sediment supplies. Most of the remaining regions with a natural coastline are found in Africa and Asia, and these regions are also projected to experience the highest coastal population and urbanisation growth in the decades to come. Coastal ecosystems have been affected to varying degrees by sea level rise, ocean warming and acidification, and extreme weather and these effects are projected to be more significant in the future. Over the coming decades, further urbanisation and adaptation to rising sea levels and intensified storms will require even more coastal infrastructure.

This will require more material extraction, such as for aggregates to build infrastructure, new methods of environmentally sensitive construction with designs capable of withstanding future climate conditions. New forms of coastal infrastructure will also be required over the coming years to meet increased demand and access to coastal space. In an era of scarcity and increasing demand for fresh water, desalinisation plants will become much more common.

3 Risks to Coastal Resilience

Globally, coastal systems are undergoing profound, rapid and undesirable environmental changes, driven by the combined consequences of climate change, coastal development pressures and pollution, which leads to habitat loss and fragmentation—subdivision of habitat into smaller and more isolated patches. This degrades the ability of these ecosystems to provide essential ecosystem services. Anthropogenic threats to coastal systems can be exacerbated due to connectivity between marine, freshwater and terrestrial ecosystems, complicating the task of governance across the land–sea interface. Likewise, coastal settlements, their people, infrastructure and economies are increasingly at risk, as they struggle to adapt to these changes. In this section, we summarise the potential impacts on coastal ecosystem and services that arise from activities related to coastal development and industries, and review the risk to human populations, settlements, infrastructure and economies.

3.1 Threats to Coastal Ecosystems

3.1.1 Habitat Clearing and Fragmentation

The globally significant net loss of coastal landforms and vegetated and biogenic habitats that has occurred over the last half-century was summarised in Sect. 2.2, and includes erosion of depositional coastlines, loss of coastal vegetated ecosystems (50% of saltmarshes, 35% of mangroves), and coral (30%) and shellfish reefs (85%). These losses vary between regions, with some of the greatest losses occurring in Asia and Africa. While some of these changes have been incremental—although cumulative over time—in other cases, rapid/abrupt and potentially irreversible changes have also occurred. In some cases, such as mangroves and saltmarshes, the rates of loss in recent decades has decreased relative to changes that occurred 40–50 years ago, but other habitats, notably coral reefs and kelp forests, faced with the likelihood of more frequent and severe marine heatwaves in the future, are likely to see further significant and widespread losses.

However, the primary factor responsible for losses to date has been the clearing of coastal vegetated habitats to make way for agricultural, urban and industrial uses, and the reclamation of intertidal and subtidal areas (see Sect. 2.2 for more details). Less obvious, but equally pervasive, are the consequences of incremental fragmentation of these habitats, which, as has been highlighted in a number of recent publications, accrues significant cumulative net losses, impairs a number of ecosystem functions and services, and leads to declines in biodiversity for a range of taxa that rely on large intact areas for their home range, or as wildlife corridors on migratory routes. Patterns of fragmentation do not necessarily correlate with deforestation, or clearing, and relate to differing land-use and extractive activities. For example, in Ca Mau province, Viet Nam, over a 24-year period, the number of mangrove patches increased by 58% but the mean patch size decreased by 52%, and fish diversity was 1.8 times lower than in less fragmented mangrove forests (Tran and Fischer 2017; Jacobson et al. 2019; Bryan-Brown et al. 2020).

Other human activities, most notably alterations to natural patterns of river and surface water discharge, and the sediment, nutrients and pollutant loads that these carry to the coast, can have detrimental impacts on adjacent coastal habitats. While ecosystems, such as seagrass, oysters and coral reefs, are particularly sensitive to too-much sediment, in depositional coastal areas an adequate supply of sediment from upstream will be required to ensure the stabilisation of shorelines and the ongoing accretion of mangrove and saltmarsh habitat.

3.1.2 Pollution

An estimated 80% of pollution load in coastal environments originates from industrial, agricultural, urban/rural and other land-based activities, and is a key threat to biodiversity (IPBES 2019). While sediment and nutrients (principally nitrogen and phosphorus) occur naturally in the environment, excessive levels released from point sources (wastewater effluent, storm-water outfalls and runoff from waste storage) and nonpoint sources (deforestation, land conversion and runoff from agriculture or ranching) into rivers and estuaries, or directly into coastal and marine ecosystems, are considered serious threats.

Among developed nations, it is estimated that more than 70% of wastewater is treated with discharges to sewered connections centralised in wastewater treatment plants, where remedial technologies improve the quality of the effluent to differing standards—tertiary treatment, which removes nutrients, being the best. The quality of the discharge is often regulated by the setting and reporting of established concentration or load-based criteria. Over recent decades, this has resulted in significant reductions in nutrient loads from major coastal cities discharged into rivers, estuaries and coastal waters. However, among developing nations only 8% of generated wastewater is treated and most people rely on some form of decentralised or self-provided services. With increasing urbanisation, especially in Africa and Asia where the urban population is expected to grow by 2.5 billion over the next 30 years, there is an urgent need to better treat urban waste (Sato et al. 2013; Gallego-Schmid and Tarpani 2019).

As detailed in the companion Blue Paper, *Leveraging Multi-Target Strategies to Address Plastic Pollution in the Context of an Already Stressed Ocean* (Jambeck et al. 2020), marine litter is a global environmental concern, entering the ocean largely through storm-water runoff, but is also dumped on shorelines or directly discharged at sea from ships. Between 61 and 87% of this litter is plastics, and since the 1950s this has increased dramatically, with current estimates of between 4.8 and 12.7 million tonnes of land-based plastic waste ending up in the ocean every year, while in the next two decades, the amount of plastics produced is expected to double (Jambeck et al. 2015, 2020; Geyer et al. 2017; Löhr et al. 2017; Barboza et al. 2019; Walker et al. 2019; Galgani et al. 2019).

3.1.3 Bio-invasions and Disease in Coastal Ecosystems

In an increasingly tele-coupled world, invasive alien species—most commonly introduced via shipping and associated coastal infrastructure—threaten global biodiversity, economies and human health. Shipping is the primary vector for 60–90% of marine invasions globally, transporting marine species, including plankton, crustaceans and molluscs, in ballast water or attached to ships' hulls. Terrestrial pest species can also be transported in carried goods and their packaging, and upon arrival at destination ports can be rapidly spread inland along transportation chains. Once introduced, alien species can rapidly establish, particularly in areas that have already been disturbed, displacing native species, altering ecosystem structure and functions such as nutrient cycling and carbon sequestration. Well-known examples include invasions of coastal wetlands, dunes and saltmarshes by vascular plant species, marine algae and plankton, which increasingly result in occurrences of harmful algal blooms, by molluscs such as the Asian green mussel (*Perna viridis*) and by echinoderms such as the Northern Pacific seastar (*Asterias amurensis*). Projected increases in global maritime traffic of 240–1200% by 2050 are forecast to lead to a 3- to 20-fold increase in global invasion risk and this will occur mainly in middle-income countries. Significantly, Northeast Asia will not only be disproportionally affected but will also be the primary vector source to other geo-regions (Pyšek et al. 2008; Early et al. 2016; Seebens et al. 2015; Carrasco et al. 2017; IPBES 2019; Sardain et al. 2019).

Marine organisms serve as hosts for a diversity of parasites and pathogens affecting not only the host population that can include vertebrates, invertebrates and plants, but can also cascade through ecosystems altering the structure and function of marine ecosystems. Marine diseases can become emergencies when they result in significant ecological, economic or social impacts, so understanding the factors responsible for the genesis and timing of diseases will be increasingly important as our use of coastal and marine resources accelerates. The billions of dollars lost in the early 1990s as a result of a global pandemic of white spot syndrome in penaeid shrimp aquaculture, and the environmental and economic impacts of coral diseases that led to widespread mass mortality in Caribbean reefs and reduced ecotourism, are salient examples.

Marine disease emergencies can also have significant social impacts, capable of disrupting public safety, threatening human health, or decreasing the resilience of local human communities. The probability of humans acquiring infections from marine mammals, avian influenza from marine birds, and cryptosporidiosis and vibriosis from consumption of shellfish is also expected to increase unless carefully managed, with better surveillance, impact mitigation, and adaptive and responsive strategies. It should be noted that COVID-19 is not considered infectious to marine organisms (Ward and Lafferty 2004; Groner et al. 2016; Mordecai and Hewson 2020).

3.2 Risks to Coastal Ecosystem Services

Coastal ecosystems, their biodiversity and functions provide important provisioning goods, as well as regulating, supporting and cultural services that underpin the ocean economy and that also have values that are not explicitly economic. Provisioning goods, such as the harvesting of fish or timber from coastal habitats, represent products that are consumed. Growing demand for these products is a key driver in the conversion of habitats for these provisioning goods. Regulating services represent intangible benefits provided when ecosystems are left intact, such as flood and erosion reduction, and underpin provisioning goods such as fisheries production. Coastal areas also provide for uses that are considered aesthetic, spiritual and cultural services, such as sacred sites or points of historic interest. Such services are not easily valued in economic terms and thus lead to questions as to whether the concept of ecosystem services is an overly transactional view of nature, and whether the benefits that people receive can be represented better by frameworks that are less anthropocentric.

A central dilemma facing coastal ecosystems, and achieving a sustainable ocean economy more generally, is reconciling the competing demands for provisioning goods and services with the need for regulating, maintenance and cultural services (HM Treasury 2020). Loss or impairment to coastal ecosystems can result in a concomitant, although often non-linear, loss of service(s). It is notable that the most recent IPBES Global Assessment Report and World Economic Forum Global Risks Report both ranked biodiversity loss and ecosystem collapse in the top five risks to the global economy (IPBES 2019; WEF 2020a).

While provisioning services can be readily measured and valued, regulatory, supporting and cultural services are much harder to quantify and only rarely are they directly accounted for in coastal management because their services are not quantified in terms familiar to decision-makers, such as (loss of) annual expected benefits (Beck et al. 2018a). There are several competing lines of thought about this conundrum. Some argue that we should accept that some values cannot, and perhaps should not, be measured and monetised, and that we need to invoke other frameworks to accommodate the different types of values (Sagoff 2008). Others argue that incorporation into systems derived from economic accounting is an efficient way to ensure that resources are devoted to conserving the ecosystems. From the latter are emerging global standards, such as the System of Environmental-Economic Accounting (SEEA), which uses natural capital accounting frameworks and associated methodologies to classify and place a monetary value on even intangible services. These frameworks can be integrated with traditional economic national accounts, allowing them to be explicitly considered in resource and environmental decision-making. They might also facilitate development of financial instruments, such as payments for ecosystem services (PES), to incentivise the conservation or repair of natural assets. More details are provided in the companion Blue Paper *National Accounting for the Ocean and Ocean Economy* (Fenichel et al. 2020), while below we briefly summarise the key coastal services, the value they provide and the risks if they are diminished or lost.

3.2.1 Coastal Protection

Coastal vegetation and reefs can contribute significantly to coastal protection by absorbing the energy of wind and waves and providing a buffer that helps to minimise erosion and limit the intrusion of storm surges and damaging floodwater. As such, they provide significant annual flood protection savings for people and property, particularly from the most frequent storms. Globally, and averaged across these ecosystems, it is estimated that they can together reduce wave heights between 35% and 71%, with mangroves and reefs providing annual storm and flood protection benefits exceeding $65 billion and $4 billion, respectively.

Along the Northeastern seaboard of the United States, saltmarshes avoided costs of $625 million in direct flood damages resulting from Hurricane Sandy in 2012. In the Philippines, it is estimated that annually mangroves reduce flood-risk for more than 613,500 people, 23% of which live below the poverty line, and avert damages of $1 billion to residential and industrial property. Coral reefs protect more than 18,000 people from flood damage and avoid costs of $272 billion.

Without mangroves, it is estimated that a further 15 million people would be potentially exposed to flooding annually across the world, while the absence of reefs would more than double the expected damage from flooding, and costs from frequent storms would triple. Many countries (notably Bangladesh, Cuba, China, India, Indonesia, Malaysia, Mexico, Philippines, USA and Viet Nam) are estimated to gain annual expected flood savings exceeding $400 million, while some small (20-km) coastal stretches, particularly those near cities, receive more than $250 million in flood protection benefits from nearby mangrove forests (Spalding et al. 2014; Narayan et al. 2016, 2017; Beck et al. 2018a, b; Reguero et al. 2019b; Storlazzi et al. 2019; Menendez et al. 2020).

3.2.2 Carbon Sequestration

Coastal vegetated wetlands, including saltmarshes, mangrove forests and seagrass meadows, are considered to be the main blue carbon habitats, due to their ability to sequester and store large amounts of carbon within their root systems and in the underlying soil in which they grow. Despite their relatively small global extent (equivalent to 0.2% of the ocean surface), these vegetated coastal ecosystems contribute approximately 50% of the carbon sequestered in marine sediments, absorb CO_2 up to 40 times faster than terrestrial forest and consequently are globally equivalent to c.10% of the entire net residual land sink. Consequently, it is now well recognised by many nations and organisations that the conservation and restoration of these blue carbon ecosystems is an effective climate solution that could deliver substantial mitigation of CO_2 through storage and sequestration, as well as delivering other important benefits, like enhancing livelihoods and reducing risks from storms. Other research commissioned by the Ocean Panel estimates that coastal blue ecosystems could, by 2030, contribute avoided emissions of 0.32–0.89 billion tonnes of CO_2e per annum and this would increase to 0.50–1.38 billion tonnes of CO_2e by 2050. However, impairment or loss of these blue carbon ecosystems can contribute significant emissions. For example, as a result of global net losses in mangrove ecosystems between 1996 and 2016, global mangrove carbon stocks have declined by 1.5% (0.16 billion tonnes) with greatest losses occurring in Indonesia, which has the largest areal extent of mangroves, but also in countries such as Myanmar, where mangrove clearing rates today still remain high. Internationally, many countries with large blue carbon stocks seek to recognise the mitigation potential as part of their national emission reduction commitments. For example, preventing mangrove deforestation in Indonesia could reduce emissions from land-use change by 30%. Efforts to halt and reverse this trend could be supported by the private sector, as many companies look to offset their carbon emissions though investments in blue carbon protection or restoration (McLeod et al. 2011; Atwood et al. 2017; Serrano et al. 2019b; Spivak et al. 2019; Lovelock and Reef 2020; Richards et al. 2020).

3.2.3 Fisheries Productivity

Another important service of mangroves, marshes, reefs and seagrass beds is that they provide breeding and nursery habitat for a number of commercially important inshore and offshore fisheries. The complex structure of these habitats provides juveniles with refuge from predators and access to a variety of food sources that sustain their growth into adulthood. The fisheries value can be highly site specific and often more than one of these habitats may contribute to the life cycle of the fishery, including larval dispersal and migration to offshore habitats. The economic values of these fisheries also vary according to specific costs associated with each fishery, proximity to economic markets and levels of utilisation. Inshore, small-scale fisheries target a variety of mollusc, crustacean and fish species, often for domestic use or in local markets, and are of relatively low economic value relative to offshore fisheries harvested mainly by industrial-scale operations. In many tropical coastal communities, gleaning—fishing for invertebrates such as sea cucumbers in water that is shallow enough to walk in—is often done by women and children, and provides a source of essential protein, micronutrients and income. Mangrove habitats adjacent to large river mouths, where freshwater and high nutrients enhance productivity, generate the highest numbers of juvenile fish (e.g. mangrove jack, *Lutjanus aregentimaculatus*) and commercially important species like shrimp. While many coastal small-scale fishers are fully aware of their reliance on mangroves, larger commercial fisheries, such as the shrimp industry, operating in offshore waters often overlook the mangroves on which they depend.

Box 7.3. Enabling Coastal Resilience in a COVID World

COVID-19 is having serious and significant impacts on national economic growth trajectories, including coastal economies. The hardening of borders, limited movement of people, shrinking income opportunities, disruption of globalised supply chains and rise in restrictive trade policies are emerging as early consequences of the global pandemic that are relevant to coastal economic sectors. Poor urban coastal communities are most vulnerable to the pandemic since they live in crowded areas in low sanitary conditions often at the water's edge. The reduction of income for coastal residents, social distancing and quarantine, and even the provision of basic food supplies to coastal communities, are proving difficult. The impacts are most profound for marginalised groups and increase the social and environmental stressors, as well as exacerbating the challenges of disaster response in coastal contexts (CIRAD 2020; UNCTAD 2020a; WEF 2020b).

Coastal and ocean economy sectors, such as fisheries, aquaculture and seafood processing, tourism and recreation, maritime transport and logistics, are most impacted by the pandemic. Restrictions to ship docking, limited road transport and access to ports, falling demand for fish products and for tourism and recreation all reduce the income of the coastal and ocean economy sectors and associated jobs, as well as impacting on those who work on board vessels, with accounts of crew being stranded at sea for months (Bennett et al. 2020; Gössling et al. 2020; OECD 2020a, b).

COVID-19 has exposed weaknesses in the complex global fisheries and seafood production system and supply chains. Impacts on the hospitality sector and live export markets has led to international demand for fresh fish dropping dramatically and prices dropping accordingly. At the same time, demand for canned tuna has been maintained as it is seen as desirable as a source of shelf-stable protein, and some markets have seen increased demand (FAO 2020c, d; OECD 2020a, b).

The small-scale fisheries sector has been particularly hard hit, especially where perishable product is dependent on being sold through wet markets and then processed locally. Small-scale fisheries and fish processing are high-employment, low-wage sectors, with a high proportion of women working in fish processing facilities, and where proximity puts workers at risk of COVID-19. Entrepreneurial vendors are using digital technology to connect directly to customers, but the closure of wet markets and the closure of processing facilities has meant that a large proportion of product has no pathway to market (Bennett et al. 2020; CIRAD 2020; Davey and Steer 2020; FAO 2020c, d; OECD 2020a, b).

Positive stories have emerged from several Pacific Island nations, where practices such as food sharing have restarted and local food networks have been revived, and where collective actions have worked to safeguard rights. There are also stories of increased pressure on natural resources, through more fishing effort, regulations being relaxed and areas being opened up to fishing, including as people move back to their home communities from major cities, because of the loss of jobs. Using coastal resources as a social safety net, and relaxing rules during times of economic crisis is a high-risk strategy and could lead to greater problems in the long term (Bennett et al. 2020; CIRAD 2020; Davey and Steer 2020).

Tourism is one of the economic sectors hardest hit by COVID-19. Economies and communities with a high dependence on international tourism receipts have been badly affected by travel bans and restrictions. Tourism is a high-employment, low-wage sector, often employing large numbers of young people, and is particularly important as a source of GDP for many SIDS economies. Many coastal hotels and recreation facilities are facing bankruptcy, and stimulus options are urgently needed for this sector to preserve the long-term potential and to engage the affected workforce. Reskilling in digital technologies, engagement in natural resource recovery programmes or mobilising the workforce into nation-building sustainable natural infrastructure programmes are all options that could be explored (Gössling et al. 2020; OECD 2020a, b; Vianna et al. 2020; WEF 2020b).

Seagrasses also support substantial fisheries, both from small-scale fisheries that target species that rely on seagrass for most of their life (e.g. rabbitfish) or species that rely on seagrass in early life stages before they move offshore (e.g. northern Atlantic cod). Seagrass meadows are also popular locations for small-scale mariculture, like sea cucumbers and seaweeds (Benzeev et al. 2017; Carrasquilla-Henao and Juanes 2017; Worthington and Spalding 2018; Waltham et al. 2019; Jinks et al. 2020; Vianna et al. 2020; Waltham et al. 2020).

3.3 Risks to Coastal Populations, Infrastructure and Economies

Coastal communities, built infrastructure, and established and emerging economic sectors are significantly affected through the disruption of coastal physical processes resulting from climate change and coastal and upstream development. Globally, around 10 million people experience coastal flooding due to storm surges, cyclones and heavy rainfall every year with impacts ranging from displacement of households and destruction of sources of livelihoods, to disruption of national economies. The World Economic Forum's two most recent Global Risks Reports ranked extreme weather, preparing cities for sea level rise biodiversity loss, and ecosystem collapse in the top five risks.

While the consequences of COVID-19 (see Box 7.3) on the resilience of coastal ecosystems will continue to unfold over many years, the immediate impacts on coastal-dependent industries, such as tourism, and the flow-on effects on the economies of nations and livelihoods of local communities, are profound (Vitousek et al. 2017; Bergillos et al. 2019; Hino et al. 2019; DasGupta and Shaw 2015; Betzold and Mohamed 2017; Kramer et al. 2017; Hagedoorn et al. 2019; WEF 2019, 2020a).

3.3.1 Populations

An estimated 310 million people, and $11 trillion in GDP, are exposed globally to the risk of a 100-year flood event. Risk is expected to increase, due to rising sea levels and other climate-related threats concurrent with population growth. If no mitigation measures are undertaken, by 2050, c.9 million of the world population, concentrated in more than 570 coastal cities, situated in low elevation areas, notably in China, Bangladesh and Indonesia, could suffer from enhanced inundation and increased coastal erosion. By 2060, up to 411 million people could be exposed to the risk of a 100-year flood event (Ericson et al. 2006; Hallegatte et al. 2013; Hinkel et al. 2014; Wong et al. 2014; Neumann et al. 2015; Reguero et al. 2015; Arnell and Gosling 2016; Lumbroso 2017; Brown et al. 2018; Barnard et al. 2019; Nicholls et al. 2020).

Both sea level rise and extreme coastal events cause massive and existential displacement of populations. Sea level rise has already affected many low-lying islands, such as Kiribati, and Isle de Jean Charles in Louisiana, USA, and resettlements of populations are either under way or planned. After the Indian Ocean tsunami, in the coastal areas of the provinces of Aceh and North Sumatra in Indonesia, over half a million people, including some 300,000 living in severely damaged areas, were displaced. The task of resettling these residents, while keeping their sense of community, serves as a test case for future events (UNDP 2005; McGranahan et al. 2007; Birkmann et al. 2013; Gray et al. 2014; Wilkerson et al. 2016; Oliver-Smith 2019; Visessri and Ekkawatpanit 2020).

The risk posed to coastal populations depends not only on the exposure to the hazard, but also on social conditions (susceptibility) and capacities to respond (resilience) and together describe the vulnerability of societies. As a result, countries have different risks, with tropical states and SIDS in the Caribbean and Oceania and coastal areas in Southeast Asia (Bangladesh, Myanmar, Papua New Guinea and Timor-Leste) being most at risk (Fig. 7.3). Countries in Africa have high overall risk, as vulnerability scores are high and exposure to coastal hazards and adaptation are generally low; in contrast, countries like the Netherlands and Japan have high exposure rates but are more resilient (Beck 2014).

Coastal indigenous peoples, particularly those inhabiting islands or archipelagos, are some of the most vulnerable populations to coastal hazards. Often their traditional and customary use areas are not recognised and their access to cultural and spiritual sites of importance is not upheld, including where national and multinational interests seek access to the coast (see Box 7.4).

To mitigate the impacts of the pandemic, government and industry need to address the immediate economic and social hardships caused by the pandemic and enable coastal communities to maintain their resilience and rapid after-pandemic recovery, while maintaining their long-term goals of protecting coastal natural resources, the coastal environment and ecosystems. This can be done by supporting the incomes of and providing healthcare to the most vulnerable groups and ensuring that evidence-based management remains in place and is enforced. It is estimated that $10–20 trillion of public funding will be mobilised into the world economy in the next 2–3 years to support and stimulate economic recovery, including the recovery of coastal economic sectors. Therefore, a unique window of opportunity exists to engage and influence relevant policy and investment decisions and ensure stimulus funds foster sustainable ocean economic pathways and support the recovery and development of impacted communities. For example, coastal restoration can be used to help economic recovery from the COVID-19 pandemic while providing co-benefits of ecosystem services, community cohesion and climate adaptation (ADB 2020; OECD 2020a).

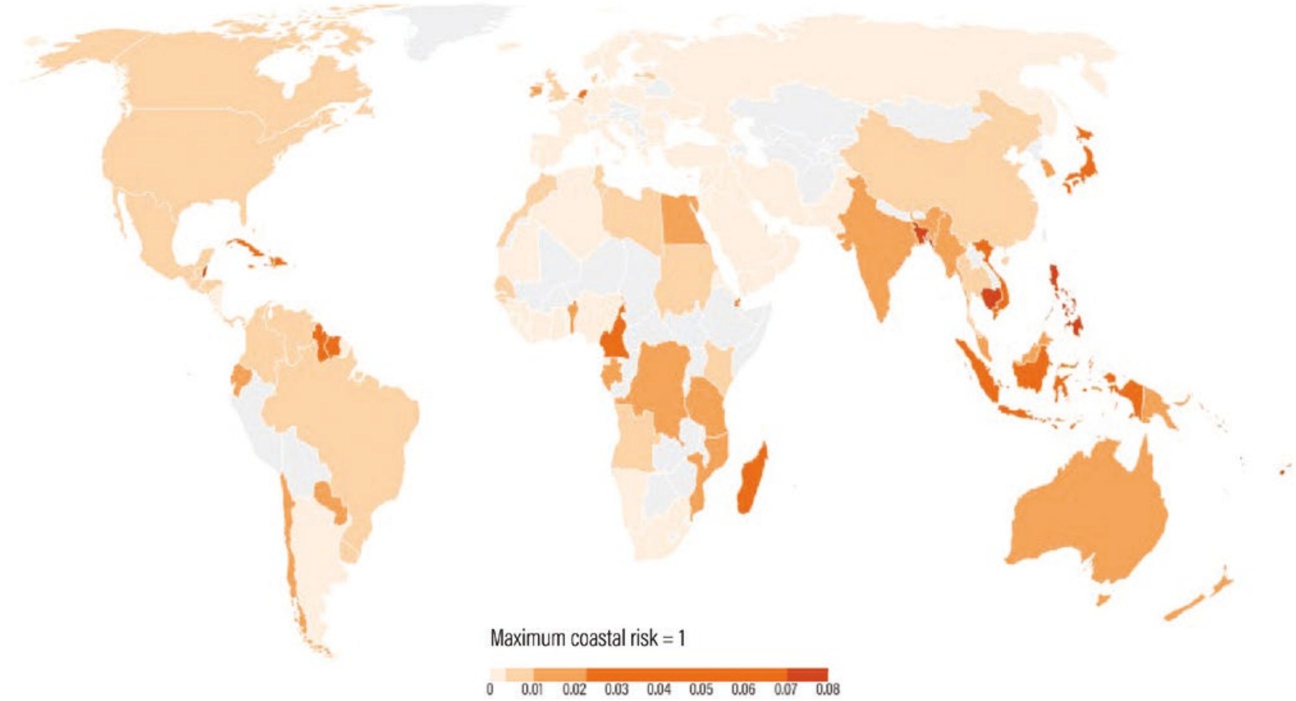

Fig. 7.3 Coastal risks to nations and geo-regions. (Source: Beck (2014). Data from The Atlas of Ocean Wealth (https://oceanwealth.org))

Box 7.4. Vulnerabilities of Coastal Indigenous Peoples and People from Traditional Communities

Coastal indigenous peoples, including those of SIDS, comprise some 370 million people, or 5% of the global population. As they rely on ocean resources and are highly vulnerable to ecosystem and economic change, the exploitation of fish resources and climate hazards pose distinct threats to these communities (Cisneros-Montemayor et al. 2016). Coastal indigenous peoples consume approximately 1.9 million tonnes of fish per year, approximately 2% of the global catch, and this seafood demand is concentrated around equatorial regions in Africa and Asia, and in the Arctic. In many of these areas' fisheries, stocks (e.g. of Pacific tuna; Bell et al. 2015) are changing migration and distribution patterns in response to global environmental changes, and traditional fisheries areas are under mounting pressure from foreign and domestic fishing fleets. Already, people in the 22 small island nations and territories of the southwest Pacific have increased their reliance on imported foods, including canned meats and packaged products, in part because of depleted fish stocks. Food imports to countries such as Samoa and Tonga now exceed total exports. These societal shifts have strong negative implications for the health and well-being of indigenous peoples. For instance, deaths in the Pacific from preventable non-communicable diseases, such as diabetes, cardiovascular disease and cancer, have risen, in part because of the dietary and lifestyle changes that have accompanied people's increased reliance on food imports (Morrison et al. 2019).

Coastal indigenous peoples are some of the most vulnerable populations to coastal hazards, such as storms, cyclones and tsunamis. While efforts to mitigate the impacts of these hazards mainly focus on defence infrastructure development, or early warning systems, the traditional and local knowledge of these communities has been found to increase their resilience and help them to manage crises—be it natural hazards, economic problems or political conflicts (Hiwasaki et al. 2014). Furthermore, many indigenous communities live in regions without strong governance, although a number of international agreements and bodies (e.g. United Nations Declaration on the Rights of Indigenous Peoples; Convention on Biological Diversity; Intergovernmental Panel on Climate Change) recognise preferential access rights for indigenous peoples, their vulnerability to climate and food security, and the value of traditional ecological knowledge (Cisneros-Montemayor et al. 2016; Vierros et al. 2020).

3.3.2 Infrastructure

Building resilient communities is a shared challenge for the world's population living along the coast now and in the future. To address this challenge, communities typically engineer barriers along the coast. However, there is growing understanding that traditional approaches to coastal protection (e.g. seawalls, bulkheads) are unsustainable. Hardened shorelines can be expensive to build and maintain, and can lead to unintended shoreline erosion, degradation or loss of habitat, impacting on communities that depend on healthy coastal ecosystems for protection, subsistence and livelihoods. However, decision-makers often lack basic information about where and under what conditions ecosystems reduce risk to coastal hazards and who would benefit from the protective function conferred by those ecosystems (Adger et al. 2005; McGranahan et al. 2007; Kron 2013).

The proportion of the world's gross domestic product (GDP) annually exposed to tropical cyclones has increased from 3.6% in the 1970s to 4.3% in the first decade of the 2000s. Flood assessment of 136 major coastal cities shows that average flood losses in 2005 were about $6 billion/year, and in the last 10 years insurers have paid out more than $300 billion for coastal storm damage. Considering the risks from sea level rise and sinking land, both the World Bank and the Organisation for Economic Co-operation and Development (OECD) estimate that, by 2050, global flood damage in large coastal cities could cost $1 trillion a year, while climate-induced declines in coastal and ocean health will cost the global economy $428 billion/year, and global infrastructure investment of more than $94 trillion will be required to reduce these risks (UNISDR 2011; Hallegatte et al. 2013; Diaz 2016; Oxford Economics 2017; IPCC 2019; ORRAA 2019; WEF 2019).

Box 7.5. Sinking Cities

Land subsidence is one of the world's under-rated problems, yet its impact on many coastal cities is increasingly apparent. Many of the world's sinking cities are built on low-lying marshes, flood plains or river deltas, where soft sediments compress under the weight of infrastructure, and this is exacerbated by groundwater or oil/gas extraction for human use, as well as reductions in sediment supply due to dams and impoundments. The increased frequency and magnitude of extreme weather events and changing sea levels further increase the risk of flooding, the consequences of which include structural damage to infrastructure, drains and sewage systems and high maintenance costs for roads and railways.

Cities that have grown rapidly, or have failed to curb groundwater usage, are particularly at risk, most notably in Asia (e.g. Jakarta, Guangzhou, Shanghai, Dhaka, Ho Chi Minh, Bangkok), but also on other continents, including the Americas (e.g. Mexico City, Houston, New Orleans), Africa (e.g. Lagos) and Europe (e.g. London, Rotterdam, Venice). Jakarta is the world's fastest-sinking city, at a rate of c.25.4 centimetres (cm)/year.

Around 40% of the city now lies below current sea levels and some coastal districts have sunk as much as 4.3 m in recent years. With further population growth, urbanisation, intensification of economic activities in deltas, and climate change, the problem is set to accelerate. Stopping the pumping of groundwater is one of the practical and local actions that can be readily implemented. A century ago, Tokyo was sinking at a greater rate than Jakarta is now. Following the Second World War, laws limiting pumping and a programme to re-inject water back into the ground has stabilised land subsidence such that, by the early 2000s, the city's subsidence slowed to 1 cm a year (Sato et al. 2006; Kramer 2018).

3.4 Summary

Coastal environments and dependent human communities are already experiencing the impacts of climate-related changes from extreme events and slow-onset changes, and the consequences of rapidly growing and urbanising populations that demand great access to greater resources, built infrastructure and services, and space. These climate and development changes can act synergistically and result in cascading and hard-to-predict impacts, as the world has seen with the global COVID-19 pandemic, in which core vulnerabilities have been exposed with devastating consequences.

While across the globe there is regional variability in how coastal environments will be affected, these changes will continue for many decades irrespective of actions taken, while no action will result in disproportionately higher risks, and a return to previous conditions should not be expected.

4 Building Coastal Resilience

To effectively manage the challenges wrought by coastal development and climate change, there are four main management strategies that can be used to secure the integrity and resilience of coastal ecosystems and their contributions to people:

1. *Protection strategies* use regulations and area-based management, to designate where and how much of specified activities can and cannot occur in coastal environments and in the adjacent catchment, and legislate areas for conservation such as marine protected areas (MPAs) or implement area, habitat and species-specific conservation plans.
2. *Mitigation strategies* aim to reduce local stressors caused by human action through the use of technology, regulation and the promotion of stewardship to minimise the introduction of pollutants, the over-exploitation of resources or activities that will otherwise harm coastal environments.
3. *Adaption strategies* explicitly consider the coastal social-ecological system and are implicitly related to resilience; adaptation leads to resilience and resilience is a property needed for having capacity to adapt (Nelson 2011). They use principles of ecosystem-based adaptation and ecological engineering to incorporate natural infrastructure into existing grey infrastructure, relocate at-risk activities and populations away from the coast, and also use incentives to change behaviours and practices.
4. *Repair strategies* seek to restore damaged ecosystems by restoring the composition and/or function of lost or fragmented habitats, restoring (reinstating) the natural hydrology, sediment and nutrient balance entering and cycling through coastal ecosystems, or by assisted evolution.

Figure 7.4 represents 17 actions that can be taken under these four strategies and highlights the enabling conditions needed to ensure their success.

All four strategies broadly fall under the umbrella framework of nature-based solutions (NbS), which are defined by the IUCN as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016). NbS is an area that covers a range of ecosystem-related approaches to protect (i.e. area-based conservation), to manage holistically (e.g. integrated coastal management or ICM), to address specific issues and to repair and restore ecosystems.

NbS approaches are now being used to reframe policy debates on biodiversity conservation, climate change adaptation and mitigation, and sustainable use of natural resources, to address conflicts and trade-offs associated with use and management of ecosystem services, and to invest in blue infrastructure and ocean finance (World Bank 2008; United Nations 2013; Nesshover et al. 2017; Thiele et al. 2020; WEF 2020c). But not all strategies are applicable in a given situation, and evaluating a broad range of actions, and combinations of actions, can help decision-makers to estimate the trade-offs of different management approaches and to maximise the co-benefits. In fact, comprehensively tackling issues, such as reducing pollution or preventing clearing of mangroves and saltmarshes, will require a mix of all four strategies.

The success of any of these strategies is predicated on the presence of a number of enabling factors or conditions that encompass the dimensions of technical readiness, social equity, economic viability and environmental sustainability. Some of these are shown in the outside ring of Fig. 7.4 and are summarised in Sect. 4.6; they also form the basis for many of the opportunities for actions outlined in Sects. 5.2 and 5.3. In particular, integrated management is listed here as an enabling factor as it provides the framework with which these various strategies can be applied across the terrestrial-coast ocean continuum, between institutional lines of responsibility, as well as integrating with other relevant agendas, such as those for climate action and urban transitions. Approaches to coastal integrated management are discussed below but are considered in detail in the companion Blue Papers *Integrated Ocean Management* (Winther et al. 2020) and *The Ocean Transition* (Swilling et al. 2020).

As part of the four strategies outlined above, the approaches and activities most useful to ensuring coastal resilience are evaluated below and form the basis for the opportunities for actions presented in the following sections: area-based measures for protecting coastal ecosystems; mitigating terrestrial impacts on coastal environments; adapting infrastructure; and restoring coastal habitats.

Fig. 7.4 Four strategies and actions for building coastal resilience and the enabling conditions to achieve them. (Source: CSIRO)

4.1 Protecting Coastal Ecosystems

The first line of defence in ensuring coastal resilience is to provide adequate protection of coastal habitats from inappropriate forms, or unsustainable levels, of human use, and to secure the rights of peoples with recognised tenure and customary access rights. Protecting coastal habitats is more cost-effective and has better ecological outcomes than rehabilitating lost habitat. For example, protection of mangroves provides an immediate benefit–cost ratio of 88, compared with restoration activities which have a ratio of 2, because they require higher logistical costs and take decades to realise the benefits (Konar and Ding 2020).

Protection can only occur where there is a clear, effective and enforceable regulatory framework in place, with national and subnational policies and regulations that, among other things, forbid the clearance of natural coastal lands for other activities, designate appropriate human activities that are allowed to occur within defined coastal areas while minimising harm, and set limits to levels of resource extraction or activity. In all cases, such regulations are most effective when ownership is clearly established. However, as many of these regulations pertain to single areas, sectors or individual developments, a priority for further enhancing protection of coastal ecosystems is to improve legislation, policies and planning frameworks to better consider multiple pressures and cumulative impacts from marine and land-based activities. Ensuring there is a comprehensive monitoring program and research agenda in place to assess and predict potential impacts and develop effective management strategies is also required (Griffiths et al. 2019).

There are a number of international conventions and agreements that relate to various aspects of coastal management, including conservation of coastal environments and biodiversity (e.g. Convention on Biological Diversity (CBD), Ramsar Convention on Wetlands) and controlling pollution (MARPOL Convention, United Nations Framework Convention on Climate Change (UNFCCC)), which can be built upon to provide greater levels and greater breadth of protection for coastal ecosystems and their services. Both the SDGs (14.5) and the CBD Aichi Targets (11) commit nations to conserve at least 10% of their coastal and marine areas by 2020; and it is now being advocated that at least 30% will need to be protected by 2030, with the remaining areas also under environmental management (World Conservation Congress 2016; Laffoley et al. 2019; Roberts et al. 2020). The UNFCCC nationally determined contributions (NDCs) for greenhouse gas emission reductions under the Paris Agreement and the Sendai Agreement for Disaster Risk Reduction 2015–2030 may secure better protection of coastal ecosystems through recognition of their carbon sequestration and climate protection services. However, many of these agreements are usually voluntary and non-binding and, as Winther et al. (2020) note, “it is failure to implement these existing international instruments at national levels that is one of the most important weaknesses of ocean governance”.

Over the last 30 years, a number of integrated planning frameworks, conservation and spatial management tools and processes have been developed and implemented to protect coastal ecosystems, and minimise multi-sector competition for resources or space. Best known is integrated coastal management (ICM), also known as integrated coastal zone management (ICZM), which aims to balance the complexities and potential conflict of growing uses of the coastal zone through the use of relevant legislation and policy and spatial and conservation management tools to integrate planning, decision-making and management across sectors and across land and sea estates, and aspires to consider cumulative effects and trade-offs (Álvarez-Romero et al. 2011; Bernal 2015; Cicin-Sain 1993; Katona et al. 2017; Stephenson et al. 2019).

ICM principles and frameworks have been implemented at global, regional and national scales. Many countries have sought to implement ICM in several forms and with various degrees of success. For example, many countries in East Asia, including Viet Nam, the Philippines, China, and the Republic of Korea, have institutionalised ICM in national legislation, and this has supported countries in the region to improve coastal management and to enhance the effectiveness of use and conservation of coastal natural resources and environment. Regionally, intergovernmental cooperation, such as the Partnerships in Environmental Management for the Seas of East Asia (PEMSEA), has for more than 25 years applied ICM solutions in dozens of sites across East Asia, covering around 38% of the region’s coastline, across 12 countries (see Box 7.6).

Success in implementing ICM in some countries has been hindered by the absence, or limited presence, of key enabling factors, including inadequacies with legal frameworks, poor cooperation between different sectors or government departments, lack of personnel, capacity and access to knowledge (White et al. 2006; Shipman and Stojanovic 2007; Borja et al. 2008; Nguyen and Bui 2014; Elmgren et al. 2015; Candel 2017; Liu and Xing 2019; PEMSEA 2020).

ICM is a dynamic process and continues to evolve, with greater emphasis on better management across the catchment–coast–ocean continuum, coupling coastal, water and urban frameworks, integrating climate and disaster risk reduction and management. A terrestrial–ocean integrated climate policy is part of a larger changing narrative about the ocean and the recognition of its untapped potential for climate regulation, mitigation and adaptation, and our aspirations for a sustainable ocean economy. There are significant opportunities for alignment with Integrated Water Resources Management initiatives, including the UN’s 2018–2028 Water Action Decade and the urban sustainability agenda (discussed further in Sect. 4.2).

Today, an integrated management framework, coupled with an ecosystem-based approach to management and supported by marine spatial planning, including the use of MPAs and other effective conservation measures (OECMs), is recognised as best practice. Ecosystem-based approaches and management are based on the application of scientific methodologies, focused on levels of biological organisation, which encompass the essential structure, processes, functions and interactions among organisms and their environment. These approaches have been most widely applied and institutionalised into fisheries management. For example, Indonesia and the Philippines have both recently adopted ecosystem-based fisheries management and spatial closures by designating a number of Fisheries Management Areas (Mokhtar and Aziz 2003; Levin et al. 2009; Saad et al. 2012; Ureta et al. 2016; Altenburg et al. 2017; Gelcich et al. 2018; Muawanah et al. 2018; Alexander et al. 2019; Alexander and Haward 2019; Kirkfeldt 2019).

MPAs are one of the most widely implemented area-based management tools used by countries to protect valuable or representative coastal and marine areas, and, increasingly, areas of the high seas. MPAs vary in levels of protection, from marine reserves and parks that provide full protection to multiple-use areas that restrict some activities in some areas, such as no-take areas. In most countries, multiple-use MPAs are the most common form (>75% in 2013). More than 40% of mangroves and warm water coral reefs are placed within gazetted MPAs, while seagrasses and estuaries are the habitats with the lowest proportion of area (<30%) contained within MPAs (Toonen et al. 2013; Costello and Ballantine 2015; Jacobsen 2019; Bryan-Brown et al. 2020; Rogers et al. 2020; UNEP 2020).

Box 7.6. Regional Coastal Management Strategies

Partnerships in Environmental Management for the Seas of East Asia (PEMSEA): PEMSEA is an intergovernmental organisation operating in East Asia to foster and sustain a healthy and resilient ocean, as well as coasts, communities and economies across the region. PEMSEA serves as the regional coordinating mechanism for the shared regional coastal and marine strategy, Sustainable Development Strategy for the Seas of East Asia (SDS-SEA), adopted by 14 countries (Brunei, Cambodia, China, DPR Korea, Indonesia, Japan, Lao PDR, Malaysia, the Philippines, RO Korea, Singapore, Thailand, Timor-Leste and Viet Nam) (Fig. 7.5). The strategy is a package of applicable principles, relevant existing regional and international action programmes, agreements and instruments, as well as implementation approaches, for achieving sustainable development of the Seas of East Asia. It offers a regional framework for the interested countries and other stakeholders to implement, in an integrated or holistic manner, the commitments they have already made, without assuming new legal obligations. It addresses linkages among social, cultural, economic and environmental issues and embodies the shared vision of the countries and other stakeholders for the Seas of East Asia, and the ways by which they will achieve that shared vision. PEMSEA has developed an ICM system that addresses complex coastal management concerns, covering governance and various sustainable development aspects. In November 2015, PEMSEA country partners committed to scale up the ICM to cover 25% of the region's coastline by 2021. To date, PEMSEA has exceeded that target and secured about 37.9% of the region's coastline, having a significant impact on 86,284 km of coastline and over 150 million people living in coastal and watershed areas. As part of ICM implementation towards achieving blue economies in the region, PEMSEA is committed to improving coastal and ocean governance, and implements programmes on climate change mitigation, disaster risk reduction, habitat protection restoration and management, water use and supply management, food security and livelihood management.

West Africa Coastal Areas Management Program (WACA): WACA was established by the World Bank in 2015 in response to demands from countries in the region to manage their growing coastal erosion and flooding problems. Countries already participating in the programme include Benin, Côte d'Ivoire, Ghana, Mauritania, Sao Tome and Principe, Senegal, and Togo, and discussions are under way with other countries. WACA is designed to improve the livelihoods of coastal communities in West Africa by reducing the vulnerability of its coastal areas and promoting climate-resilient integrated coastal management. The programme's mix of technical assistance and investments will seek to preserve and rehabilitate the natural coastal resources essential for livelihoods; spur economic development and increase social welfare; and support the sustainable development of key growth sectors, such as agro-industry, fisheries, offshore petroleum exploration and production, and tourism. WACA is also a convening platform to help countries obtain the finance and expertise they need to sustainably manage their coastal areas. It also serves as a forum within which countries and regions can share lessons learned.

Southeast Pacific Data and Information Network in Support to Integrated Coastal Area Management (SPINCAM): SPINCAM is an IOC-UNESCO/Flanders and Permanent Commission for the South Pacific (CPPS) initiative, created in 2008 to develop a framework of indicators in various pilot sites of the southeast Pacific (Chile, Colombia, Ecuador, Panama and Peru). SPINCAM supports the development of decision-making tools and implementation of ICM through regional and national investment for improved data and information management capacity, knowledge, communication and networking at national and regional level (COI-UNESCO and CPPS 2016). Main outputs so far have been the development of information systems, in the form of substantial ICM atlas and web-based portals for the associated metadata. The main outcomes expected from SPINCAM include: institutionalisation of coastal and marine governance at national and regional level; improved regional networks on coastal and marine issues; regional strategic recommendations on marine spatial planning, sustainable blue growth, monitoring systems and decision support tools; reduction of national technical disparities on capacity development; and improved communication and participatory processes.

Fig. 7.5 PEMSEA ICM sites

There is now a recognition that conservation is enhanced when the people and communities dependent on resources take on some of the responsibility for managing (making decisions about) those resources. The most widely used OECM is locally managed marine areas (LMMAs), whereby coastal communities limit or prohibit extractive or destructive practices within a defined area. One example is the Territorial Use Right for Fisheries (TURFs), where local communities, or associations or cooperatives, of fishers have exclusive property rights to harvest resources within defined areas.

TURFs, in combination with no-take-areas, are now being implemented throughout the Americas, Oceania and Southeast Asia, and demonstrate a range of positive effects, including increased yields, ancillary biodiversity conservation, and social and ecological enabling conditions for local stewardship. For example, in Chile, the combination of TURFs and small-scale aquaculture are showing promising results for livelihood diversification, production and food security. LMMAs generally operate on more limited spatial (1–10 km^2) scales than contemporary MPAs, potentially reducing their conservation effectiveness. There are also, however, a number of less-encouraging aspects, including biases towards only reporting positive results and focusing on sedentary biota, lack of effective enforcement, misalignment between yields and sharing agreements, and operating as isolated silos that can't meet ecological and economic expectations (Christy 1982; Jupiter et al. 2014; Afflerbach et al. 2014; Albert et al. 2016; Viana et al. 2017; Andrachuk et al. 2019; Sepulveda et al. 2019; Villaseñor-Derbez et al. 2019; Aceves-Bueno et al. 2020; Halim et al. 2020; Nguyen et al. 2017).

Recognition of indigenous rights to, and ownership of, significant coastal estate in some countries (e.g. Australia, Canada, New Zealand) is having a growing role in marine governance and conservation and aspirations for blue economy livelihood opportunities. Across many cultures, traditional owner communities have often long practised conservation of coastal ecosystems and resources through application of traditional ecological knowledge, such as spatial and seasonal closures, and there is growing recognition of the need to incorporate such knowledge within modern conservation practices (Kerr et al. 2015; Charles 2017; Ban and Frid 2018; von der Porten et al. 2019a, 2019b; Rist et al. 2019; Reid and Rout 2020).

To empower and to incentivise local communities as custodians to protect and restore local coastal areas, the application of payments for ecosystems services (PES) is increasingly being adopted. With this approach, stewards (traditional owners or community groups generally) of a coastal area are incentivised (paid) to carry out activities that preserve or enhance the provision of ecosystem services. Those who pay for PES are motivated by direct benefits (e.g. environmental protection helps a business) or indirect benefits (e.g. offsetting carbon footprint), and PES transactions are generally regulated by independent organisations who certify that measurable units of benefit (e.g. carbon sequestered) have been created by the project's activities and allow the resulting credits to be sold or traded in relevant marketplaces (UNEP 2020).

Beyond designating areas with a level of protected status, many factors can define success or failure of individual MPAs. Without careful governance, planning and execution, MPA designations can amount to little more than "paper parks". Multi-stakeholder engagement is considered a critical factor affecting success, as is whether zoning and plans identify and resolve conflicts among users, and whether effective performance monitoring and evaluation occurs. Even when MPAs are effective, issues can arise with unmet expectations by communities, upfront costs from decreased fishing in new protected or regulated grounds, loss or change of cultural uses, and unequal distribution of resources (Cinner et al. 2012; Fox et al. 2012; Ehler 2018; Giakoumi et al. 2018).

Marine Protected Area design continues to evolve as it seeks to meet a range of emerging challenges. Irrespective of the level of protection afforded from human-use impacts, effective MPA management must now also consider the consequences of a changing climate (recurrent coral bleaching, for example) and the role of MPAs in addressing the impacts on biodiversity—for example, through creating refugia and connected networks of "bright spots" and incorporate projected future distributions of coastal ecosystems rather than focusing on past conditions.

4.2 Mitigating Catchment Impacts Through Terrestrial Reform

Achieving a sustainable ocean economy relies on the adequacy of upstream urban and hinterland infrastructure to provide the transport, energy and water services required to support ocean industries and their supply chains. Equally important, however, is addressing the downstream impacts of inappropriately designed and operated infrastructure and activities on coastal ecosystems. The activities of concern are those that clear, convert or modify coastal ecosystems to other land uses; extract resources such as surface water, groundwater and sand; and introduce land-based pollutants, such as excessive nutrients, sediments and manufactured chemicals (e.g. agricultural, industrial pharmaceuticals and personal care products), and litter.

In relation to the last of these, the companion Blue Paper *Leveraging Multi-Target Strategies to Address Plastic Pollution in the Context of an Already Stressed Ocean* (Jambeck et al. 2020) proposes several relevant interventions that would reduce pollutant inputs: improve wastewater and storm-water management, adopt green chemistry and new materials, recover and recycle materials, implement coastal zone improvements, and build local systems for safe food and water.

Given growing water scarcity worldwide, there is also opportunity for better reuse of wastewater to meet these demands as well as to reduce impacts on coastal environments. There are well-established technologies that can be deployed to increase the amount of wastewater that is recycled and reused. As a result, cities across the globe are establishing ambitious targets and developing policies to support zero discharge concepts (UN Water 2017).

As noted in Sect. 4.1, there are significant opportunities for closer integration with current global water, urban and climate agendas and initiatives.

The High Level Panel on Water articulated an agenda for water reform that encompassed: establishing a *foundation for action* based on better understanding, valuing and managing water; *leading an integrated agenda* to provide sustainable and universal access to safe water and sanitation, build more resilient societies and economies, invest more and more effectively in water-related infrastructure, and build sustainable cities and human settlements; and *catalysing change, building partnerships and international cooperation* to encourage innovation, promote partnerships and strengthen cooperation, and leverage finance and institutional support. The High Level Panel on Water highlighted the need to consider "urban deltas, coastal areas and other environmentally sensitive areas" and "to integrate appropriate measures into sustainable urban and territorial planning and development" (High Level Panel on Water 2017).

To support these efforts, the UN General Assembly proclaimed the period 2018–2028 as the Water Action Decade, which—given that it overlaps with the 2021–2030 UN Decade of Ocean Science for Sustainable Development—means that there are considerable opportunities to harmonise initiatives to develop a "source-to-sea" approach that explicitly considers downstream impacts of terrestrial infrastructure and activities on coastal ecosystems. The strength of source-to-sea management is that it considers the entire system, highlighting upstream and downstream environmental, social and economic linkages, and stimulating coordination across sectors and across different authority levels. Source-to-sea approaches have been implemented in many countries, often under different names (e.g. catchment-to-coast, ridge-to-reef), while globally this approach is recognised as essential to addressing SDG implementation by ensuring that linkages between the different goals and their targets are considered (Mathews et al. 2019; Singh et al. 2020).

Mitigating the impacts of diffuse land-based sources of pollution, including the application of nutrient fertilisers and agricultural chemicals (pesticides and herbicides), as well as the erosion of sediment on sensitive adjacent coastal ecosystems (seagrass beds and coral reefs), is now the principal concern among developed nations, and globally. For example, in Australia, management of activities to mitigate the loads on nutrients, sediment and pesticides discharged from catchments adjacent to the Great Barrier Reef have been in place since the 1990s and encompass regulations that range from setting end-of-catchment load reduction targets to regulating and incentivising land-practice activities, such as precision and regenerative farming that retain soils on-farm, and minimise the use of agrochemicals. Further downstream, the retention of vegetative buffer strips along the banks of rivers, estuaries and shoreline, and the use of natural and constructed wetlands to trap sediments and filter nutrients, are also effective ways of minimising discharges to coastal environments (Brodie et al. 2012; Day 2018; Adame et al. 2019; Saderne et al. 2020).

While ecosystems such as seagrass, oysters and coral reefs are particularly sensitive to too much sediment, in depositional coastal areas an adequate supply of sediment from upstream will be required to ensure the stabilisation of shorelines and the ongoing accretion of mangrove and saltmarsh habitat. Regulation of the amount of water used by upstream activities, removal of unnecessary impoundments and barriers, sustainable sediment management in reservoirs, and the setting of dedicated natural environmental hydrological flows that can reach the coast unimpeded are needed to ensure that deltas and estuaries can keep pace with sea level and erosion (Kondolf et al. 2014; Anthony and Goichot 2020).

The carbon sequestration and storage of areas of mangrove, saltmarsh and seagrass is now widely considered by many countries with large blue carbon stocks as part of their national emission reduction commitments, and they are now active in conserving and restoring these ecosystems (see Sect. 4.4).

Emerging initiatives are focusing attention on the importance of action to curb the over-extraction of sand from rivers and coastal areas and stop critical deltas from "sinking and shrinking". For example, WWF's Resilient Asian Deltas initiative (WWF 2019) focuses on Asia's six largest delta systems—Ganges–Brahmaputra–Meghna, Indus, Irrawaddy, Mekong, Pearl and Yangtze—with an emphasis on the importance of building with nature and the benefits nature provides as a key solution for delta and coastal resilience. From restoring fluvial and coastal sediment flows to creating more room for rivers, from reconnecting floodplains to restoring mudflats, mangroves and other wetlands, from minimising the impact of new infrastructure on river flows to creating ponds and sponge cities to compensate for expanding areas of impermeable concrete, building with nature across their river basins would transform the future of these deltas.

Likewise, over-abstraction of groundwater, leading to subsidence in low-lying areas and cities, requires a comprehensive approach to better manage these resources. Given that these abstraction and extraction activities can occur

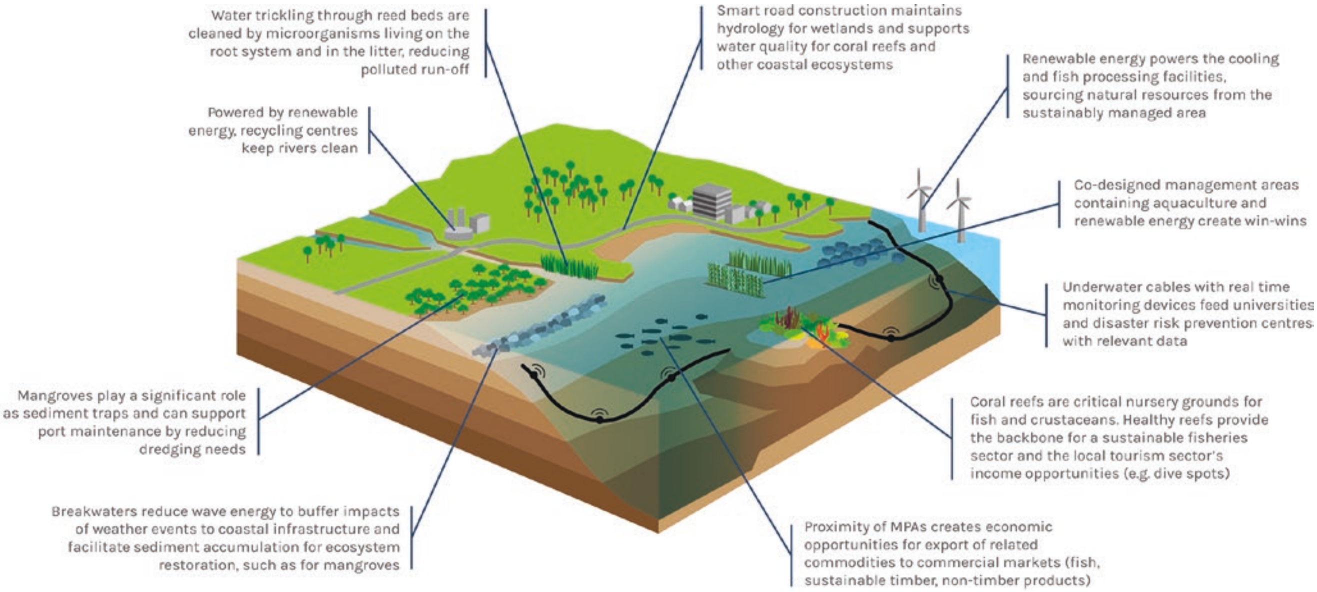

Fig. 7.6 Benefits of implementing blue infrastructure. (Source: Thiele et al. (2020). IUCN)

many hundreds of kilometres from the coast, and sometimes in adjacent countries, regional, or transnational source-to-sink approaches are required.

4.3 Adapting Coastal Infrastructure

The coastal adaptation strategies considered here are principally concerned with using nature-based approaches to adapting infrastructure to increase resilience to changing conditions, and to minimise the loss of ecosystem services. This also requires a change in behaviours or practices by which we make use of coastal environments and the resources they provide, and the way in which we value the direct and indirect benefits derived from these ecosystems.

Traditional coastal infrastructure is typically built with "hard" or "grey" engineering techniques and materials (e.g. concrete, steel) and designed to specifications for withstanding probabilistic exceedances that are based on the assumption that the past can reliably predict the future; as discussed in Sect. 2.1, this is no longer the case and puts many low-lying settlements at risk. These hard approaches have also left a legacy of environmental impacts affecting the structure, function and connectivity among adjacent coastal habitats and diminishing biodiversity. The next generation of coastal infrastructure will have a critical role in meeting these increased climate-driven challenges, as well as accommodating continued urbanisation and the needs of blue economy industries. To ensure that the right infrastructure is built, we must adopt resilient approaches, and policymakers will need to establish long-term visions for sustainable national infrastructure systems, informed by the SDGs (Thacker et al. 2019).

Softer, natural approaches—often labelled "green" for terrestrial or "blue" for marine—that apply ecological engineering principles are increasingly being used to build coastal defence structures that "mimic" natural coastal areas, including dynamic coastal landforms, such as beaches, barrier islands and dunes; coastal vegetation, such as mangroves, seagrasses, dune vegetation, saltmarshes and kelp forests; and reef systems, such as mussel beds, oyster reefs and coral reefs. Figure 7.6 illustrates the cbenefits of implementing blue infrastructure, and Table 7.4 summarises the advantages and disadvantages of each form of infrastructure.

The direct benefits of natural infrastructure are principally protection from flooding and from erosion. Consequently, such approaches are now recognised as a way of balancing continuing development with solutions that deliver climate change resilience and adaptation benefits, alongside multiple ecosystem benefits, including enhancing biodiversity and carbon sequestration and improving water quality by filtering storm water (Francis 2010; Lai et al. 2015; Perkins et al. 2015; Sutton-Grier et al. 2015; Firth et al. 2016; Vikolainen et al. 2017; Gracia et al. 2018; Burt et al. 2019; Browder et al. 2019; Conger and Chang 2019; Liu et al. 2019; Thacker et al. 2019).

Table 7.4 Summary of selected management approaches advantages and disadvantages

Advantages	Disadvantages
Grey infrastructure	
• Significant expertise exists on how to design and build such approaches at large scales	• Does not adapt with changing conditions such as sea level rise
• Decades of experience with implementation	• Weakens with time and has a built-in lifetime
• Excellent understanding of how these approaches function and what level of protection will be provided by different types of structures built to specific engineering standards	• Can disrupt longshore coastal sediment transport and cause downdrift coastal erosion
• Infrastructure is ready to withstand a storm event as soon as it is constructed	• Can cause coastal habitat loss and have negative impacts on the ecosystem services provided by nearby coastal ecosystems
	• May sustain more damage during small storm events
	• Only provides storm protection benefits when a storm is approaching; no co-benefits accrue in good weather
	• Needs continuous monitoring and regular maintenance
	• Barrier to dispersal and movement of fauna and flora, resulting in loss of ecosystem connections
Natural and hybrid infrastructure	
• Capitalises on best characteristics of built and natural	• Little data on how well these systems perform to date
• Allows for innovation in designing coastal protection systems	• Does not provide the same benefits that natural systems provide
• Provides some co-benefits besides coastal protection	• More research is needed to design the best hybrid systems
• Can provide a greater level of confidence than natural approaches alone	• Growing but limited expertise in the coastal planning and development community on which approaches to use
• Can be used in areas where there is little space to implement natural approaches alone	• Hybrid systems, due to the built part of them, can still have some negative impacts on species diversity
• Balances conservation with development	• Uncertainty in cost-effectiveness and long-term performance
	• Permitting for hybrid projects can be a more difficult process than for built projects
	• Response to native species colonisation is unpredictable
Ecosystem restoration	
• Provides many co-benefits in addition to coastal protection, including fishery habitat, water quality improvements, and carbon sequestration and storage, and can provide these benefits to coastal communities all the time, not just during storm events	• The development of best practices for how to restore ecosystems is needed, according to a set of starting criteria
• Ecosystem grows stronger with time as establishes	• Provides variable levels of coastal protection (non-linearity of the provisioning of coastal protection benefits), depending on the ecosystem, geography and also on the type and severity of storm events; more research is needed to better understand how to estimate or predict the coastal protection provided
• Has the potential to self-recover after a storm or other disturbance event	• In the case of restored ecosystems, it can take a long time for ecosystems to get established so that the natural systems can provide the necessary level of coastal protection
• Can keep pace with sea level rise	• Likely requires a substantial amount of space to implement natural approaches (such as ecosystem restoration or protection of existing ecosystems), which may not be possible in highly urban or industrial contexts
• Can be cheaper to construct	• Uncertainty in cost-effectiveness and long-term performance
• Increased CO_2 storage capacity in created, maintained or restored ecosystems; reduction of urban heatwave island effect; improvement in water quality	• Permitting for natural projects can be a more difficult process than for built projects
• Can enhance tourism, recreational and local employment opportunities included in establishment and maintenance	• Uncertainty over responsibility for ownership and maintenance
• Enhances the natural environment and implicit value	• Uncertainty in assessing levels of risk for insurance cover and premiums for coastal assets
• Saves raw materials and improves public health	

However, as the design and performance of this natural infrastructure is often influenced by local ecological, social and political conditions, increasingly *hybrid* approaches blending strategic use of natural assets and ecological principles with grey-engineered techniques and existing infrastructure are being adopted. Hybrid approaches provide cost-effective hazard protection solutions and are increasingly being adopted in urban areas where green approaches may be insufficient to meet the rising impacts of climate change, or where space is limited. There are now numerous examples and guidance on applying these approaches to applications that range from the landscape scale to individual breakwaters. Restoration of wetlands, sand-dunes and beaches can be integrated with supporting grey structures for flood or erosion management (e.g. levees, breakwaters and seawalls), providing a solution that is more comprehensive, robust and cost-effective than either solution alone. Small-scale engineering interventions to coastal defence structures can be implemented at relatively low cost, in intertidal and shallow subtidal zones to increase faunal and algal abundance and diversity. The modification of these structures, by adding grooves, pits, ledges and texture, can be incorporated into the design of coastal defence structures or retrofitted to existing structures. For example, the Living Seawalls project (see Box 7.7) is fitting seawalls with various shaped tiles—made with 3D printing technology—that enhance relief and facilitate settlement of a variety of benthic organisms, or create habitat for small cryptic fishes (Borsje et al. 2011; Depietri and McPhearson 2017; Strain et al. 2018a, b; Browder et al. 2019; Conger and Chang 2019).

Another area of adaptation is the development and use of building materials that are more environmentally benign. There are now a number of green concretes—made with waste material as a partial or complete replacement for cement or aggregate, including recycled demolition waste aggregate, blast furnace slag, manufactured sand, glass aggregate and fly ash. While green concrete requires less energy for its production and produces less CO_2, the higher cost of reinforcement, and the shorter life of buildings constructed with green concrete are limitations that are being addressed (Zhang et al. 2014; Khazaleh and Gopalan 2019; UNEP 2019).

Many cities around the world are now developing and implementing green urban infrastructure plans and demonstrating that urban transitions integrating green, blue and grey infrastructure are possible and affordable, and lead to more efficient, multipurpose infrastructure. Recognition that these solutions can be applied in other parts of the world has led to a number of international city networks, notably the C40 Cities Climate Leadership Group, the World Mayors Council on Climate Change and the Urban Climate Change Research Network, now actively collaborating and learning from each other to improve their adaptive capacity.

Similarly, many seaports around the world, facing growing environmental concerns about their construction and operation, have sought to align their performance with sustainability considerations, as well as planning protection from the impact of climate change. A shift to greener, integrated ports is now recognised as a long-term economic choice, and an increasing number of ports now implement a range of in-port operations, including energy conservation, environmental protection and development planning that considers the adjacent environment, other coastal operations and nearby cities. A range of incentives are also used to reduce emissions, such as using shore-based electricity for ships at berth, requiring slow vessel speeds, and incentivising rail and barge transport, rather than roads, from ports. Some ports also reduce fees based on indices that assess the environmental performance of individual vessels, such as the Environmental Ship Index. However, the voluntary nature of such schemes means that progress on significant emission reductions remains slow. Consequently, regulators and policymakers must be prepared not merely to nudge and incentivise but to take more concrete action (PIANC 2014; Gonzalez et al. 2018; Bergqvist and Monios 2019; Psaraftis 2019; de Boer et al. 2019; Dundas et al. 2020; WPSP 2020; UNCTAD 2020b).

With growing offshore sprawl, there are opportunities to find synergy in sharing infrastructure between industry sectors that might previously have been in conflict. For example, combining aquaculture with wind or solar operations, and even conventional oil and gas platforms, is now increasingly common. Such multifunctional use is, however, still very much in its infancy and requires technical and economic feasibility as a basic prerequisite, as well as alignment among sectors and national jurisdictions of environmental, safety and regulatory regimes and practices. Similarly, a growing legacy of ageing marine (e.g. oil and gas platforms and pipelines) and catchment (e.g. small dams) infrastructure that must be decommissioned in the near to medium future is driving the development of policy and science that seeks to minimise environmental harm while ensuring cost-effectiveness (Buck and Langan 2017; Buck et al. 2018).

Multilateral funding and investment agencies and the insurance industry now recognise that integrating blue and grey infrastructure can help to fill the need for the next generation of climate-resilient infrastructure solutions and allow for the devising of new risk financing for nature-based solutions, such as the recent insurance for the Mesoamerican Reef (Reguero et al. 2019b). There is a large and growing pool of funding for natural infrastructure—although the availability is geographically uneven—with the largest opportunities in the redirection of post-disaster recovery funds to pre-disaster investments in risk reduction. However, the largest barriers for securing adequate resources are identifying locations where natural infrastructure can play a significant role in flood risk reduction, developing the experience and standards to overcome institutional biases that favour grey infrastructure, and developing institutional arrangements capable of matching available funding with the needs of individual situations (Colgan et al. 2017).

Policy support for green/blue/hybrid infrastructure can make good politics and has an important social dimension, as adoption will be most successful when it meets the needs and interests of local stakeholders and communities. However, much clearer integrated policy pathways to promote adoption of blue and hybrid infrastructure are required, and while “green” and “blue” are often used to delineate terrestrial and marine approaches, in fact, “teal” approaches are what is required to effectively address coastal development (Browder et al. 2019; Dundas et al. 2020).

A body of policy and practitioner guidance has emerged in recent years that provides tools to enable integration and the use of natural infrastructure solutions, lessons from implementation, and policy recommendations to ensure that infrastructure meets sustainable development objectives (Browder et al. 2019; Conservation International 2019; Thiele et al. 2020). At a macro level, the 2019 G20 Principles for Quality Infrastructure Investment provide clear policy guidance for the consideration that needs to be taken around infrastructure planning, including that in the coastal zone. The principles include a focus on maximising the positive impact of infrastructure on achieving sustainable growth and development through the positive economic, environmental, social and development impact of infrastructure and encourages the use of a virtuous circle of economic activities, including the use of ecosystem-based adaptation where possible. They highlight the need for comprehensive disaster risk management planning in the design of infrastructure, including in terms of considering the re-establishment of essential services, as well as the need to ensure long-term adaptability and to build for infrastructure resilience against natural disasters and the slow onset of environmental changes. Finally, they highlight the importance of finance and insurance mechanisms, including well-designed disaster risk finance, to help incentivise resilient infrastructure through the financing of preventive measures, and the need to make transparent the additional benefits of sustainable infrastructure projects to enable the use of green finance instruments, including in the delivery of NDCs (G20 2019).

Box 7.7. Living Seawalls: A Green Engineering Solution with Global Significance

The Living Seawalls project enhances the ecological value of seawalls by using modular habitat panels, constructed using 3D design and printing technology, to mimic features of natural shorelines (SIMS 2020). Panels with crevices and ridges, in New South Wales, Australia, enhance native biodiversity and the survival of Sydney rock oysters, a native habitat-forming and economically important species (Strain et al. 2018a, b). Individual panels can be designed to mimic the natural habitat features of a locality, and panels of multiple designs can be configured in mosaic arrangements to provide a variety of habitats to maximise diversity.

To date, panels of multiple designs have been installed at six locations in Sydney Harbour to create “living seawalls”. Within hours of installation, panels were inhabited by microbes and mobile macro-invertebrates, and within just a few months, the complex panels supported more diverse and abundant marine communities than flat surfaces. This project, a collaboration between marine biologists, designers and engineers, was made possible by a forward-thinking local council (North Sydney), which has long supported seawall greening and provided access to their seawalls (Fig. 7.7).

Urban stakeholders are supportive of green engineering initiatives and local stakeholders reported a greater sense of well-being associated with these initiatives. The enormous potential of the Living Seawalls habitat panels to transform seawalls around the world has captured the attention of local and state governments, consultants, marine managers and ecologists from around Australia and abroad. At present, the main barriers to implementation are the lack of clarity on seawall ownership due to jurisdictional boundaries within the intertidal and shallow subtidal environment, confusion around required documentation for the permitting process, and the slow rate at which these questions are resolved.

4.4 Repairing Coastal Ecosystems

It is now widely accepted that protection is not enough to reverse trends in coastal habitat loss and degradation, and efforts to repair these ecosystems, through at-scale habitat restoration efforts and by re-establishing natural coastal and hydrological processes, are required. It is also increasingly accepted that these efforts can deliver substantial environmental co-benefits (Sect. 4.5), including biodiversity protection, coastal protection, coastal carbon storage and fisheries production, as well as direct and indirect employment co-benefits related to installation, maintenance, recreation, tourism and education. Several studies have begun to quantify the singular and bundled value of the direct and indirect benefits that accrue from repairing coastal ecosystems, and demonstrate substantial economic gains and cost avoidance relative to business-as-usual scenarios.

Restoration science and practice is also fundamental to creating new nature-based infrastructure for coastal defence (Sect. 4.3). Recent analysis commissioned by the High Level Panel for a Sustainable Ocean Economy notes that restoration activities provided a benefit of four dollars for every one invested, but due to higher logistical costs and the longer

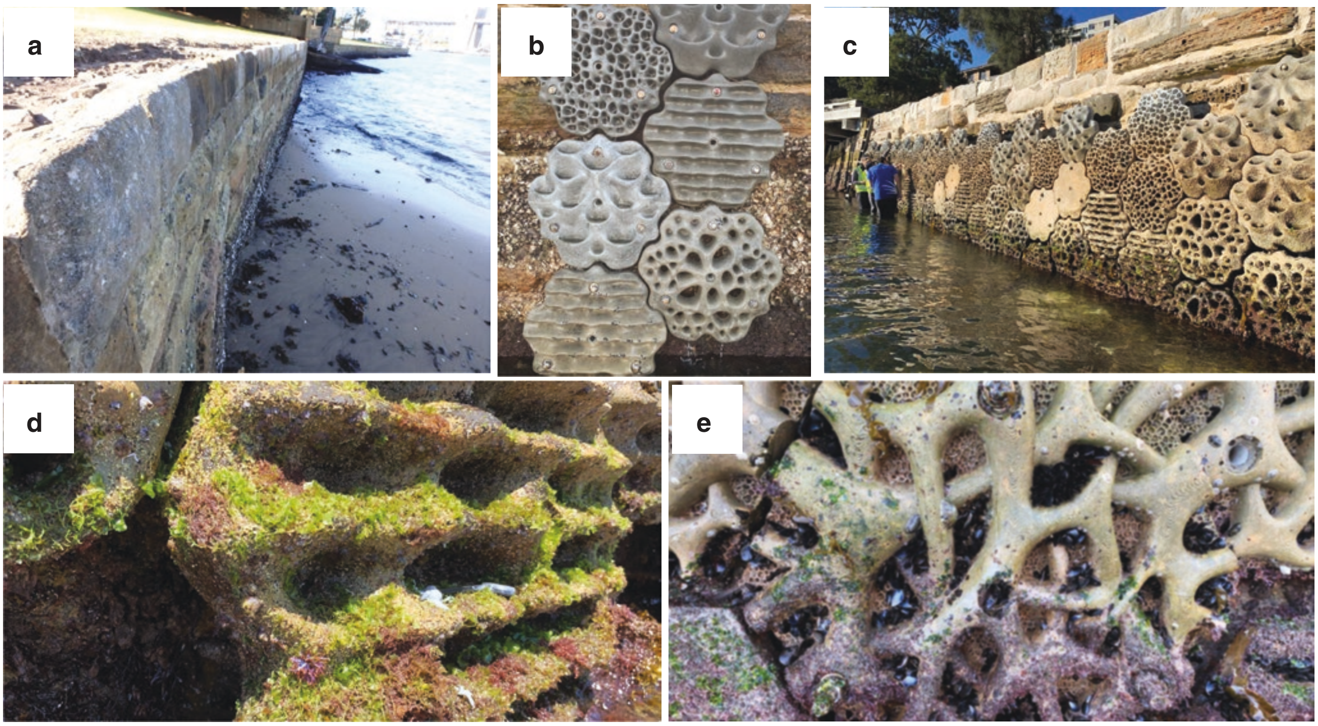

Fig. 7.7 Living seawalls. Living Seawalls panels can be affixed to existing seawalls that are generally flat and featureless, and otherwise provide little protection for marine life (**a**). Panels have been designed using 3D printing technology to incorporate complex texture and a variety of microhabitat features (**b**). Seawalls can be retrofitted in a variety of configurations to suit site conditions, ecological objectives or aesthetic preferences (**c**). Within months, the complex panels were colonised by a variety of invertebrate and macroalgae and fish (**d**, **e**). (Source: Maria Vozzo)

timescales taken to realise the benefits, this ratio is at least 20-fold less than implementation of protection measures (Konar and Ding 2020).

Globally, there are a number of initiatives actively seeking to scale up restoration. The UN General Assembly has declared 2021–2030 the UN Decade on Ecosystem Restoration, promoting global cooperation on the restoration of degraded ecosystems to combat climate change, protect biodiversity, assist with food security and deliver clean water for the planet. The Bonn Challenge seeks to restore 350 million ha of the world's degraded and deforested lands by 2030, while the Global Mangrove Alliance has set a target of increasing global mangrove extent by 20% within this time period.

While the reasons for restoration are varied, it should be understood that the aim of restoration activities is not to return degraded coastal ecosystems to any particular past reference point, but rather to focus on increasing the extent and abundance of key habitats and keystone species, and use metrics that include presence of structure, functions, resilience and ecosystem services to evaluate success (Bayraktarov et al. 2016, 2019, 2020a; Friess et al. 2019; Duarte et al. 2020).

Depending on the habitat to be restored, as well as local conditions, a variety of restoration methods have been used and there are now numerous examples of successful and unsuccessful projects that have allowed the development of extensive practical guidance on restoration (Gann et al. 2019). Box 7.8 summarises some of these principles and learnings, and Boxes 7.10–7.13 provide relevant examples of mangrove, seagrass, coral and shellfish reef restoration.

For coastal marine ecosystems, mangrove restoration is the most well established and is widely undertaken throughout the world. Mangrove restoration occurs predominantly by planting seedlings and saplings in projects that vary from small (<1 km^2) to large (1000 km^2) scale, and by 2010, nearly 4000 km^2 had been restored. Online tools, such as the Mangrove Restoration Potential Map (maps.oceanwealth.org/mangrove-restoration/), allow users to explore at global, regional and national levels the opportunities for mangrove restoration.

The map identifies c.8120 km^2, or 6%, of former mangrove area as restorable, with the greatest opportunities in Southeast Asia (Worthington and Spalding 2018). The Global Mangrove Alliance (http:// www.mangrovealliance.org/gma/) provides practical advice on mangrove restoration.

The reinstatement of natural hydrological conditions for rivers, as well as tidal areas that have been restricted, is an important pre-condition for restoration in coastal marine habitats. In many cases, the removal of bunds and other structures restricting natural tidal flows can be sufficient to assist revegetation of coastal areas that had previously been cleared for other land use, including agriculture and aquaculture (Kelleway et al. 2020).

Technically, to improve the success of restoration efforts, the rigorous application of science to design and select areas that are suitable for restoration is needed, and the use of "big data" can be utilised for such assessments. Continual evaluation of project progress with metrics that assess effectiveness rather than effort will help to ensure that lessons are learned from past failures and successes so that restoration practices are improved and resources can be maximised in the most cost-effective manner. Harnessing knowledge of the life histories of the habitat-forming organisms, using technologies such as drones to identify suitable areas for restoration and to disperse pods into ideal locations, or using commercial vessels equipped with oil booms to collect wild coral-spawn slicks for re-seeding target reefs (see Box 7.11) are just a few examples to help achieve the scale of restoration required (Fairhead et al. 2012; Baker and Eckerberg 2013; Doropoulos et al. 2019a, b; Vanderklift et al. 2020; Worthington et al. 2020; Waltham et al. 2020).

Apart from the technical challenges of undertaking restoration at ecologically meaningful scales, restoration must operate within a complex and dynamic interplay between technical decision-making, legal constraints, social licence to operate, ideologies and politics. As a result, many efforts are considered value-laden, context-driven and prone to disagreement and compromise. In developing countries, restoration projects must also operate and respect the cultural norms and traditional ownership/rights issues relevant to the project area, while at the same time addressing perceptions of "green grabbing". Governance and institutional issues can also hamper rehabilitation if there is poor coordination among agencies, many of whom often have conflicting production/development and environmental protection mandates.

In addition to the ecosystem services that restoration of coastal habitats can provide, there are also significant flow-on benefits through the creation of new jobs and supporting local economies. Marine habitat restoration is recognised as a "jobs-intensive" industry and strong driver of economic growth, creating immediate employment in transport, construction, marine engineering, project management, science and aquaculture. For example, the economic impact of 50 coastal habitat restoration projects funded through the American Recovery and Reinvestment Act (2009) created on average 17 jobs per million dollars spent, which was higher than traditional industries, including coal and gas, roads and energy generation. Many jobs are created in rural and regional coastal areas and offer a range of skilled and low-skilled positions, considerably enhancing economic opportunities in regional areas. Longer-term employment can be created through the flow-on benefits of these ecological improvements to new and increased opportunities for fishing, aquaculture and tourism and their service sectors (Edwards et al. 2013; Powell et al. 2018).

Marine habitat restoration is also almost unparalleled in its capacity to deliver collaborative, partnership-based approaches for restoration. Active involvement and meaningful consultation between practitioners, local communities and the science sector that leads to integration of best-practice science and local knowledge is essential for effective implementation. Factors for success include local government support, community involvement, property rights, education and preparation, and supplementary livelihoods. Citizen science activities are regularly incorporated into projects to reduce costs and expand community participation and education. Engagement with traditional landowners can result in shared learning, application of traditional ecological knowledge and improved coastal management and indigenous engagement (Diefenderfer and Adkins 2003; Stojanovic et al. 2004; Ismadi and Yamindago 2014; Dharmawan et al. 2016; McLeod et al. 2018; Powell et al. 2018; Waltham et al. 2020).

Box 7.8. Success Factors for Coastal Restoration

1. Planning: Careful planning is necessary and should include identifying the causes of degradation and conducting preliminary small-scale interventions to test effectiveness prior to applying any full-scale restoration activities.
2. Create the right preconditions: Removal or mitigation of stressors, such as poor water quality, and limiting conditions, such as lack of suitable substrate or inadequate supply of propagules, is necessary before natural recovery can occur. Stressors that enhance mortality, such as disease and predation, particularly during early stages of growth, also need to be minimised.
3. Consider the right scale and context: The need to scale up restoration activities means that the patch-based approaches must consider processes at the broader landscape and regional scales—for example, movement of water or dispersal of biota.
4. Location: Ensuring restoration takes place in the locations that maximise success for the system being

restored, in terms of considering scale, access, disturbance history and forecasting, and downstream benefits, is vital.

5. Focus on tangible outcomes, not targets: While ambitious area-based targets (e.g. size of area planted, number of seedlings planted) for restoration are being widely advocated, these should be reframed to focus on success criteria linked to environmental outputs (e.g. percentage survival, vegetation densities similar to natural forests) and incorporate social-ecological outcomes of restoration.
6. Engage partners and community: Active involvement and meaningful consultation between practitioners, local communities and the science sector—that leads to integration of best-practice science and local knowledge—is essential for successful implementation and longevity.
7. Harness technology: Technology must be developed and utilised to effectively scale up restoration efforts. Remote sensing technology opens new ways to monitor and inform conservation and restoration.
8. Long-term monitoring and adaptive management: It is important to plan for, commit to and invest in long-term monitoring, so that small issues can be quickly rectified.
9. Investment: Besides public investment, restoration efforts clearly need private investment, and this investment could be accessed via new financial instruments, including payment for ecosystem services, green bonds, biodiversity offsets, carbon credits, debt-for-nature swaps, and water quality credit markets.

Box 7.9. Mangrove Protection and Restoration: Nature-Based Solutions to Multiple Problems

Mangrove conservation—including actions that both protect and restore—is becoming a priority for international policy, in part because mangroves provide multiple benefits, including carbon sequestration, coastal protection and fish habitats. Currently, around 36% of the world's mangroves have some form of legal protection, and they are also implicitly or explicitly included under multiple international policy frameworks, including the Ramsar Convention on Wetlands of International Importance.

Many nations are developing policies and legislation that afford increased protection. For example, the island nation of Sri Lanka—one of the countries most affected by climate change—has implemented legal protection for all of its mangrove areas, as well as a policy to rehabilitate 10,000 ha of mangrove forest, while Indonesia aims to restore 50,000 ha of mangroves by 2024. However, policy frameworks still include incentives (such as expansion of aquaculture) that contribute to mangrove degradation and loss, and removing such perverse incentives is key to reversing decline.

Efforts to restore mangroves have taken many forms, from using seedlings grown in pots or directly inserting mangrove propagules into the soil, to simply allowing the tide to return and letting nature take its course. The approach has varied, depending on the purpose, such as whether the focus is on stabilising an eroding coast or generating carbon credits. Many of these initiatives often fail completely (for example, all the seedlings die), or they do not achieve the intended result. However, many successful initiatives exist, which shows the enormous potential of restoration. For example, in Bali, Indonesia, restoration of abandoned aquaculture ponds has yielded excellent results over more than a decade, including high rates of carbon sequestration. Breaching the barriers around the ponds (i.e. pond walls and gates) has allowed the tide to return, promoting rapid natural mangrove regeneration and accumulation of carbon-rich soil (Fig. 7.8).

In southwest Madagascar—a nation that lost 21% of its mangroves in the 20 years from 1990 to 2010 alone—coastal communities are almost entirely reliant on the resources they get from the sea. Blue Ventures has worked with these local communities using participatory approaches to develop a suite of activities designed to encourage sustainable use of mangroves, including development of sustainable alternative ways of generating income. Among the activities is the implementation of a locally managed marine area, alongside local regulations (Dina) to prevent overharvesting mangroves. The project also includes mangrove restoration by directly inserting into the soil the viviparous propagules of *Rhizophora mucronata, Ceriops tagal* and *Bruguiera gymnorhiza*, which are collected from parent trees nearby. The survival rate of planted mangroves is high, and measurements also include the carbon content of mangroves and the underlying soil, to develop carbon credits for sale in the voluntary carbon market, and so generate an additional source of income for local people.

Fig. 7.8 Mangrove restoration in Bali, Indonesia. (Source: Mangrove Nusantara)

Box 7.10. Seagrass Protection, Adaptation and Restoration

Seagrasses globally have been degraded over recent decades, and there is ample evidence from well-studied parts of Australia, North America and Europe showing that millions of hectares of seagrass meadows have died around the world (Waycott et al. 2009).

Can we begin to reverse this pattern through restoration? Advances in seagrass restoration techniques suggest that we can. Broadly, there are two main ways of restoring seagrass, which take advantage of the way that seagrasses (like grasses on land) can multiply both asexually and sexually. In asexual growth, seagrasses send out rhizomes (structures like horizontal stems) that colonise new areas; sometimes parts of an adult plant can break off and be transported to a distant area through sea currents, where it can then establish and grow. This characteristic of seagrass has been harnessed for decades in attempts at seagrass restoration, by methods which involve taking shoots from a healthy meadow, and planting them elsewhere. It can be laborious, and sometimes survival is low. But, if circumstances are right, it can be very successful. One example is Oyster Harbour, an enclosed embayment on the southern coast of Australia. After the original causes of seagrass death were ameliorated, efforts were made to transplant rhizomes of *Posidonia australis*, it with its characteristic large leaves attached. These were replanted in areas that once hosted seagrass, taking care to bury the rhizomes below the sediment surface, holding them in place with a wire hook. Survival was high, and the transplanted seagrass began to extend outwards. After 8 years, individual transplants could not be distinguished and meadows of transplanted *Posidonia* had begun to merge with existing natural meadows. When rates of carbon burial were measured 18 years after the original planting, rates inside meadows that grew from transplanted seagrass were similar to those in natural seagrass—further demonstration of the success of that project (Bastyan and Cambridge 2008; Marbà et al. 2015; Serrano et al. 2020).

Another restoration method yielding promising results harnesses the use of the seeds that seagrasses produce. In this method, seeds are dispersed into areas where seagrass once grew. Although only a small proportion survive and grow, many seeds can be dispersed, so that the overall chances of success are improved. In coastal bays of Virginia (USA), a project started in 1999, which involved scattering seeds of eelgrass (*Zostera marina*) from a boat across 125 ha over several years, had, by 2010, formed seagrass meadows covering greater than 1700 ha (Orth et al. 2012). Similar successes are now being reported at multiple locations around the world, highlighting that this method offers considerable promise (Fig. 7.9).

Fig. 7.9 Seagrass (Syringodium isoetifolium) in Mauritius. (Source: Mat Vanderklf)

Box 7.11. Restoration and Adaptation of Coral Reefs

With widespread and more frequent bleaching events, it is now widely held that conventional management approaches are not enough to protect coral reefs, and that restoration at ecologically meaningful scales is urgently needed to aid and accelerate recovery of damaged reefs.

Restoration methods developed over the last 40 years have traditionally involved transplanting coral fragments or adding artificial substrate, with other approaches such as larval addition, rubble stabilisation or algal removal infrequently applied (Boström-Einarsson et al. 2020). The coral gardening approach was pioneered in the 1990s and programmes using this approach now operate in more than 150 coral nurseries across 20 countries. Most interventions have traditionally been small, labour intensive and costly (replanting coral fragments grown in a nursery costs between $1 million and $4 million per ha) and have had mixed results (Rinkevich 1995; Edwards and Gomez 2007; Lirman and Schopmeyer 2016; Bayraktarov et al. 2016, 2019, 2020b; Anthony et al. 2017; van Oppen et al. 2017; Ladd et al. 2018; National Academies of Sciences, Engineering and Medicine 2019).

Some recent studies have begun to demonstrate longer-term and larger-scale (around 1–2 ha) successes (Fox et al. 2019; Williams et al. 2019; Bayraktarov et al. 2020a, b). One promising approach shown below is the harvesting, culturing and release of wild coral-spawn slicks to targeted reefs. Recent studies in Australia have demonstrated the feasibility of such large-scale restoration, and have been accomplished by incorporating technologies used in oil spill remediation, dredging operations and land-based aquaculture. Such an approach allows for long-distance translocation of corals and maintenance of coral diversity, and has virtually no impact at source (Doropoulos et al. 2019a, b).

Assisted evolution, such as selective breeding, assisted gene flow, conditioning or epigenetic programming, and manipulation of microbiome could also help coral reefs, which are particularly sensitive to warmer water temperatures (van Oppen et al. 2017). Moreover, including strategic decision science (Doropoulos and Babcock 2018) alongside novel interventions (Anthony et al. 2017) is necessary to maximise the long-term effectiveness of restoration activities (Fig. 7.10).

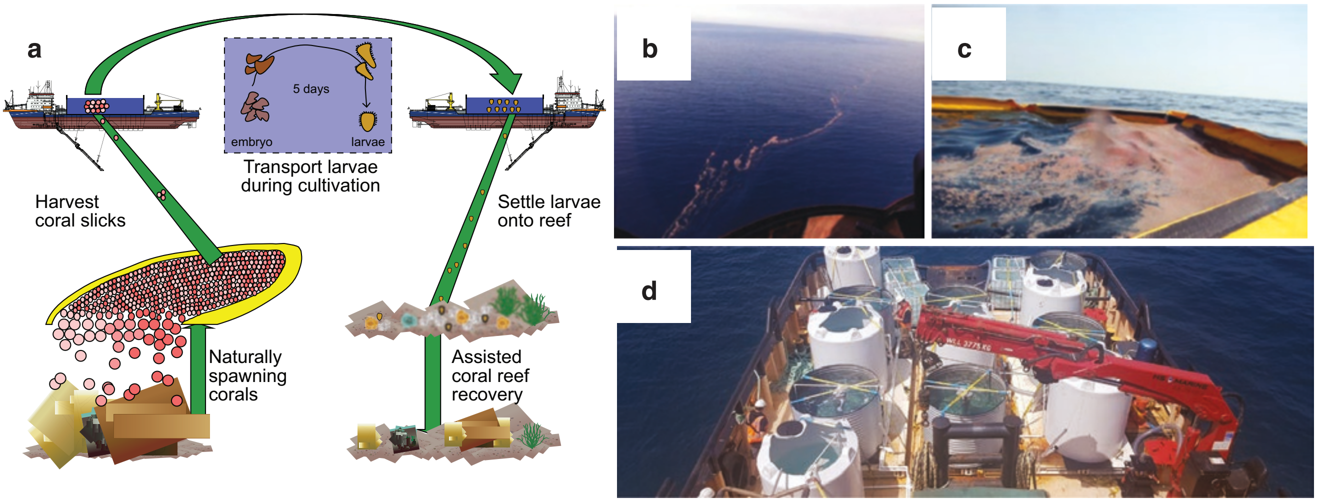

Fig. 7.10 Coral-Spawn Slicks. (**a**) Conceptual diagram for the harvesting of wild coral-spawn slicks following mass spawning events for transport during cultivation and release onto degraded reefs to assist in recovery. (**b**) Kilometre-long slick seen from the sky. (**c**) Slick contained in an oil boom. (**d**) Slick cultivated on a floating aquaculture system built on a commercial tug-boat in the first field trial. (Source: CSIRO)

Box 7.12. Shellfish Reef Restoration

Shellfish restoration has been successfully undertaken in several countries at scale and has employed approaches ranging from natural regeneration, assisted regeneration and reconstruction approaches. Shellfish reef restoration now frequently occurs at large scales (>10 ha), engages across government, non-governmental organisations (NGOs) and local communities and is innovative in addressing financing options. Examples of shellfish restoration around the globe include:

- In the United States, the Chesapeake Bay Executive Order requires oyster populations of 20 Chesapeake Bay tributaries to be restored by 2025. Three estuaries have been restored thus far, including 390 ha of restored reef at a projected total cost of $72 million. The economic investment was returned in less than 5 years through the increased catch of commercial fish and crab fisheries as a result of increased productivity from restored reefs (Knoche and Ihde 2019).
- In China in 2004, over 20 tonnes of hatchery-reared seed oysters were successfully transplanted onto two around 50-km concrete dykes previously constructed in the Yangtze River (Quan et al. 2009).
- In South Australia in 2018, a 20-ha native flat oyster reef was restored at a cost of c.$3 million, to support recreational fishing tourism and regional jobs at an employment ratio of 8.5 jobs per million invested. Key success factors included using case studies of the environmental and social benefits of reef restoration (particularly from the United States) to help educate the community and government stakeholders on the benefits of natural habitat restoration compared with artificial reefs; identifying a clear social beneficiary stakeholder (i.e. recreational fishers) and economic beneficiary stakeholder (i.e. local service businesses that financially benefit from the predicted increase in recreational fishers in the region); and successfully articulating marine ecosystems as natural infrastructure, which is synonymous with built infrastructure in terms of providing a beneficial service to communities and which can be quantified like other types of infrastructure (Econsearch 2016).

The benefits of restoring shellfish reefs to coastal communities and industries are well quantified, with the economic value of the full suite of ecosystem services derived from natural oyster reefs in North America estimated to be as high as $100,000 ha per annum (Grabowski et al. 2012) and including job creation and economic development, fish production, water filtration and dentification, coastal protection and providing habitat for many other marine species (Fig. 7.11).

Fig. 7.11 Shellfish Reef Restoration at Windara Reef in South Australia. (Source: Chris Gillies)

Box 7.13. Promoting Gender Equality for Coastal Resilience

Promoting gender equality is essential for ensuring coastal resilience, as women play key roles in many marine sectors and are important negotiators and decision-makers. Women can make up more than half of the workforce in some marine industries, especially small-scale fisheries, aquaculture and processing plants. However, women, particularly in developing countries are often disadvantaged through gender inequalities caused by unequal power relations and structures, lack of training, discriminatory laws and customs, and unequal access to and control of resources, and as a result, there are very few women in leadership positions. Women are also more vulnerable than men to climate change and natural disaster impacts.

Many examples from developing countries show that, where women are empowered and can contribute to decision-making processes, social well-being is enhanced and conflict reduced, the health and education of children is improved, and the environment is better protected. Thus, developing and implementing education programmes and capacity building, not only for women but men in the community as well, and establishing women's cooperatives and advocacy groups are needed (Tschakert and Machado 2012; Alston 2013; Monfort 2015; CARE 2016; Dah-gbeto and Villamor 2016; Smucker and Wangui 2016; Tran et al. 2016; de la Torre-Castro et al. 2017; MFF 2018; UNFCCC 2019; Stacey et al. 2019; Ravera et al. 2020).

Box 7.14. Incentivising Coastal Development and a Sustainable Ocean Economy

The Asian Development Bank (ADB) gives us an example of how a multilateral development bank is moving to incentivise coastal development and a sustainable ocean economy. In its operational plan, ADB highlights the importance of building resilience as part of its overarching vision for a “prosperous, inclusive, resilient, and sustainable Asia and the Pacific”. Many Asia Pacific countries, particularly low-lying nations and SIDS, are highly exposed and vulnerable to natural hazards and the impacts of climate change. Disaster losses are already growing due to insufficient regard for climate and disaster risk in either the design or location of new infrastructure. A clear priority is planning and delivering infrastructure that builds resilience in a climate and disaster risk resilience context, with a number of different categories of resilience being identified (see Box 7.1).

ADB’s Action Plan for Healthy Oceans and Sustainable Blue Economies, launched in 2019 (ADB 2020), is an example of an integrated approach to promoting ocean health and sustainable coastal development. It includes a commitment of $5 billion in investments and technical assistance in focus areas that include sustainable infrastructure, blue economy livelihoods, ecosystem management and pollution control management, supported by an ocean financing initiative.

4.5 Coastal Co-benefits and Trade-Offs

4.5.1 Co-benefits

All too often coastal management strategies are undertaken in order to meet a single objective, without recognising the multiple other benefits that can result from an action. Only by accounting for these can we truly place the full value of ecosystem services into a planning and management context. Value can be expressed in many ways other than direct monetary metrics, including food security, health and cultural values. The benefits that people receive from ecosystems may accrue far from where they are produced. In the last decade, there have been significant advances in developing methods to quantify non-market benefits of coastal ecosystems and to map additional benefits that cascade from them.

Today, ecosystem service valuation is increasingly being used as a tool to assist coastal planning and management to achieve better informed and more holistic decision-making about resource use, and identify opportunities for effective conservation. For example, ecosystem-service approaches can help to inform coastal and marine planning by modelling the likely outcomes of management strategies for objectives expressed in terms of value to people, whether monetary or otherwise.

A number of studies demonstrate that spatially explicit scenario modelling of ecosystem services allows stakeholders and policymakers to better refine zones of human use, identify how different regions may contribute to the flow of services on a larger scale, and test the efficacy of different management strategies. One such recent global analysis finds that, under business as usual, the biggest economic impacts that could result from the loss of nature would be increased coastal vulnerability, followed by loss of carbon sequestration potential, while a “global conservation” scenario would deliver economic gains that result principally from improved natural coastal defences (Johnson et al. 2020). These results suggest that one clear opportunity for action is to focus on protecting and rehabilitating natural infrastructure. These types of nature-based solutions are increasingly being viewed as critical actions to reduce societal risk regarding a number of complex problems, from coastal protection to food security (Whelchel et al. 2018).

4.5.2 Trade-Offs

A key challenge in coastal marine conservation and management is how to manage trade-offs between social and ecological goals, so that both benefits and costs can be distributed equitably across individuals or communities (Halpern et al. 2013). For example, the decision to protect a mangrove to avoid carbon emissions or to slow erosion may have an impact on current timber harvesting or future opportunities to develop the coast for aquaculture or urban expansion. For the people who rely on these for their livelihoods, there is no obvious benefit and therefore little incentive, unless alternative sources of income can be provided.

Globally, climate and coastal development projections over the coming decades mean that we are inevitably faced with compelling circumstances requiring trade-offs to maintain viable environmental conditions and standards of living (Whelchel et al. 2018). Navigating these trade-offs will require thoughtful consideration of the distribution of costs and benefits, and development of mechanisms that protect the livelihoods of those least able to bear the cost. For example, in southwestern Madagascar, efforts to reduce mangrove deforestation have involved developing partnerships with local communities that include finding alternative fuel sources, and alternative ways of generating food and income (Rakotomahazo et al. 2019).

Understanding trade-offs can be complex and cannot be limited to assessing only quantifiable costs and benefits, but needs to consider less obvious factors that can result from complex social-ecological interactions, or that arise because the trade-offs affect marginalised individuals. Concepts of social equity, justice and human rights need to be incorporated in assessing these trade-offs and co-benefits, especially within the wider global discourse on governing the blue economy. While efforts to meet SDG 14 will typically be compatible with those for other SDGs, protecting and conserving coasts to meet SDG 14 targets can also lead to social and economic trade-offs and the downstream effects of such trade-offs can be especially pronounced in low-income coastal communities (Allison et al. 2012; Daw et al. 2015; Galafassi et al. 2017; McClanahan et al. 2016; Nippon Foundation–Nereus Program 2017; Gattuso et al. 2018; Kittinger et al. 2017; Davies et al. 2018; Singh et al. 2018; Bennett 2019; Cohen et al. 2019; Lombard et al. 2019).

To avoid these effects, consideration of trade-offs requires a deliberative approach engaging stakeholders through participatory processes, and harnessing marine spatial planning and scenario modelling tools that allow multiple perspectives and objectives to be considered. As a result, final decisions may reflect open debates about trade-offs and can inform solutions that balance multiple objectives—and surprising synergies may occur (e.g. developing infrastructure to meet multiple uses) that transform a trade-off to a co-benefit (Arkema et al. 2015).

It is important to adopt a long-term perspective when considering trade-offs. For example, short-term losses of livelihoods or income resulting from the creation of MPAs can lead in the long term to ecological, socioeconomic and cultural benefits upon the recovery of fish populations and marine habitats. Intergenerational equity must also be an essential criterion when balancing short-term trade-offs and long-term benefits.

Unintended consequences can also arise. For example, a focus on gross area targets for MPAs may promote the creation of very large marine protected areas, which, by virtue of their size, are generally located in offshore areas, where space is available, tenure arrangements are less complicated and the numbers of stakeholders involved are lower. This may, however, discourage the further protection of mangroves, saltmarshes and seagrass, as their coastal location, often fringing and disjunct distributions, and their location along coasts with multiple land uses and stakeholders make it more complicated to create large protected areas (Friess et al. 2019).

4.6 Enabling Conditions

The coastal zone is crowded, jurisdictionally complex, contains an extremely diverse set of user and interest groups and is subject to multiple competing demands, particularly for space and access. It is a complex socioeconomic system, where achieving sustainable ocean economy outcomes that are resilient to current and future shocks will depend on strong institutions, clear and appropriate governance and finance, an inclusive and equitable approach, and a set of information and science needs. These enabling elements are by nature cross-cutting and are listed below.

- *Strengthening governance and recognising customary rights:* A key influence on the choice and likely success of management options is the existing regulatory framework, through which management authorities, such as permitting and other approvals, are distributed across local, regional, state and/ or federal entities. Most coastal landscapes in the tropics have complex and unclear land tenure and sea use arrangements, especially for indigenous peoples and traditional communities. Furthermore, in many countries indigenous peoples and traditional communities have traditional and customary tenure and rights to significant coastal assets, often defined by LMMAs. Ensuring that these rights are respected and indigenous peoples and traditional communities are engaged in the stewardship of these coastal assets and the creation of alternative livelihood opportunities will be essential.
- *Multilateral partnerships:* Any decision pathway necessarily involves multiple stakeholders who will be interested and involved in the decisions surrounding interventions that sustain or repair coastal ecosystems: practitioners, science and engineering, regulators, industry, investment community, traditional owners and local communities. Developing ecological engineering solutions will require much closer collaboration between scientists and engineers, plus the funding for and a commitment to scientifically test a range of bold innovations at sufficient scale. Where successful, this knowledge should be shared to understand how these innovations could be applied in other settings. Globally, the private sector is seen to have a major role in the implementation of the SDGs and in conserving coastal ecosystems. The International Chamber of Commerce has explicitly stated that sustainability is no longer a luxury business investment, but a core driver of business productivity and growth.
- *Valuing and accounting for coastal assets and ecosystem services:* Coasts and coastal natural infrastructure are essential to the economies of countries and the livelihood of their inhabitants. Impairment of coastal ecosystems that leads to a reduction in resilience or productivity can be a significant cost to the economy. Many ecosystem assets and services remain unquantified. Better methods for valuing non-market assets and services, and applying these consistently within national Systems of Environmental-Economic Accounting (SEEAs), will better inform choices relating to what areas or assets can be developed and what needs to be protected.
- *Quantify co-benefits and trade-offs:* As discussed in Sect. 4.5, analysing trade-offs requires a deliberative approach,

with stakeholder values at the centre. Obtaining full stakeholder involvement through participatory integrated and ecosystem-based marine planning is an important component of assessing trade-offs because it allows for the articulation of multiple perspectives that can inform solutions that balance multiple objectives (Galafassi et al. 2017; Gattuso et al. 2018; Lombard et al. 2019).

- *Science, technology and innovation:* Implementing these various strategies and actions must be underpinned by multidisciplinary science that informs wise decision-making. Although many of these issues encompass the complexity of human decision-making, institutional structures and governance arrangements, science is pivotal to developing more sophisticated and evidence-based policy and management. Integrated management must be underpinned by a deeper understanding of how biophysical and human systems are coupled and an understanding of singular and cumulative impacts. Technological innovation underpins the emerging "science of solutions" that will guide the choice of interventions chosen to safeguard and restore coastal ecosystem resilience. Novel approaches have originated from the growing understanding of biology and ecology, inspiring new theories (e.g. positive species interactions) on which new interventions can be built and tested at scale. There is an important role for the social sciences to be included in future intervention study design, implementation efforts and the collection of evaluation effectiveness metrics.
- *Monitoring and assessment:* Ongoing synoptic and finer-scale observations are required to assess changes in the coastal ecosystems and the surveillance of activities that are occurring within and adjacent to coastal zones. A new generation of in situ sensors, observational platforms, environmental satellite capabilities and informatics provide unprecedented capability and are increasingly accessible and affordable.
- *Capacity building and sharing knowledge:* Supporting the capacity and adaptability of nations—especially least developed and small island states—to successfully implement these strategies requires ongoing, not one-off, capability development that includes both training and access to best-practice information.
- *Financing the future:* Financing for green and grey-green infrastructure is in an exciting growth phase as private investors and development banks increasingly recognise the high potential of this type of infrastructure to tackle development challenges. Initiatives such as the WWF's Sustainable Blue Economy Finance Principles (WWF 2018) lay the groundwork for such investments and need to be broadly and full adopted by public and private sector finance organisations. Strong and effective national sustainable blue economy strategies or plans, based on a clear vision for and definition of a sustainable blue economy, help to foster an enabling environment that reduces risk and builds investor confidence. *The* creation of targeted finance and investment opportunities, such as blue bonds, blended finance, public–private partnerships, insurance payments for risk reduction and corporate stewardship, have emerged as novel ways to build resilience, restore natural capital, and reduce environmental, social and economic risks and investor risk (Herr et al. 2015; Colgan et al. 2017; Niehörster and Murnane 2018; Sumaila et al. 2020; Thiele et al. 2020).

5 Conclusions and Opportunities for Action

5.1 Conclusions

The coastal zone has the world's highest population density, is where the vast majority of resources that underpin the world's ocean and maritime economic sectors are located, and where the majority of many coastal nations' commercial, residential, transport and national defence infrastructure is situated. Coasts sustain livelihoods for hundreds of millions of people in endeavours that range from artisanal small-scale fisheries and aquaculture to transnational fishing, shipping, energy and tourism industries.

Over the last 30–50 years, there have been significant, and, in many cases, rapid/abrupt and irreversible, changes across all of the world's coastal ecosystems. These have included erosion of depositional coastlines, loss of coastal vegetated ecosystems (50% of saltmarshes, 35% of mangroves), and coral (30%) and shellfish reefs (85%), and significant reduction in system resilience.

Coastal ecosystems have evolved in dynamic spatial contexts and many are adapted to disturbance and perturbation or perform a stabilisation and energy dissipation function. Climate change impacts are increasing the physical stress and damage to coastal habitats from storms, flooding and inundation, and are also directly affecting ecosystems through warming and changing ocean chemistry on the abundance and distribution of species and ecosystems.

Humans are also directly affecting coastal ecosystems, with pressures from increasing population growth and urbanisation, poor upstream land practices, alteration of freshwater and sediment flows, habitat conversion, water quality degradation, litter, pollution and over-exploitation of resources. Agriculture operations in catchments can lead to alteration of flows, and increased sediment, nutrient and chemical loads, while coastal fisheries and aquaculture can have direct and indirect effects on coastal ecosystems and habitats. Energy production and resource extraction infrastructure have high freshwater requirements, while urban infrastructure growth leads to habitat conversion, hardening of coastlines, channelisation of flow, and sand-mining in upstream catchments altering sediment budgets at the coast. The result is direct physical loss, fragmentation and alteration of many ecosystems, as well as a functional loss of resilience—which diminishes their ability to resist and recover from such perturbations—that is unprecedented historically. The drivers of this change in coastal ecosystems are complex and interconnected and result from unsustainable levels of human modification to, and resource extraction from, coastal ecosystems.

A rapidly growing and urbanising coastal population, and expansion of existing and new industries, has generated additional demand for coastal space and resources, while incompatibility between different uses—and sometimes ideologies—has also led to conflict in coastal environments. Coastal population growth and increasing urbanisation, catchment degradation and mismanagement, loss of coastal foreshore amenities, environmental impacts from industry, incompatible or unsustainable resource use, and climate change are some of the major challenges that can result in conflict and require careful management.

The physical loss of ecosystems and habitats leads to the loss of their ecological function within the coastal zone socioeconomic system, including provisioning and protection functions. Coastal communities, especially those that are poor and vulnerable and that rely directly on coastal resources for food security, nutrition and livelihoods, are often those most at risk of climate impacts or disasters. COVID-19 has shown us the vulnerabilities that exist in many coastal economic sectors, and again it is those who are poor and vulnerable who appear to be most at risk.

If current trends continue unabated, or without significant interventions, projections over the next 10, 30 and 80 years comprehensively demonstrate the widespread and potentially catastrophic risks to coastal ecosystems, human populations, built infrastructure and economies that will result. The rapid population growth that will occur across Asia, and, even more significantly, Africa, will increase demand for coastal resources and services, and potentially expose coastal cities and settlements to increased impacts. It is here, as well as in the many small island nations spanning the Indo-Pacific and in the Caribbean, that the greatest risks occur.

Failure to properly manage our coastal resources will result in further significant environmental damage to coastal environments, loss of economic well-being for existing industries that operate in the coastal zone (and disincentive for new industries to invest), and inadequate infrastructure development to meet the demands of changing demographics and climate change impacts.

Actions that aim to deploy protection as the "first line of defence" are no longer enough; strategies and technology solutions that mitigate threats, assist in the adaptation of human activities, infrastructure and behaviours, or seek to repair coastal natural systems through restoration and facilitated adaptation will be required. Over the coming decade, implementing these actions *at scale* must be accelerated and assistance to less-developed countries will need to be stepped up.

There are, however, a range of positive policy, planning and coastal infrastructure developments that are cause for cautious optimism as we look towards 2030. Nature-based and hybrid approaches are increasingly being used to adapt existing, and design new, infrastructure to increase resilience to changing climate conditions, and to minimise the loss of ecosystem services. There is great interest, and a large pool of funds, from the investment, insurance and business sectors to implement natural and hybrid approaches for the next generation of climate-resilient infrastructure, and to empower nations and communities to protect coastal ecosystems through a range of financial mechanisms that remunerate for the protection and enhancement of ecosystem services. Intergovernmental bodies, funding agencies (the World Bank, Global Environment Facility, Green Climate Fund), the insurance industry and investment banks all recognise the need for investing in nature-based solutions. However, the availability of support is geographically uneven and there are many barriers to implementation of such approaches at scale.

Building the socioeconomic resilience of those who are most vulnerable, and empowering and engaging natural resource users and coastal communities, especially those who rely directly on coastal resources for food security, nutrition and livelihoods, are critical aspects of ensuring healthy coastal ecosystems and realising a sustainable ocean economy.

5.2 Opportunities for Action

To ensure environmental, economic and social sustainability of our space-constrained coastal systems, the great challenge will be to balance ongoing development and multiple competing uses. By realising the following opportunities for action, it will be possible to reverse the trend of degradation, including from terrestrial and extractive activities, and instead optimise the benefits of healthy ecosystems, natural infrastructure, and inclusive and equitable approaches, to build a coastal zone and coastal economy that is robust, sustainable and resilient.

5.2.1 Building Coastal Resilience

The resilience of coastal ecosystems, and the people who rely upon them, can be enhanced through actions that increase their ability to withstand pressures, and actions that help them to recover when damage occurs.

- Coastal ecosystems must be better protected by strengthening regulations and increasing area-based conservation to halt the net loss, increase the extent and improve the condition of critical coastal habitats, such as sand-dunes, saltmarshes, mangroves, seagrass, and coral and shellfish reefs.
- At-scale habitat restoration, and re-establishing natural coastal and hydrological processes, are required in order to repair many damaged coastal ecosystems and restore functional resilience.
- Restoration also delivers significant co-benefits that extend beyond ecosystem goods and services by creating jobs related to restoration activities, and once established, livelihood opportunities from tourism, enhanced fisheries and payment for ecosystem services, such as carbon sequestration and storage.

5.2.2 Creating Coastal Community Resilience, Equity and Access

Actions that build the socioeconomic resilience of communities, including gender equity and social inclusion, are important in mitigating and recovering from climate and disaster risks and shocks, such as COVID-19, where the impacts are greatest among the poor and vulnerable.

- The multiple benefits coastal communities derive for ocean and coastal services should be included in the valuing and accounting of the ocean economy.
- Communities and coastal fishers should be recognised as legitimate resource users and also stewards of marine ecosystems. This is particularly true for SIDS and remote coastal regions, where communities are often isolated from major governance centres and where marine tenure has remained or is being reinvigorated.
- Governance approaches must be inclusive, incorporating indigenous and local knowledge in planning and decision-making processes.
- It is vital to ensure that business processes are inclusive and that incentives exist to protect and restore coastal ecosystems and enhance local livelihood opportunities.
- Local supply chains should be prioritised, so that pregnant women and infants, and those at risk of malnutrition or hunger, gain access to the nutritional benefits from locally sourced sustainable fish.
- Governments should prioritise poverty reduction and social protection programmes that build community resilience, including to climate change and disasters, and channel post-disaster support to affected poor households. In particular, they should build the resilience of those who are most vulnerable, especially by promoting gender equality and empowering women.

While the consequences of COVID-19 for the resilience of coastal communities will continue to unfold over many years to come, as nations begin to rebuild their economies, there is a unique window of opportunity to ensure relevant policy and investment decisions also address these coastal challenges. In addition, they must foster sustainable economic pathways that support the recovery and development of impacted communities and build the resilience of coastal ecosystems, safeguarding the services they provide.

- Coastal fiscal and economic stimulus and recovery packages must be designed with a sustainable and equitable ocean and coastal economy outcome as a primary objective, and meet multiple SDGs.
- High-employment sectors should be prioritised if they are essential services, or support sustainable ocean economy opportunities. Options include micro-canneries for domestic consumption, mangrove restoration for disaster risk reduction, and investments in effective waste management systems that reduce disease prevalence.
- Vulnerabilities in coastal economic sectors and supply chains should be prioritised for investment and innovation. Examples include the development of product alternatives that have a longer shelf life, using digital means to connect to customers and local markets, and adopting electronic and digital verification systems in supply chains.
- Climate change projections and impacts should be incorporated into all aspects of COVID-19 recovery planning and sustainable infrastructure design. This includes the protection and restoration of coastal ecosystems and fisheries as part of building resilience.

5.2.3 Mitigation of Terrestrial and Extractive Activities on Coastal Ecosystems

The impacts of terrestrial and extractive activities on coastal ecosystems may be cumulative and may be amplified by climate change effects, while the downstream impacts of upstream activities can lead to conflicts among user groups.

- Integrated management underpinned by good spatial planning and coastal ecosystem planning must be fully integrated into urban, catchment and land-use planning frameworks.
- Urban and agriculture water use should be managed to ensure that coastal ecosystems receive healthy surface flows and that coastal groundwater reserves are maintained.
- Upstream catchment diversions and dams should be managed to ensure that adequate freshwater flow and adequate sediment supply is maintained to the coast. Promotion of

alternatives to mega dams, such as building small dams with sediment release facilities, is a priority.

- Regional multi-sector dialogues should be initiated to address upstream sand extraction and sand scarcity, particularly in relation to coastal city subsidence and stability of urbanised deltas.
- Closer integration should be pursued between the current global water, food and energy nexus, and the water, urban and climate agendas and initiatives, including the High Level Panel on Water, and the overlapping UN decade initiatives for Oceans, Water, and Ecosystem Restoration.

5.2.4 Sustainable, Future-Ready Blue Infrastructure

The following opportunities for action are designed as ones that industry, government, scientists and communities can take to promote the uptake, resourcing and deployment of natural infrastructure.

- Identify locations where natural or hybrid infrastructure can play a significant role in natural hazard risk reduction, and adapt and upgrade existing coastal infrastructure through the adoption of nature-based approaches for more sustainable designs, including retrofitting coastal defence structures.
- Develop and scale cost-effective, hybrid approaches that enhance resilience by integrating nature into mainstream infrastructure systems. Encourage closer collaboration between scientists and engineers, and dedicate funding to develop eco-engineering opportunities.
- Build the skills and capacity of government staff in the design of sustainable ocean economy recovery programmes and in the design and maintenance of sustainable green coastal infrastructure, such that there is a common understanding of the benefits and opportunities.
- Embed opportunities for future-ready blue infrastructure and nature-based solutions within existing planning and management approaches, including within spatial management tools such as marine spatial planning, ecosystem-based integrated ocean management, marine protected areas and community-based natural resource management tools and approaches.
- Support the restoration of coastal ecosystems, including mangrove forests, saltmarshes, seagrass meadows, kelp and other seaweed forests, and coral and shellfish reefs, to optimise their function for coastal defence, coastal stabilisation or as part of hybrid coastal defence structures. Recognise that coral reef and mangrove restoration in particular offer cost-effective options for risk reduction of climate hazards.
- Develop the experience and standards to overcome institutional biases that favour grey infrastructure, and develop institutional arrangements capable of matching available funding with the needs of individual situations.
- Design new and innovative financial instruments to provide the pathways for investors to direct private finance into nature-based solutions, including through public–private investments.
- Establish standards and principles for developing and financing blue infrastructure and appropriate blended finance instruments, a good example of which are the Sustainable Blue Economy Finance Principles.
- Enable the use of green finance instruments, including in the delivery of NDCs, and use them to promote the uptake of natural infrastructure and sustainable infrastructure projects, including in developing and low-income countries seeking financing from multilateral development banks.

5.3 Enabling Conditions to Support Coastal Resilience

For any of the above actions to be successful in delivering coastal resilience, a number of enabling conditions need to occur. These were summarised in Sect. 4.6, while enabling actions specific to the coastal context are given below.

Strengthening governance and recognising customary rights: The enabling conditions for inclusive and effective local governance must be put in place, so coastal communities can effectively advocate for their rights to access coastal resources. Power imbalances must be acknowledged and addressed, to allow coastal communities the necessary influence and impact in governance and policy fora. As suggested in SDG 14, Target 14.b, the will and needs of coastal communities should be recognised, respected and reflected in policymaking and decision-making, and in the implementation of the SDGs. Local and national policies recognise the role of communities in the management of coastal resources, incorporate advice from community members in decision-making, and facilitate more equitable and inclusive access of communities to natural resources and markets.

Science, technology and innovation: The cross-disciplinary nature of grey-green infrastructure and natural infrastructure brings together ecology and engineering in the emerging discipline of ecological engineering, in designing societal services such that they benefit society and nature. As the implementation of hybrid and grey-green infrastructure solutions grows, there needs to be a body of research on all aspects and at a range of scales, in order to optimise the design of individual projects and to facilitate scaling. It is an area that is ripe for the application of technological innovation, consistent with the use of intelligent and smart building design in green buildings. COVID-19 has stress-tested contemporary coastal economic and logistical systems, and identified weaknesses and vulnerabilities that need to be prioritised for research, innovation and technological solutions.

Multilateral partnerships: Ensuring traditional owners and local communities have a voice and are engaged in the co-design and development of strategies and plans will be essential for gaining social licence. Ensuring a role in the stewardship and day-to-day management of activities that use these coastal assets and creation of alternative livelihood opportunities must be a priority.

Capacity building and sharing knowledge: Translating coastal research to best practice and "how to" guidance on coastal issues, such as dredging, coastal modelling, water and sediment quality standards, restoration methodologies, coastal and eco-engineering, and emergency preparedness, is required. Making this information available through a clearinghouse of coastal information will encourage adoption by regulators, environmental consulting and analysis sectors and organisations, and communities seeking to undertake restoration activities.

Financing the future: Green infrastructure and hybrid infrastructure designed with co-benefits in mind opens up a range of possible finance options in addition to the standard government financing model. It allows projects to be promoted to governments, the private sector or development agencies as stand-alone investment opportunities, matched to particular motivations. The private sector has the ability to provide substantial investment to support nature-based solutions, including through bonds and other novel instruments. However, the amount they currently invest is small because of constraints such as limited evidence of the returns on investment and lack of appropriate financial instruments. Development agencies with core mandates of climate resilience, poverty reduction and environmental sustainability also have a strong motivation to invest in such projects. The next decade should see significant growth in green and grey infrastructure, as investment pipelines grow, the capacity for designing and managing such investments is increased in target countries, and as challenges to scaling are overcome.

Acknowledgements We wish to thank the many people who generously provided material, advice and review for the report: Russ Babcock, Elisa Bayraktarov, Melanie Bishop, Katherine Dafforn, Dorothee Herr, Alexander Goad, Mariana Mayer-Pinto, Peter Steinberg and Torsten Thiele. The paper's technical reviewers, Audrey Legat, Borja Reguero, Julien Rochette, Alan Simcock and Sharon Tatman, as well as its arbiter, Jane Lubchenco, all provided helpful technical comments.

While our colleagues were very generous with their time and input, this report reflects the views of the authors alone, and is not necessarily the views of their organisations. Thank you to Em Muirhead, Lauren Hardiman and Derek Fulton for providing administrative, editing and graphic design support.

The authors thank Sarah Chatwin for copyediting and Romain Warnault for design.

Glossary

Ecological engineering The design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. The approach has developed over the last 30 years, rapidly over the last 10 years, and its goals include the restoration of ecosystems that have been substantially disturbed by human activities and the development of new sustainable ecosystems that have both human and ecological values.

Green grabbing The appropriation of land and resources for environmental ends, where "green" credentials are called upon to justify appropriations of land, and the restructuring of rules and authority in the access, use and management of these resources may have profoundly alienating effects.

Green infrastructure Green infrastructure (also sometimes called natural infrastructure or engineering with nature) intentionally and strategically preserves, enhances or restores elements of a natural system, such as forests, agricultural land, floodplains, riparian areas, coastal forests (such as mangroves), among others, and combines them with grey infrastructure to produce more resilient and lower-cost services.

Grey infrastructure Traditionally used to manage coastal hazards, often constructed out of concrete with a uniform and smooth texture, often costly to install and maintain, usually has low flexibility, and when it fails can generate catastrophic impacts on social and ecological domains.

Nature-based solutions (NbS) Actions to protect, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits. IUCN defines nature-based solutions as actions to protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

Ocean economy Also known as the blue economy, encompasses a sustainable economy for the ocean-based marine environment, related biodiversity, ecosystems, species and genetic resources, including marine living organisms (from fish and algae to microorganisms) and natural resources in the seabed, while ensuring their sustainable use and hence conservation.

Rehabilitation The replacement of structural or functional characteristics of an ecosystem that have been diminished or lost.

Resilience The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or re-organising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.

Restoration The process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed.

Social-ecological Refers to systems that emphasise humans as part of nature and stress that the delineation between social systems and ecological systems is artificial and arbitrary. While resilience has somewhat different meanings in social and ecological contexts, the social-ecological approach holds that social and ecological systems are linked through feedback mechanisms, and that both display resilience and complexity.

Source-to-sea A source-to-sea system is the land area that is drained by a river system, its lakes and tributaries (the river basin), connected aquifers and downstream recipients, including deltas and estuaries, coastlines and near-shore waters, as well as the adjoining sea and continental shelf and the open ocean. A source-to-sea system can also be defined at a larger scale to include a sea and its entire drainage area, which may include several river basins.

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