Pollution Mitigation and Ecological Restoration

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Contents

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Acronyms and Abbreviations

NOAA	National Oceanic and Atmospheric Administration
SER	Society for Ecological Restoration
UNEP	United Nations Environment Program
USA	United States of America
USD	United Stated Dollar

15.1 Introduction

► Chapter 1 presented to you the problem of marine pollution and through the book we explored the wide range of polluting substances with many chapters highlighting specific management approaches. ► Chapter 1 also highlighted that we are all potentially part of the solution to marine pollution. While pollution prevention must be considered a primary goal, research and practice that focuses on successful habitat improvement is a rapidly expanding area (e.g. Edwards et al. 2013). This chapter provides a general understanding of the **restoration of marine ecosystems** and includes the important role that pollution reduction (or mitigation) plays in order to gain positive outcomes.

Restoration ecology is a relatively new discipline area, particularly for marine ecosystems and has gained increased attention since the 1990s (e.g. Geist and Hawkins 2016; Basconi et al. 2020). The establishment of societies and organisations has helped to develop key principles and standards and ensure scientific rigour. For example, The Society for Ecological Restoration (SER) was established in 1988 to:

> “*bring together academics, researchers, practitioners, artists, economists, advocates, legislators, regulators, and others who support restoration to define and deliver excellence in the field of ecological restoration*”

(SER 2021) (► https://www.ser.org/). It is an international society with branches in many countries and there are other similar societies, networks and organisation established in many countries of the world that help enable local on ground activities (e.g. Australian Coastal Restoration Network: ► https://www.acrn.org.au/). Of further interest, in 2021 the United Nations Environment Program (UNEP) launched the United Nations Decade on Ecosystem Restoration 2021–2030, which globally encompasses environmental restoration of all degraded ecosystems including in coastal and marine environments (► https://www.decadeonrestoration.org/).

Public and private partnerships and collaborations are important elements in successful restoration programs. The partnerships may be between large organisations such as The Nature Conservancy and the National Oceanic and Atmospheric Administration (NOAA) and help to connect communities, expertise and funding. Grant opportunities also help to grow partnership and develop skills and expertise. There are many existing programs for coastal and marine ecosystem restoration in numerous countries and they most commonly focus on improvements to oyster reefs, clam beds, seagrasses, saltmarshes, mangroves, macroalgae forests and coral reefs (e.g. Bayraktarov et al. 2016; Basconi et al. 2020). Interestingly, there is now even interest in deep-sea ecosystem restoration (e.g. degraded canyons impacted by illegal dumping, litter and waste in the Mediterranean Sea (O'Conner et al. 2020). Importantly evaluating success and ecological outcomes needs to consider the desired goal and monitoring that shows a trajectory to reaching that desired goal. This evaluation helps to refine techniques, understand ecosystem services and economic benefits of the restoration (e.g. Abelson et al. 2015; Adame et al. 2019).

There is much more depth that can be explored in expert texts and a wide range of journal articles that are dedicated to marine habitat restoration. This chapter and the reference list of this chapter provides a helpful start.

15.2 What is Restoration?

There are many words used to describe habitat improvement, **restoration** relates to the active re-creation of favourable conditions and is similar to **rehabilitation** and **remediation** (Geist and Hawkins 2016). Rehabilitation and remediation have been suggested to represent less comprehensive restorations actions but there are many detailed definitions and arguments (Geist and Hawkins 2016). Like Geist and Hawkins (2016), this chapter will use the term **restoration** in a broad sense and readers are invited to explore the semantics on concepts and terminology in the wider literature for themselves.

Importantly when discussing degraded habitats, the stressors that have caused the impacts are not always pollution, they may be related to overfishing, destructive fishing such as dynamite fishing in coral reef areas, or changed physical conditions from coastal development to mention a few. In order for an ecosystem to recover, the stressors need to be alleviated and, in some cases, removing these pressures might be all that is required. These limited measures that support **passive recovery** are sometimes considered separate to **active recovery** (e.g. Elliot et al. 2007). Restoration in general should not be considered a one-off event but as an ongoing process over a time scale of years which is likely to need adaptive management (e.g. Edwards and Gomez 2007).

Sometimes ecosystems are so degraded that actions cannot re-create favourable conditions for restoration. In these instances, investment might be made in creating a **replacement** (or novel) ecosystem which is some form of acceptable new ecosystem that restores some ecological integrity, ecosystem services, amenity and recreational opportunities.

15.3 Key Principles of Practices in Ecological Restoration

To understand the processes required to improve ecosystem health the **specific stressors** acting on the site need to be identified along with the history of the site and the degree of perturbation—these can be the keys to effective decision-making to ensure success of restoration efforts (Laegdsgaard 2006). It is important to have some understanding of how restoration efforts are going to affect the ecosystems in need of improvement (i.e. Will the effort work? How does the ecosystem recover? Is it capable of recovery? How will it function? What is a measure of successful recovery?). Some of these questions can be answered with a thorough understanding of the mechanisms behind recovery and the ecology of the ecosystem. For example, knowledge of successional patterns, plant and animal physiology, environmental conditions for recruitment of keystone species, establishment and growth, diversity, amongst other ecological functions is required. These features should be incorporated into monitoring studies to assess improvement in the ecosystem condition.

As noted earlier, **restoration begins with mitigating the stressors**, after this, the chemical, physical and structural properties (e.g. hydrodynamics) need to be considered. Once these conditions are suitable, biological attributes generally follow. Some natural biological recovery may occur if the restoration site has connectivity with other similar habitats but active restoration is assisted by transplantation of keystone or foundation species.

As the science and practice of marine ecosystem restoration has developed, it has become evident that successful restoration and the ability to measure success requires many factors which are summarised in ◘ Table 15.1.

◘ **Table 15.1** Principles for success ecological restoration (*Detail sourced from*: Gann et al. 2019; Basconi et al. 2020)

Principles of ecological restoration	Detail
Engagement of stakeholders	Restoration is carried out to satisfy not only conservation values but also socioeconomic values, including cultural ones (e.g. of indigenous people).
Draws on many types of knowledge	Bring multidisciplinary scientists, practitioners, local community, indigenous knowledge together for projects inception, implementation and monitoring. Include socioeconomic concepts.
Practice is informed by native reference ecosystems while considering environmental change	Key attributes of a reference ecosystem: •physical condition (suitability and similarity with restoration site) •species composition •community structure (food webs) •ecosystem function (processes) •external exchange (interaction with surrounding environment •absence of stressors or threats
Supports ecosystem recovery processes	Ensure restorative practices enhance the natural recovery process. Pre-planning assessment to reinstate the missing biotic or abiotic elements. Consider climate change implications. Consider ecosystem services.
Assessed against clear goals and objectives using measurable indicators	Each project should define a set of goals that can be measured and used to assess the short-term and long-term success of the project.
Seeks the highest level of recovery attainable	It is important to bear in mind that the desired outcome may take a long time to achieve (e.g. years to decades). Managers should adopt a policy of continuous improvement informed by sound monitoring (e.g. five-star system of ecological recovery wheel described in McDonald et al. 2016).
Gains cumulative value when applied at large scales	Small projects can be beneficial but many ecological processes function at landscape, watershed, and regional scales. Degradation occurring at larger scales can overwhelm smaller restoration efforts. In some cases, investing in gradual improvements at larger scales (e.g. catchment runoff) may achieve greater results than more intense work at smaller scales or over shorter periods of time.
Part of a continuum of restorative activities	Progress evaluation. Formal field experiments can also be incorporated into restoration practice, generating new findings to both inform adaptive management and provide valuable insights for the natural sciences.

15.4 Cost and Success of Restoration

Average reported costs for one hectare of marine coastal habitat restoration were between US$80,000 and US$1,600,000, varying widely between ecosystem types and noting that projects may be up to 30 times cheaper in developing economies compared to developed economies (Bayraktarov et al. 2016). The categories of developing and developed economies have most recently been defined by United Nations (UN 2021).

The reviews of costs and feasibilities of marine restoration by Bayraktarov et al. (2016) and Basconi et al. (2020) are summarized in ◘ Table 15.2. Techniques are evolving and attributes of success noted in ◘ Table 15.2 may change over time. Most marine restoration projects reported in the literature have been conducted in countries with developed economies, in particular Australia, Europe and USA, although there are likely many unreported projects in countries with developing economies (Bayraktarov et al. 2016). They are mostly funded by government and private companies (as compensatory habitat) (Basconi et al. 2020). Partnerships with the government and other private, community and/or non-government entities and the development of markets for ecosystem services may provide incentives for financial investments into marine restoration projects (Murtough et al. 2002; Basconi et al. 2020).

Suitable site selection is essential for the success of restoration projects, and low survivorship of transplantations of seagrass, coral reef and mangroves has been attributed to poor site selection (Bayraktarov et al. 2016; Sheaves et al. 2021), lack of habitat-based research and limited reliable success metrics (Basconi et al. 2020). There is very limited long-term data on the success of restoration projects and long-term monitoring (e.g. 15–20 years) yet this has been commonly recommended (e.g. Hawkins et al. 2002; Bayraktarov et al. 2016; Basconi et al. 2020; Pollack et al. 2021). Although there is a cost associated with long-term monitoring, it provides valuable data to support adaptive management and improve techniques.

15.5 Marine Pollution Mitigation and Reduction

Marine ecosystems become degraded by a wide variety of threats. Degrading factors can be physical, biological or chemical (◘ Table 15.3) and may occur simultaneously or sequentially at any one site. If these degrading factors are not mitigated the likely success of restoration projects is compromised (e.g. Sheaves et al. 2021). Mitigating measures need to target the source of the degradation. Mitigation steps in restoration projects are initiated for many reasons including marine pollution accidents (e.g. oil spills), unexpected pollution (e.g. tributyltin) and more broadly because of diffuse source inputs (e.g. catchment runoff) and coastal development (Hawkins et al. 2002). The different sources need to be managed differently and in general it is less complicated to manage point source discharges and one-off events than complex diffuse sources with numerous polluting substances (see also ▶ Chapter 1). This section introduces you to some tools and approaches that are used to mitigate pollution (◘ Table 15.3). Where appropriate, some of these tools and approaches may be incorporated into restoration programs in coastal catchments and marine ecosystems.

◘ **Table 15.2** A summary of the relative costs and success of marine restoration projects in the published literature (*Data sources*: Bayraktarov et al. 2016 and Basconi et al. 2020)

Ecosystem	Relative cost of restoration	Attributes of success[a]	Relative scale of sites
Coral reefs	High	Transplanting, coral gardening and coral farming projects	Small scale
Seagrasses	High	Transplanting seedlings, sprogs, shoots and rhizomes	Small scale
Mangroves	Low	Facilitation of natural recovery through planting of seeds, seedlings or propagules	Largest scale
Macroalgae forests	Unknown	Transplantation of adults, sporophyte, seedlings, germlings or juveniles	Increasing
Saltmarshes	Medium	Construction and planting, seeds, seedlings or sods	Small-medium scale
Oyster reefs	Medium	Establishment of no-harvest zones and transplanting hatchery raised juveniles	Unknown

[a] Success based on survival was more dependent on ecosystems, site selection and techniques rather than money spent

Table 15.3 Marine pollution mitigation strategies

Treat or stressor	Mitigation strategies (current and recommended)	Further reading
Chemical		
Polychlorinated biphenyls (PCB)s	Stockholm convention Capacity building for inventory and destruction facilities	Chapters 8 and 16 Stuart-Smith and Jebson (2017)
Tributyltin (TBT)	International bans Development of suitable and low toxic alternatives	Chapters 6 and 13
Metals	Bioremediation Biosorption	► Chapter 5 Michalak (2020)
Brine (desalination waste)	Brine mining (recovery) Reduce liquid waste discharge Dilution	► Chapter 12 Panagopoulos and Haralambous (2020)
Illegal ship waste oil dumping	Reduction -onboard pyrolysis technology Improved disposal facilities in ports Improved policy and regulations	Mazzoccoli et al. (2020)
Nutrients	Catchment management Wastewater treatment Bioremediation Multitrophic aquaculture Water quality off-sets	► Chapter 4 Lang et al. (2020) Michalak (2020)
Pesticides	Pesticide use regulation Catchment management Enhanced microbial degradation Ecological risk assessment	Chapters 7 and 8
Oil spills	Double hull tankers Rapid implementation oils spill response programs	Chapters 6 and 16
Physical		
Plastic	Ecolabeling for informed consumer decisions Reduction, reuse, recycling Bans and imposed fees Policy and Conventions (e.g. OSPAR Convention 1998) Clean up strategies Behavioural change strategies Biotechnology (bioplastics) Extended producer responsibility Credit system Waste to energy Life cycle assessment of products and packaging	► Chapter 9 Ogunola et al. (2018) Lee (2021) Li et al. (2021)
Turbidity	Silt curtains Catchment riparian vegetation reinstatement Catchment management	► Chapter 12
Development of urban and port infrastructure	Rescue and relocation of species Development strategies	Liñán-Rico et al. (2019)
Noise	Rerouting of vessels and noise generating activities in area during high animal density and biologically important areas Noise reduction programs [e.g. SILENV (Ships oriented innovative soLutions to rEduce noise and vibrations 2009–2012)] Acoustic deterrent devices Reducing ship speed Vessel quieting technologies Voluntary agreements Passage planning Optimising ship handling and maintenance	► Chapter 12 Chou et al. (2021) Vakili et al. (2021)
Biological		
Introduced species	International agreements (e.g. Convention of biological diversity) Quarantine regulations Containment and eradication Precautionary approach (avoid the economic cost of invasion)	► Chapter 12 Occhipinti-Ambrogi (2021)

(continued)

Table 15.3 (continued)

Treat or stressor	Mitigation strategies (current and recommended)	Further reading
Harmful algae blooms	Nanoparticle treatment technology See nutrient mitigation strategies	▶ Chapter 12 Gonzalez-Jartin et al. (2020)
Disease	Quarantine regulations	▶ Chapter 12 Sampaio et al. (2015)

15.5.1 Mitigating Coastal Catchment Discharges

Catchment runoff is a major source of pollution to coastal environments and includes a combination of point and non-point sources which may be a result of both current and legacy (historic) activities. Not all pollutants generated in catchments reach the marine environment (e.g. Waterhouse et al. 2012), in general, and logically, lower transport rates to the ocean occur for pollutants generated further upstream in catchments (e.g. Star et al. 2018). The type and amount of pollutants that reach the ocean from catchments depends on the land use, rainfall intensity and duration, geomorphology, integrity of the riparian zone, chemical behavior of specific pollutants, and other physiochemical properties of the environment (see ▶ Section 7.5.1, Chapter 7).

Mitigating Inputs from Agriculture

Agricultural activities in coastal catchments create diffuse sources of eroded soils, nutrients and pesticides that are delivered to the marine environment (Chapters 4 and 6). Management actions to mitigate inputs from agriculture have had scalability issues and sometimes limited results (e.g. Cook et al. 2013; Creighton et al. 2021; Waltham et al. 2021). However, it is important to note that mitigating activities may take several years to show measurable differences in inputs at the catchment scale (e.g. Star et al. 2018) and groundwater transport of pollutants to the ocean needs to be considered in the pathways of inputs (e.g. Carroll et al. 2021). ▶ Box 15.1 shows an example of a long-term water quality improvement plan for the Great Barrier Reef, Australia, to mitigate the effects of land-based human activities including agriculture.

Diffuse nutrient runoff from agriculture can be managed directly through best practice farm management including a reduction in fertiliser use and by using tools such as cover crops (e.g. Vilas et al. 2022). However, the elimination of fertilisers is a highly unlikely proposition. Therefore, treating drainage water before it enters river systems and the ocean is an important mitigation strategy. There are several approaches used to reduce the nutrient loading in drainage water including constructed wetlands, water retention ponds, denitrifying bioreactors, riparian buffer zones and/or a combination of these. Some approaches capture the benefits that ecosystem services offer for nutrient uptake and storage (e.g. Carstensen et al. 2020; Hsu et al. 2021). Constructed wetlands and riparian buffer zones also provide biodiversity values and are forms of ecosystem restoration in their own right.

In situations where the sources are difficult to manage (e.g. low lying, low-productivity land as a source of dissolved inorganic nitrogen) land-use conversion may be appropriate (Waltham et al. 2021). Land-use conversion may include support to farmers for developing alternative crops and grazing, aquaculture opportunities or forestry, or may require buy-back to reinstate natural vegetation (Waltham et al. 2021).

The selection of the approach or combination of approaches used requires stakeholder involvement, cost benefit assessment, and consideration of the local geographical and climatic conditions including the integration of future changes such as climate and land use (e.g. Carstensen et al. 2020).

Box 15.1: Reef 2050 Water Quality Improvement Plan—A Mitigation Strategy

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The Great Barrier Reef (GBR) is the world's largest reef running for over 2500 km along the east coast of Queensland, Australia. It is under threat from a range of stressors including: climate change; coral bleaching; crown of thorn starfish outbreaks; commercial and recreational fishing; mining; urban development; commercial and recreational shipping; agriculture and the quality of water entering the GBR lagoon. In terms of water quality, suspended solids from soil erosion, nutrients (nitrogen and phosphorus) and pesticides have been identified as the key pollutants. These pollutants all originate from land-based human activities and are predominantly transported to the lagoon via surface and ground-

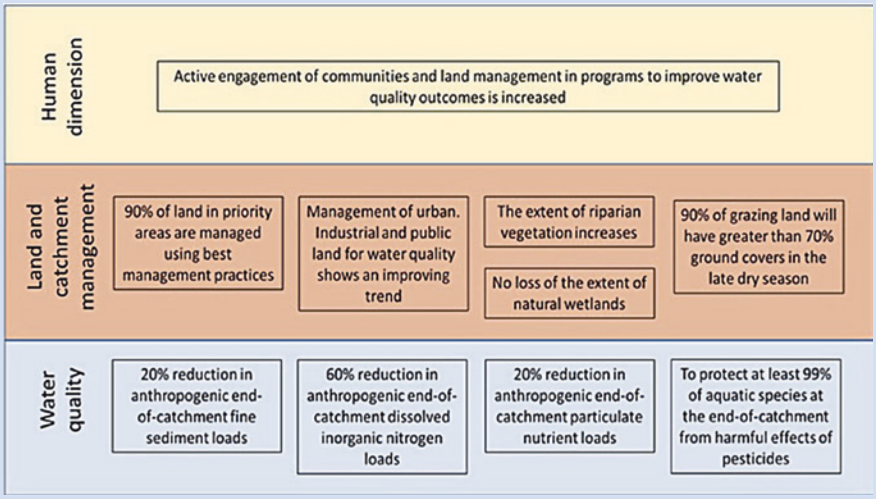

Figure 15.1 ► Box 15.1: The targets in the reef 2050 water quality improvement plan. Adapted from AGQG, 2018 by M St. J. Warne

water. To address this, the Australian and Queensland governments developed a series of plans to improve the quality of water entering the lagoon and thus improve the health and resilience of the reef—these can be considered mitigation strategies. The current plan is the Reef 2050 Water Quality Improvement Plan 2017–2022 (► https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0017/46115/reef-2050-water-quality-improvement-plan-2017-22.pdf) and a new plan will be released in 2023. The underpinning assumption of these plans is that by reducing the ecological stress from poor water quality the overall stress will decrease and the reef ecosystems will have a greater ability to deal with other stressors including climate change.

Each water quality improvement plan has had a series of targets that aim to improve water quality and land management practices. The targets have been modified in the plans to reflect improved scientific knowledge of what is required to increase the health and resilience of the reef. The current targets are presented in Figure 15.1 and the aim is that they should be met by 2025.

The Paddock to Reef (P2R) Integrated Monitoring, Modelling and Reporting Program was developed to implement the plans. The P2R uses an adaptive management approach (also termed a Monitoring, Evaluation, Reporting and Improving (MERI) framework) to drive progress towards meeting the targets. Monitoring is done on land, in waterways and in the GBR lagoon. As the magnitude of the pollutant loads (mass) are highly correlated to climate, Source Catchments Models are used to remove the climatic signal and to estimate annual progress towards meeting the water quality targets. Progress to meeting the targets and the current ecological condition of the GBR is summarised and presented in the semi-annual Reef Water Quality Report Card (► https://reportcard.reefplan.qld.gov.au/home?report=condition%year=611f443aba3074128316eb07).

Figure 15.2 ► Box 15.1: The reported inshore conditions of the GBR ecosystems in 2020. Condition ranges from A—very good to E—very poor. D is poor condition. *Source*: Queensland Government CC BY 4.0

Research conducted since the previous Water Quality Improvement Plan is synthesised approximately every five years in the Reef Scientific Consensus Statement which is then combined with the results of the Reef Report Card (e.g. Figure 15.2) and other information to determine the targets in the next Water Quality Improvement Plan.

Until recently the governments have been encouraging adoption of Best Management Practices and have co-invested (50:50) with farmers to purchase improved equipment (e.g. hooded spraying rigs) or infrastructure (e.g. water retention ponds or artificial wetlands). But recently the Queensland Government has introduced mandatory measures to drive further improvement of land management practices—the Reef Protection Regulations which address the issue of fine suspended solids and dissolved inorganic nitrogen.

Mitigating Inputs from Urban Stormwater

Rainwater water is often captured in stormwater drainage infrastructure, particularly in heavily populated urban environments with hard surfaces and limited permeability. Urban stormwater may also be a diffuse source of pollution to the ocean, through infiltration and groundwater movement and surface runoff.

Various solutions have been developed to mitigate stormwater from urban areas carrying pollutants to estuaries and marine waters. These tools have different names around the world; Water Sensitive Urban Design (WSUD) in Australia and the United Kingdom, Low Impact Development (LID) in Canada and the USA, Nature-Based Solutions in the EU and Sponge Cities in China (Zhang et al. 2020). These systems are usually effective in removing various pollutants from stormwater, and some jurisdictions have regulations that require their installation as part of infrastructure development (e.g. New South Wales, Australia; State Environmental Planning Policy (Building Sustainability Index: BASIX 2004). Furthermore, stormwater management has additional benefits such as flood mitigation, microclimate improvement, improvement in the amenity values in urban landscapes and harvested stormwater can be a valuable water resource (Zhang et al. 2020 and references therein).

Mitigating Inputs from Municipal and Industrial Wastewater

Sewage and industrial wastewater **discharges** are complex mixtures including organic compounds (Chapters 8 and 12), inorganic compounds (▶ Chapter 5) and microplastics (▶ Chapter 9) (e.g. Mintenig et al. 2016; Prata 2018; Schernewski et al. 2020; Sridharan et al. 2021). There are excellent technologies through large- and small-scale treatment facilities to reduce the flow of chemicals to the environment. Such facilities are often legally required for developments and activities, particularly in countries with developed economies. As with all infrastructure these facilities need to be maintained since leaking and broken pipes can be a source of contaminants through groundwater inputs. Furthermore, suboptimal treatment can be caused by exceeding capacity of built infrastructure (e.g. when an urban population increases more rapidly than infrastructure updates) or poorly operating facilities.

According to the United Nations (2017), about 70% of the municipal and industrial wastewater generated by high-income countries is treated. In upper middle-income countries and lower middle-income countries that ratio drops to 38% and 28%, respectively. In low-income countries, only 8% is treated in anyway. Globally, 80% of wastewater is discharged untreated (UN 2017). Where there is limited use of treatment facilities, it is often related to a lack of financial resources (◘ Figure 15.3). The United Nations Sustainable Development Goals highlight the importance of clean water and sanitation (Goal 6) and life below the water (Goal 14) and may potentially be drawn upon to invoke action to upgrade and deliver municipal services in developing economics and reduce wastewater discharges to the marine environment.

◘ **Figure 15.3** Waterways carry waste through cities to the ocean. Open drains, like the one pictured, are often used to dispose of unwanted wastes and no treatment occurs before the waterways reach the ocean. *Photo* A. Reichelt-Brushett

15.6 Marine Habitat Restoration

Keystone and foundation species are essential for particular types of ecosystem structure. These species may be plants (e.g. mangroves) or animals (e.g. scleractinain corals) and we often name ecosystems after their keystone species. In essence, without these species present the ecosystems do not function. Indeed, marine ecosystem restoration attracts large amounts of funding. In the USA many coastal and marine habitat projects are funded by NOAA with an annual budget of around US$10 million (2019) that is distributed through a competitive grant submission process. In this section of the chapter, some types of marine habitat restoration are discussed. Restoration projects can be developed with basic tools and good knowledge of the ecosystem requirements but at times engineering and technology can support and enhance restoration outcomes.

15.6.1 Oyster Reefs

Oyster reefs and beds may be intertidal or subtidal biogenic structures formed by oysters living at high densities and building a habitat with significant surface complexity (Baggett et al. 2014 and references therein). Historically, most oyster restoration efforts focused on the recovery of oyster fisheries and mitigating losses from natural and anthropogenic effects. More recently there has been recognition of the **valuable ecosystem services** provided by oyster beds such as water biofiltration, benthic habitat for biodiversity (e.g. for epibenthic invertebrates), nutrient sequestration, shoreline stabilisation and enhanced secondary production (Baggett et al. 2014). Many of these values are now included in the goals of restoration projects (Baggett et al. 2014 and references therein). According to Bayraktarov et al. (2016), harvest sanctuaries and transplanting juvenile oysters from hatcheries achieve positive results. An example of a large-scale oyster reef restoration project is the Billion Oyster Project in New York Harbour (▶ https://www.billionoysterproject.org/) and smaller scale work includes Lau Fau Shan and Tolo Harbour in Hong Kong (▶ https://www.tnc.org.hk/en-hk/what-we-do/hong-kong-projects/oyster-restoration/). However, oyster bed restoration projects still have limited monitoring, even in well-known projects like in Chesapeake Bay, USA, monitoring from 1990 to 2007 was limited and project goals were not well defined (e.g. Kennedy et al. 2011). This omission has reduced adaptive management and development of standard methodologies.

The *Oyster Habitat Restoration-Monitoring and Assessment Handbook* by Baggett et al. (2014) was produced to address the shortfall of previous programs and to support programs to demonstrate successful outcomes. The handbook provides standard techniques (named Universal Metrics) that can be used for comparisons among sites and to help develop performance criteria. This focus on monitoring and assessment enables an understanding of the basic project performance and how the performance meets ecosystem services-based restoration goals (Baggett et al. 2014).

More recently, enhanced approaches are being considered to include, **focused site selection**, potential use of **artificial substrates**, and **oyster species and selection of genotypes** for seeding to support oyster survival and delivery of ecosystem services (Howie and Bishop 2021; Pollack et al. 2021). The consideration of the most suitable growth form is important because it influences ecosystem service delivery (Howie and Bishop 2021); however, trade-offs might be required depending on the goals (e.g. high elevation reefs are most effective at attenuating waves) (Hogan and Reidenbach 2022). Furthermore, oyster species and genotypes should be selected according to their environmental suitability, resilience to environmental change, and the size and shape of reefs they form (which influences ecosystem services) (Howie and Bishop 2021) (▶ Box 15.2). Choosing stock from aquaculture or wild populations also needs to be a key consideration and will sometimes depend on availability.

Box 15.2: Assess Before you Invest: The Need for Careful Site Selection in Shellfish Reef Restoration

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It is estimated that over 85% of oyster reef ecosystems have been lost globally (Beck et al. 2011; Ford et al. 2016), due to a range of human activities including unsustainable harvest, destructive trawling and bottom dredging, increased sedimentation from clearing of riparian vegetation, decreased water quality and disease. Oyster reefs were once extensive in many estuaries, but are now reduced to remnant reef areas or in some cases are considered functionally extinct (Beck et al. 2011; Ford et al. 2016; Gillies et al. 2018). However, oysters are being increasingly recognised as ecosystem engineers that play an integral role in benthic-pelagic coupling, water clarification, carbon sequestration, habitat provision for invertebrates, fish and algae, and the protection of shorelines (Coen et al. 2007; Grabowski et al. 2012). This has triggered significant efforts to restore degraded oyster reef habitats at key locations, in at least seven countries (Fitzsimons et al. 2020).

Figure 15.4 ▶ Box 15.2 Leaf oyster reefs provide good habitat to other invertebrates and fish (left) and can improve water quality as part of an active catchment management plan. When in decline due to significant runoff from intensive agriculture, with pesticides, high sediment and nutrient loads smothering by algae growth but can occur (right). *Photos*: K. Benkendorff

Restoring oyster reefs on the scale required to recover ecosystem services requires significant infrastructure and financial investment. The return on investment for oyster restoration has been shown to vary widely but tends to increase with the scale of the project (Bersoza Hernández et al. 2018). Consequently, the first stage in oyster reefs restoration programs must be to undertake a thorough assessment of the proposed location and develop a feasibility plan (Fitzsimons et al. 2020). It is essential that the causes of the original decline are well understood and effectively mitigated. Persistent problems with water quality, pollutants and sedimentation will cause chronic stress, reducing the resilience of oysters and increasing the likelihood of disease and mortality. Unfortunately, habitat suitability indexes for oyster restoration (Theuerkauf and Lipcius 2016) don't consider water quality beyond the basic physicochemical parameters or the surrounding land use practices that influence the likelihood of ongoing exposure to aquatic pollution. A catchment wide assessment is required to determine the likelihood of chronic exposure to contaminants, such as pesticides that are known to impact oyster health (e.g. Ewere et al. 2020).

For biosecurity reasons, the use of local species is also essential for oyster reef restoration. Oysters sourced from near-by populations are also more likely to have adapted to the local conditions. We have been investigating the potential for including the large reef-forming leaf oyster *Isognomon ephippium* (Figure 15.4) in oyster reef restoration programs (Benthotage et al. 2020). These leaf oysters occur in slow moving estuarine creeks and bays often covered in silt. We have recorded populations in areas with high agricultural nutrient runoff and fluctuating pH reaching as low as 5 from acid sulphate soil runoff. However, these are long lived oysters and some populations appear to be in decline. Further research is required to understand the tolerance range of these and other oysters and match these to environmental conditions at locations proposed for oyster reef restoration. In some cases, a whole of catchment approach will be required to manage terrestrial runoff to ensure the future viability of oyster reefs and their inherent ecological value.

15.6.2 Coral Reefs

Coral reef degradation results from many different stressors, some of which are caused by polluting substances such as nutrients (▶ Chapter 4), metals (▶ Chapter 5), pesticides (▶ Chapter 7), sedimentation (▶ Chapter 12) and atmospheric gases (▶ Chapter 11). Other stressors such as coastal development, over harvesting, destructive fishing, invasive species, outbreaks of predatory organisms such as Crown of Thorns Starfish (▶ Chapter 4), prolonged elevated water temperatures leading to coral bleaching and impacts from recreational activity need to be included in mitigation strategies as there may be a multitude of stressors to address at any one site (Pandolfi et al. 2003). As with all restoration projects the removal of the stressors is a key mitigation step required at the very first stage of restoration. As discussed, catchment management and sewage treatment can help remove polluting impacts such as sedimentation and chemical loads. Mitigating effects of anthropogenic temperature change and ocean acidification are more challenging undertakings and may require specific interventions such as assisted evolution (van Oppen et al. 2017). Considerations of **socio-economic contexts** are required to optimise recovery (Gouezo et al. 2021). Restoration of coral reefs has not yet resulted in fully functional reefs but some success has occurred on the scale of up to a few hectares (Edwards and Gomez 2007). The field of coral reef restoration has advanced rapidly over the past 10–15 years and continues to evolve.

Coral transplantation has been used in coral reef restoration efforts for many years (e.g. Ferse et al. 2021). In this method fragments of coral are taken from donor reefs and secured at the restoration sites. This

Figure 15.5 Small coral transplants are taken from donor reefs and attached mid water to enable grow out before transplanting to restoration sites. *Photo*: "Coral nursery, Coral Restoration Foundation" by kareneglover CC BY-NC 2.0

strategy creates impacts at donor reefs. To help mitigate these impacts sometimes these donor colonies are taken as small fragments and then used in coral gardening or coral farming which provides more space to grow up colonies in mid water (Figure 15.5) or in benthic gardens before use at the restoration site (e.g. Feliciano et al. 2018). Other programs have **grown corals from** spawning **in laboratory conditions and out-planted the juveniles** (Guest et al. 2014; Bayraktarov et al. 2016). More recently collection of gametes from wild coral spawning events has been successfully trialled, with larvae reared in the laboratory or in floating larval pools on reefs (Harrison et al. 2021). The approximately 5-day old larvae (that are ready to settle) are then distributed by various methods directly onto target reef areas. This process is known as mass larval settlement (dela Cruz and Harrison 2017; Harrison et al. 2021) (▶ Box 15.3). By **collecting slicks of broadcast** spawning **corals** many millions of potential recruits, that in natural conditions would not survive, are utilised. This approach takes the pressure off donor reefs that occurs with transplantation and coral gardening.

Coral genotypes that can survive extreme conditions including temperature and pH anomalies may be used as sources for selective breeding to support assisted evolution and focus recruitment strategies (van Oppen et al. 2017; Basconi et al. 2020; Rinkevich 2021). These techniques are evolving rapidly.

Box 15.3: Scaling up Coral Restoration for Reef Recovery

Professor Peter Harrison and Dr. Dexter dela Cruz, Coral Reef Ecologists.
Marine Ecology Research Centre, Southern Cross University, Australia.
Accelerating loss of foundation reef corals in most reef regions around the world is impairing the natural resilience of coral communities and resulting in reef degradation (Burke et al. 2011). Consequently, increasing attention is being focused on active coral restoration interventions on degraded but recoverable reef areas where the previous impacts and immediate threats are being managed (Harrison et al. 2021). Reef corals have two primary modes of reproduction in their life cycles: **asexual** budding of genetically identical polyps to create complex colonies or solitary individuals, and in some cases growth forms that enable breakage and fragmentation of colonies to produce new corals; and **sexual** reproduction involving broadcast spawning or gametes and planktonic larval development, or internal brooding of larvae that are released at an advanced stage of development (Harrison and Wallace 1990). These two modes of coral reproduction have enabled the development of two different approaches to coral restoration using asexual fragmentation and cloning, or sexual production of millions of coral larvae for settlement on degraded reefs.

Figure 15.6 ▶ Box 15.3: Asexual fragmentation and coral gardening enhanced coral recovery at smaller scales in the Philippines. *Photo*: D. dela Cruz

Coral fragmentation and production of genetically identical colonies with subsequent direct transplantation on the reef has been the most common asexual method for restoration (Figure 15.6). The methods have been refined to include an intermediate nursery phase to produce larger quantity of nubbins and reduce the high rates of mortality of coral fragments during the early phase of outplanting onto reefs (Rinkevich 1995; Shaish et al. 2008; Edwards 2010). Advantages of fragmentation, coral gardening and outplanting approaches include relatively simple training and engagement of diverse stakeholder groups, varied approaches for different reef environments, rapid increases in coral colonies and cover on degraded reefs, and potential for healthy fragments to grow quickly if environmental conditions on the reef are still suitable (Young et al. 2012; dela Cruz et al. 2014; Omori 2019; Howlett et al. 2021). Disadvantages of asexual propagation include damage to healthy parent donor colonies, increased diseases from damaged tissues, low genetic diversity among coral colonies from few parental genotypes leading to low resilience to different stressors such as temperature stress and mass bleaching events, and high costs associated with manual collection and outplanting on reefs plus increased costs from establishing and maintaining coral nurseries (Edwards 2010; Bostrom-Einarsson et al. 2020). Consequently, coral gardening approaches are considered to be relatively expensive and more suitable for smaller-scale restoration projects such as increasing coral cover on damaged high value reef patches important for tourism (Bostrom-Einarsson et al. 2020; Howlett et al. 2021).

In contrast, sexual propagation promotes increased genetic diversity of restored coral populations and communities. The production of genetically diverse larvae from cross-fertilisation of eggs and sperm from many different colonies, increases the potential for rapid evolution of heat-tolerance and other traits that may enhance survival and resilience in rapidly changing reef environments (Baums 2008; Harrison et al. 2016, 2021; Randall et al. 2020). However, most corals are broadcast-spawners characterised by high production of gametes but low survival and settlement of planktonic larvae coupled with high post-settlement mortality during early life stages, which can create a bottleneck in reproductive success (Harrison 2011, 2021; Randall et al. 2020). Studies have used sexual larval propagation methods and two main approaches have been trialled. First, larvae can be cultured in tanks and settled onto tiles and other devices and reared in laboratory hatchery systems or in in-situ nurseries prior to outplanting on reefs (Guest et al. 2014; Chamberland et al. 2017). Alternatively, larvae can be directly settled ('seeded') onto reef areas with or without the use of larval mesh enclosures (Heyward et al. 2002; Edwards et al. 2015; dela Cruz and Harrison 2017; 2020; Harrison et al. 2021). Larval settlement onto tiles and devices and laboratory nursery rearing has some advantages. It reduces post-settlement Mortality, but significantly increases production costs per coral (Guest et al. 2014), and may select for genotypes that are maladapted to degraded reef environments. In contrast, mass larval production and direct larval settlement on degraded reefs is more cost-efficient and can produce breeding populations within two to three years (dela Cruz and Harrison 2017; Harrison et al. 2021) (Figure 15.7). However, post-settlement survival can be low during the first few weeks and months after settlement due to strong selective pressures operating in degraded reef environments (dela Cruz and Harrison 2017, 2020).

Reef restoration activities and methods are now rapidly expanding in many regions and include innovative approaches to increase scales of larval production and reproductive success across many stages of the coral life cycle. Re-

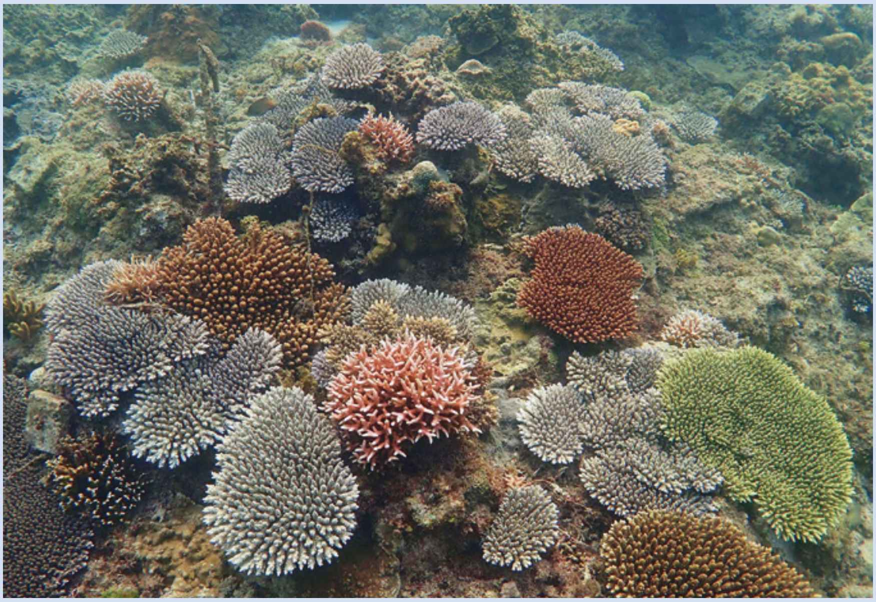

Figure 15.7 ► Box 15.3 Mass supply of branching *Acropora tenuis* coral larvae significantly increased coral cover and restored breeding populations within a few years on badly degraded reef systems in the Philippines. *Photo*: P. Harrison

cent developments include direct capture of large spawn slicks from surviving healthy corals using floating spawn catchers and mass culture of many millions of larvae in floating pools moored on reefs (Harrison et al. 2021), hybridisation to enhance environmental tolerance and climate resilience (van Oppen et al. 2017; Chan et al. 2018), cryopreservation of gametes and artificial breeding for assisted gene flow (Daly et al. 2022), and selective breeding and provision and uptake of heat-tolerant Symbiodiniaceae microalgal symbionts and the use of probiotics (van Oppen et al. 2017; Quigley et al. 2020). These sexual propagation approaches and combination of culture techniques have great potential for massively increasing the scale and success of coral restoration to enable the recovery of degraded coral communities and reef systems around the world, but reef restoration will only be successful in the longer-term if effective action is taken to reduce global greenhouse gas emissions and global warming.

15.6.2 Seagrasses

Seagrasses are submerged vascular plants known to support marine biodiversity with an historic total global cover of 171,000 km^2 (Green and Short 2003). Human population expansion has been considered the most serious cause of seagrass habitat loss particularly increasing contaminant inputs to the coastal oceans (Short and Wyllie-Echeverria 1996; Zenone et al. 2021). Efforts at restoration have occurred in Australia, Florida, India, Indonesia, Italy, Sweden and New Zealand (Nadiarti et al. 2021 and citations there in) and probably in other areas too that have more limited reporting. Early restoration projects occurred in Florida in the 1980s and the resource value of seagrasses was well recognised before then (Fonseca et al. 1996 and references therein). Unfortunately, global seagrass loss has been dramatic and was estimated at about 7% a year in 2009 (Waycott et al. 2009).

Well restored seagrass sites have shown longevity for many decades in both tropical and subtropical areas (Thorhaug et al. 2020). Data that can show such long-term success is a testament to well-planned restoration programs and continued funding for monitoring and on-going restoration work to counter effects from extreme weather events. However, data documenting restored ecosystem services have not been collected consistently and frequently enough to provide marine resource managers with hard data as to the ecosystem services returned, except in the Atlantic USA where fisheries food webs and carbon sequestration assessment were included in monitoring (Thorhaug et al. 2020).

The highest survival of seagrass in restoration projects used a range of techniques including transplantation of seedlings, sprigs, shoots and rhizomes (Bayraktarov et al. 2016) with methodologies and success somewhat dependant on location and species used (e.g. *Zostera marina* the most commonly transplanted species in temperate regions) (see also Thorhaug et al. 2020). However, reduced genetic diversity has been identified in planted seagrass beds compared to natural ones (Williams and Davis 1996) and this could lead to longer term vulnerabilities.

15.6.3 Mangroves

Global mangrove forest cover is an estimated 84,000 km^2 spread across 105 countries (Hamilton and Casey 2016). **Deforestation** is one of the main causes of mangrove loss, however, they exist in depositional environments acting as traps for fine particles, organic matter and associated chemical and physical pollutants (see Chapters 5 and 6). For this reason, restoration projects must consider the site contamination and risk of pollutants to diversity and structure. The main reasons for restoring mangrove ecosystems include conservation and landscaping, economic security, food security and coastal protection (Field 1998).

Mangrove restoration can be conducted relatively cheaply and easily and is **arguably the most established marine ecosystem restoration activity**. It is relatively easy to engage community groups in planting programs and this gains similar community engagement to tree planting programs on land (◘ Figure 15.8). Most mangrove restoration projects that achieve high survival rates include facilitation of natural recovery by planting of seeds, seedlings and propagules, investment in the planting of saplings and small trees, hydrological restoration and weed management (Bayraktarov et al. 2016).

Since 1965 Singapore has lost > 90% of its mangrove forest and attempts to restore these have had limited success (Ellison et al. 2020). However, some sites of Mangrove rehabilitation in Singapore have provided new knowledge on how to enhance ecological diversity and ecosystem services in an urbanised coastal setting. For example, the Pulau Tekong hybrid engineering project demonstrated how mangrove vegetation can be incorporated into engineered coastal defence structures (Friess 2017) and highlighted the value of multiple species plantings and matching species traits to prevailing environmental conditions (e.g. Field 1998).

Mangrove forests also sequester carbon (blue carbon) (see ► Chapter 11). However, estimates of above ground and underground carbon storage are variable between studies and depend upon different scenarios (e.g. Moritsch et al. 2021). More research is required to understand long-term carbon storage potential.

15.6.4 Saltmarsh

Saltmarsh are found in 99 countries throughout the world (particularly mid and high latitudes and) in the **upper tidal limits of lower estuaries** (Mcowen et al. 2017). The saltmarsh environment is harsh, as the community is exposed to extreme salinity, desiccation, and tidal flooding. For this reason, saltmarsh plants are known as halophytes with specialised adaptations to grow in salty conditions. **Micro-elevation and the tidal inundation** regime strongly influence the gradation between saltmarsh (on the landward side) and mangroves (to the water side) (Adam 2000; Green et al. 2009a). Saltmarsh require fewer tidal inundations per year compared to mangroves. The species composition is mostly contributed to by plants, but fauna groups consist of terrestrial species (e.g. birds, and bats) and aquatic species (e.g. fish, molluscs and crustaceans), with some being specialized salt marsh dwellers (Laegdsgaard 2006). The most conspicuous invertebrate fauna in saltmarshes are crustaceans and molluscs and in a comprehensive study of 65 saltmarshes around Tasmania, Australia, Richardson et al. (1997) found over 50 species.

◘ **Figure 15.8** Community collaborations can be small scale. This site is near Pattimura University (Ambon, Maluku, Indonesia) will be monitored over time by students. This collaboration was between staff and students of Southern Cross University and the University of Pattimura (led by Y. Male), **a** the site prior to any activity, **b** litter removal, **c** planting mangrove seedlings and **d** celebration of working together for positive environmental outcomes. *Photos*: A. Reichelt-Brushett

Saltmarsh habitats have been degraded in the past due to their lack of perceived value and usefulness, being disregarded and used as illegal dump sites, off-road motorbiking and four-wheel driving as well as being at risk from the encroachment of urban, industrial, and agricultural development and localised runoff (e.g. Bucher and Saenger 1991; Green et al. 2009a) (► Box 15.4). Furthermore, they are vulnerable to floating pollutants such as oil and plastics that are transported and deposited through tidal inundations. Today saltmarshes are valued ecological communities providing fish feeding habitat during flood tides, carbon sequestration, coastal protection and other ecological services (Mcowen et al. 2017). In some countries, they are protected habitats.

Actions such as fencing to remove cattle and recreational vehicles from saltmarsh areas, diversion of stormwater and weed removal are the most common first steps in rehabilitation for saltmarsh. Large-scale saltmarsh restoration projects have been undertaken in North America since the late 1980s (e.g. Sinicrope et al. 1990; Fell et al. 1991; Frenkel and Morlan 1991). In Australia, saltmarsh restoration occurred at the Sydney Olympic Park among other sites in the late 1990s and related research improved knowledge of germination and establishment of saltmarsh species (Burchett et al. 1998; Laegdsgaard 2006).

Box 15.4: Case Study: Fingal Wetland Rehabilitation Project, New South Wales, Australia

Dr. Joanne Green, Restoration Ecologist.

The aim of the Fingal Wetland Rehabilitation Project was to reverse ongoing degradation of a saltmarsh area due to sand mining, exotic weeds, rubbish dumping (including old cars and trail bikes (▣ Figure 15.9)) and four-wheel drive recreational activity. The project encompassed an agreement between Tweed Shire Council and the Tweed Byron Local Aboriginal Land Council, plus an initiative developed by Wetland Care Australia with assistance from NSW Fisheries and The Fish Unlimited Project (funded by Federal Government through the Sustainable Regions Program). The area was characterised by fragmented patches of remnant saltmarsh dominated by three plant species, Saltcouch (*Sporobolus virginicus*), Sea Blite (*Suaeda australis*) and Samphire (*Sarcocornia quinqueflora*).

After the removal of cars and other rubbish, the natural topography was restored by connecting the patches of remnant saltmarsh with suitable fill and allowing natural regeneration to occur. Surface sediments were stripped back so the topsoil could be used to inoculate the new surface thus providing a source of silt, nutrients and the micro-fauna assemblages that were already occupying this niche. Saltcouch was also planted at low tide using 1 m quadrats made of PVC conduit. The conduit quadrats allowed accurate spacing and layout across the site for maximum use of donor material and future counting of success.

An associated research program (Green et al. 2009a, b; Green et al. 2010) measured changes in the soil carbon, algae first colonisers, plant coverage and invertebrate colonisation for several years after restoration work. Variables measured included soil moisture, pH, electrical conductivity, Total Organic Carbon and Total Nitrogen. Other measurements included soil algal abundances (Chlorophyll *a*), diatom abundance, and flora and fauna colonisation. Chlo-

▣ Figure 15.9 ► Box 15.4 Cars removed from the Fingal Wetland Rehabilitation site prior the restoration works. *Photo*: T. Alletson rophyll *a* results showed that the restored saltmarsh sites were progressing towards, but were not equivalent to, the reference site two years after restoration despite the fast growth rates of algae and its role as a primary coloniser. The analyses of variables showed that solar radiation, rainfall and tidal inundation were influential to micro algal growth. Measurements of the flora and fauna at restoration sites showed that the sites were moving towards a saltmarsh ecosystem but climatic conditions can affect short-term measures. For this reason, seasonal and longer term sampling is recommended.

The project success to date is the result of strong collaboration between all the stakeholders with a focus on a common goal: the removal of threatening processes and the restoration of the saltmarsh vegetation. The ongoing commitment by the project partners culminated in a successful grant from the NSW Government Environmental Trust to undertake additional works in the area.

15.6.5 Engineering, Technology and Marine Ecosystem Restoration

Artificial habitats are sometimes developed using science and engineering technologies to support restoration. An artificial reef is "*a submerged structure placed on the seafloor deliberately to mimic some characteristics of a natural reef*" (OSPAR 1999). Seaman (2007) highlighted the use of artificial structures in restoration projects in four case studies: kelp beds (California, USA), coral reefs (Florida, USA), oyster beds (Chesapeake Bay, USA), fisheries populations (Hong Kong, China). Engineering and technology are being used in multidisciplinary approaches to ecological restoration and collaborations help to support innovation (NRC 1994), some examples include

- ecological engineering and augmented evolution for coral resilience to climate change (e.g. van Oppen et al. 2017; Rinkevich 2021);
- cathodically protected steel mats to replace plastic for reseeding oyster reefs (Hunsucker et al. 2021);
- sustainable cementitious composite substrate for oyster reef restoration using recycled oyster shells and low cement content (Uddin et al. 2021);
- development of a lattice structure made out of a biodegradable potato starch to support seagrass restoration (MacDonnell et al. 2022); and
- biodegradation of micro- and nano-plastics in liquid and solid waste (Zhou et al. 2022).

Successful engineering and technology solutions will likely result when biotic needs are strongly connecting with engineering and technology solutions in a feasible and cost effects manner.

15.7 Marine Species as Bioremediators

Another angle of environment improvement and contaminant removal from the environment includes bioremediation activities. The process is similar to land-based phytoremediation and other bioremediation research except using marine species. Clearly, there are ecosystems service provisions that help to mitigate pollution, such as water quality improvement from oyster beds, but there is also targeted research on particular species. Brown marine algae (*Sargassum natans* and *Fucus vesiculosus* and *Turbinaria ornata*) and green algae (*Cladophora fascicularis*, *Enteromorpha prolifera* and *Ulva reticulata*) show promising bio-sorbant properties for some metals (Brinza et al. 2007; Mudhoo et al. 2012 and references there in; Areco et al. 2021). Marine diatoms can play a role in the degradation, speciation and detoxification of chemical wastes and hazardous metals using mechanisms both external to the cell and internally (Marella et al. 2020). Marine bacteria show promise in helping to develop biotechnology for ocean clean-up of metal contaminants (Fulke et al. 2020) and plastics (Jenkins et al. 2019; Wei and Wierckx 2021). These developments provide an exciting field of discovery that focuses on environmental remediation.

15.8 Summary

There are numerous important ecological habitats in marine environments and many have been impacted by human activities, including pollution. Marine ecosystem restoration has been gaining increasing attention since the 1990s and those ecosystems that have had committed restoration works include **coral reefs**, **seagrasses**, **mangroves**, **macroalgae forests**, **saltmarshes** and **oyster reefs**. Each of these requires specific conditions for habitats to thrive and discussion and examples are provided.

Mitigating pollution and other stressors is an important first step in ecological restoration and may take several years to achieve measurable improvements, particularly for diffuse source inputs such as agricultural activities. It is important to follow the major principles of successful ecological restoration explained in ◘ Table 15.1. ▶ Section 15.5 describes important pollution mitigation practices and highlights the importance of mitigating land-based sources of stressors including nutrients, metals, pesticides, and turbidity. Other human activities such as shipping and infrastructure development also create stressors such as oil spills and noise as well as acting as vectors for invasive species.

Engineering and technology solutions play a developing role in marine pollution mitigation and ecosystems restoration activities.

15.9 Study Questions and Activities

1. Describe ecological restoration in your own words.
2. Create a table that highlights ecosystem features and considerations for successful coral reef, seagrass, salt marsh, mangroves and oyster reef restoration. If you think you have done a great job, send it to the editor and we may discuss including it in the next edition of this book.
3. Select one of the types of pollutants shown in ▣ Table 15.3 and expand on the mitigation strategies through literature searches of your own.
4. Consider the United Nations Sustainability Goals and discuss how they may be used to invoke action to upgrade and delivery municipal services in developing economies and reduce wastewater discharges to the marine environment.

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