Chapter 2
Coral Reefs and Blue Economy

M. F. M. Fairoz

Abstract Coral reef ecosystems are rich in biodiversity, providing a variety of services and products relevant to blue economy that include sectors such as tourism, fisheries, biotechnology/bioprospecting, and coastal protection. Almost half a billion people, 8% of the total global population, live within 100 km of a coral reef and about 100 developing countries are highly dependent on coral reefs for their livelihoods. However, the health of coral reefs is at risk. Reefs are severely affected by ocean warming and acidification as well as land- and sea-based human activities that lead to coral disease and destruction of reef habitat. This chapter addresses aspects of coral reef ecosystems that are critical for their contribution to sustainable blue economies. The chapter discusses the structure and function of coral reefs, their current distributions, the threats they experience and their potential impact as a blue economy resource. The chapter then discusses necessary measures to detect, monitor, and reduce the adverse impacts, as well as the available science and technologies to monitor reefs. Finally, the chapter provides information about ongoing international efforts on reef research and monitoring, and the application of state-of-the-art tools that might be of interest to countries developing blue economies.

Keywords Coral reefs · Structure · Symbiosis · Bleaching · Threats · Research and monitoring · Ocean acidification

2.1 Introduction

Coral reefs cover about 1 million square kilometers (km^2) of Earth's surface. They are built by coral organisms producing their own mineral substrates, with thousands of different species living in coral ecosystems. Coral reefs are comparable with tropical rain forests in terms of their high levels of biodiversity and complexity of their ecosystems. They are also among the most productive ecosystems, in terms of

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gross organic production (Odum and Odum 1955; Lewis 1977; Birkeland 1983) and are often an oasis of life in otherwise rather barren tropical marine environments (Gove et al. 2016). Beside their ecological value, coral reefs are of major economic, social and cultural importance to the countries they border (Cesar 2000). Almost half a billion people, 8% of the total global population, live within 100 km of a coral reef and about 100 developing countries are highly dependent on coral reefs for their livelihoods.

A large number of studies have estimated the economic value of healthy coral reefs (e.g., Brander et al. 2012), which come from a variety of renewable resources that can be harvested (subsistence, commercial and recreational fishing) from reef areas, and services provided by reefs, including recreational opportunities (e.g., skin diving and SCUBA, enjoying aesthetic values), tourist development (hotels, vacation rentals), coastal protection provided by intact reef structures (Sheppard et al. 2005), and cultural value of reefs to local populations. Brander et al. (2012) compiled 160 separate reef valuation studies and used 45 of these to conduct a meta-analysis of reef value. The studies included in the analysis used a variety of common valuation methods. Brander et al. (2012) predicted (through modeling) a loss of 16–27% of global coral reef area under different IPCC scenarios available at that time. They estimated an annual loss of $870 billion in 2100 under the IPCC scenario A1 ("a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies"). However, these figures could be an over-estimate, as they do not consider the capacity of human populations to adapt, particularly if the ecosystem changes happen gradually (Hoegh-Guldberg et al. 2019).

This chapter gives a brief overview of reef ecosystems in relation to their role in blue economies and outlines the latest developments in coral reef monitoring and research technologies against the background of current scientific research, which is integral to the successful conservation and management of reef areas.

2.2 Structure, Taxonomy

Coral reefs are calcium carbonate features, precipitated by individual animals (polyps) (Fig. 2.1), that form large colonies that make up the three-dimensional structure of a reef. It is this structure that protects fragile fauna from being preyed on and also forms a fortress that defends reef biota against the destructive action of hydraulic stress created by waves and currents. The form and the shape of the reef construction largely result from the specific interactions of the coral colonies with the hydrodynamic stress to which they are exposed (Veron 2004).

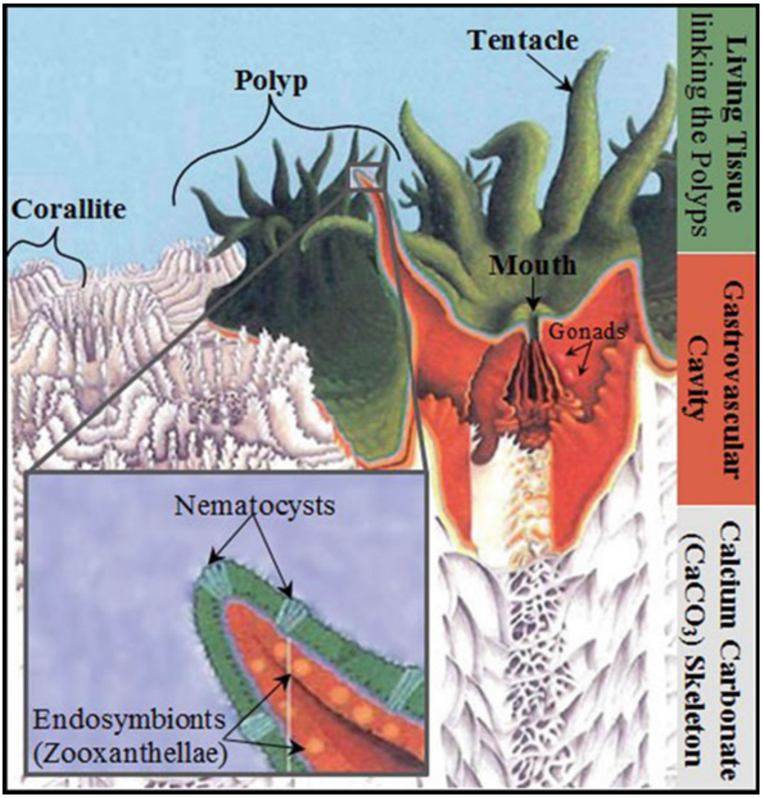

Fig. 2.1 General structure of the polyp and the underlying skeleton of reef building organism (*Source* Lentz 2012)

2.2.1 Classification of Coral Reefs

There have been many attempts to classify different types of reefs. They can be classified according to their geological history, shape, position relative to land masses, and by the nature of the material of which they are made. In spite of a great morphological variety of reef forms, common elements pertaining to the geomorphology such as buttress system, reef flat, lagoon, patch reef zone, etc. indicate a certain regularity in their origin and growth on different structural foundations of shelf and island coasts, across different parts of the coastal zone. This regularity, first recognized by Darwin (1842), can be distinguished into three basic types of coral reef: (1) fringing reefs, (2) barrier reefs, and (3) atolls (Fig. 2.2). Fringing reefs are directly attached to volcanic islands, barrier reefs are separated from volcanic islands or land masses by lagoons, and atolls are formed by ring reefs which enclose only a lagoon.

Fringing reefs grow in shallow waters and border the coast closely or are separated from it by a narrow stretch of water (Fig. 2.2a). They consist of several zones

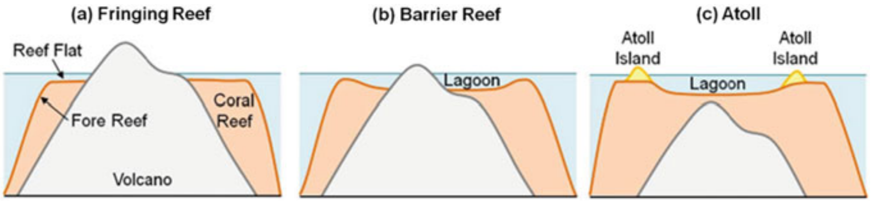

Fig. 2.2 Classification of coral reefs. **a** Fringing reef. **b** Barrier Reef. **c** Atoll (*Source* Pearson 2016)

that are characterized by their depth, structure of the reef and by plant and animal communities associated with them. These zones include the reef crest (part of the reef over which waves break), fore reef (the region of medium energy) and buttress zone or spur and groove (region of coral growth, which includes rows of corals with sandy canyons or passages between each row).

Barrier reefs are separated from land by a lagoon; examples are the Great Barrier Reef off Australia and the Belize Barrier Reef System. These reefs grow parallel to the coast and are large and continuous. Barrier reefs also include regions of coral formation that include the zones found in fringing reefs along with patch reefs (small reefs), back reefs (the shoreward side of the reef), as well as bank reefs (reefs that occur on deep bottom irregularities) (Fig. 2.2b). Barrier reefs also include reef flats (the reef not exposed); the reef crest runs parallel to the coast and is protected from waves and coral terrace (slope of sand with isolated coral peaks). Another coral terrace and a vertical drop follow these features into deeper waters (Veron 2000).

Atolls are annular reefs that develop at or near the surface of the sea when islands (usually volcanic) that are surrounded by reefs subside (Fig. 2.2c), and as sea level changes through glacial cycles (Droxler and Jorry 2021). Darwin (1842) proposed that atolls as corals continue to colonize sinking volcanic islands that eventually sink below the sea surface. More recently, Droxler and Jorry (2021) demonstrated that most modern atolls from the Maldives Archipelago and from the tropical Pacific and southwest Indian oceans occur on top of late Pliocene flat-topped banks. The volcanic basement, therefore, has had no influence on the late Quaternary period development of these flat-topped banks into modern atolls. During the multiple glacial sea-level low stands that intensified throughout the Quaternary, the tops of these banks were eroded by dissolution; then, during each of the five mid-to-late Brunhes deglaciations, coral reoccupied their raised margins and grew vertically, keeping up with sea-level rise and creating the modern atolls.

2.2.2 *Taxonomy of Reef Building Corals*

Corals belong to the Phylum Cnidaria (Fig. 2.3) and are characterized by the presence of tentacles, a central digestive cavity and radial symmetry. Although coral reefs are commonly found in nutrient-poor waters of the tropics, paradoxically, they are among

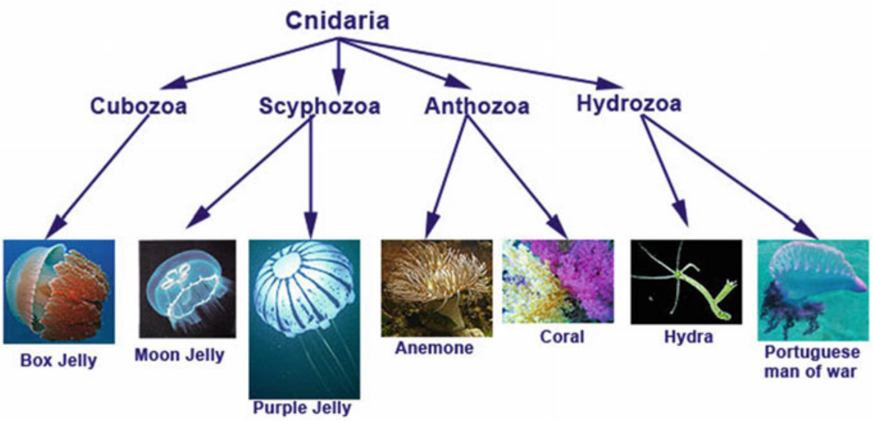

Fig. 2.3 Corals in the Phylum Cnidaria (*Source* http://www.mesa.edu.au/Cnidaria/default.asp)

the most productive of marine environments (Barnes 1987). Coral reef formation and maintenance are driven by the symbiosis between the coral animal and single-celled photosynthetic algae (dinoflagellates) belonging to the genus *Symbiodinium* that live within the tissues of stony coral polyps (Levinton 1995). The endosymbiotic dinoflagellates supply carbon from photosynthesis to the coral host, which in return provides the algae with nitrogen (Szmant et al. 1990). In addition, coral-associated bacteria play a key role in the health of the coral (Fairoz et al. 2008; Ziegler et al. 2016). Together this association is referred to as a holobiont (Rohwer et al. 2002) and the complex interactions among animal, algae and the microbiome intricately shape coral health and resilience (Bourne et al. 2016; Epstein et al. 2019).

Since the success of this symbiotic relationship relies largely on the photosynthetic output of the *Symbiodinium* algae, the distribution and growth of corals is strongly light-dependent (Levinton 1995), and limits reef growth to the top 100 m of the ocean. Therefore, coral reefs commonly thrive in clear, nutrient-poor water characteristic for tropical areas.

2.3 Global Distribution and Status

It has been estimated that shallow coral reefs occupy less than 0.1% of the world's ocean area (Costanza et al. 1997), an area about half the size of Madagascar (Fig. 2.4). This is less than 1.2% of the world's continental shelf area (Spalding et al. 2001). A mass coral bleaching event in 1998 (caused by a major El Niño), resulted in a decrease of hard coral cover by 8%, but reefs mostly recovered by 2009 (GCRMN 2021). From 2009 to 2018, however, there was a 14% decline in the coral coverage of shallow-water reef areas globally (Fig. 2.5a), accompanied by an increase in algal cover of reefs (Fig. 2.5b), due to various natural and anthropogenic processes

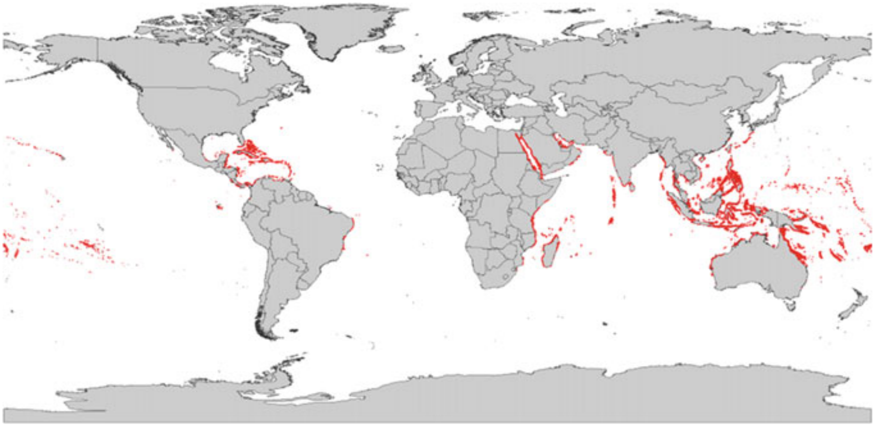

Fig. 2.4 Distribution of the coral reefs of the world (*Source* Teh et al. [2013]. Reef areas are indicated by shading. Attribution 4.0 International [CC BY 4.0])

(GCRMN 2021). The worldwide decline in coral cover is believed to be primarily the result of recurring coral bleaching events due to increasing sea surface temperatures (Fig. 2.6), augmented by local outbreaks of coral diseases and crown-of-thorn starfish (*Acanthaster planci*), as well as local effects of pollution and destructive fishing practices. Projected increases in sea surface temperatures with global warming will undoubtedly lead to continued coral bleaching events and further losses of coral cover (Schoepf et al. 2015).

The shift in reef areas from coral cover to algal cover (Figs. 2.5a and b), referred to as a regime shift (Bozec and Mumby 2015), was already noticed more than a decade ago (Hughes et al. 2007). These will be discussed in Sect. 2.6. Algal overgrowth appears to be most severe in South Asia and the Middle East, where regional-scale impacts of human activities have prevented coral recovery, even during short periods of favorable temperatures, particularly when reefs face greater challenges when exposed to multiple stresses simultaneously.

2.4 Ecosystem Services

Coral reef ecosystems provide services such as food, livelihood opportunities, carbon sequestration, and buffering against extreme climate events, which are critical resources for blue economy sectors. A large body of literature has quantified the values of coral reef ecosystem services from a global perspective (Table 2.1).

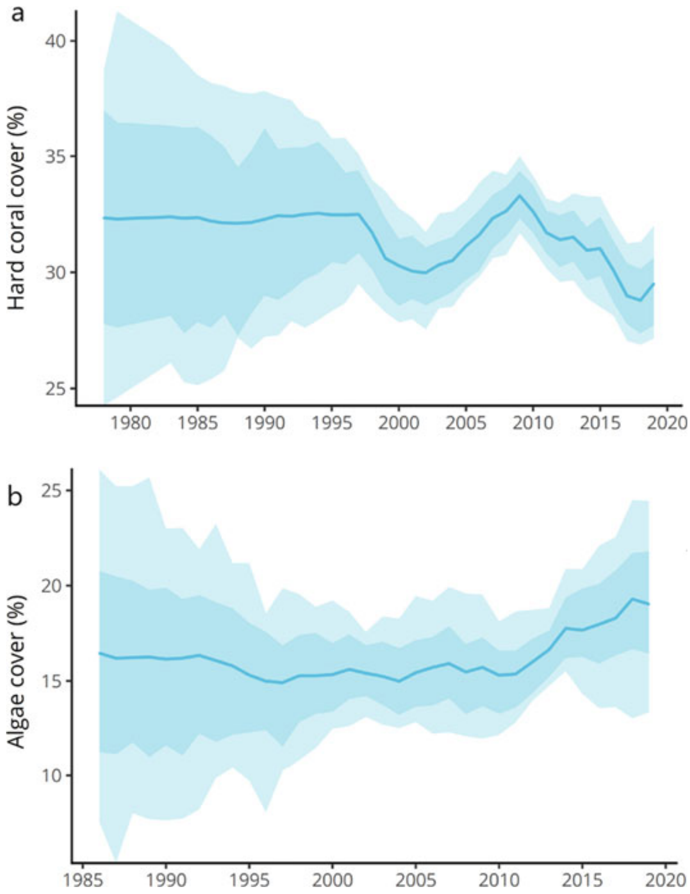

Fig. 2.5 **a** Estimated global average cover of hard coral (solid line) and associated 80% (darker shade) and 95% (lighter shade) uncertainty intervals. **b** Estimated global average cover of algae (solid line) and associated 80% (darker shade) and 95% (lighter shade) uncertainty intervals (*Source* GCRMN [2021])

2.4.1 Biodiversity

Millions of people living in countries with coral reef ecosystems gain benefits due to reef's unique capacity to host diverse groups of marine organisms (Fig. 2.7). Globally, it is estimated that there are between 600,000 and more than 9 million reef species (Knowlton 2001). There is evidence that ecosystems with higher biodiversity are more stable. Marine biodiversity can yield both ecosystem services and products that benefit blue economies. For example, biodiversity is an important attraction for marine ecotourism (see Chap. 6 on Tourism) and makes it possible for fishers to catch a variety of species (see Chap. 4 on Fisheries). The multitude of different species

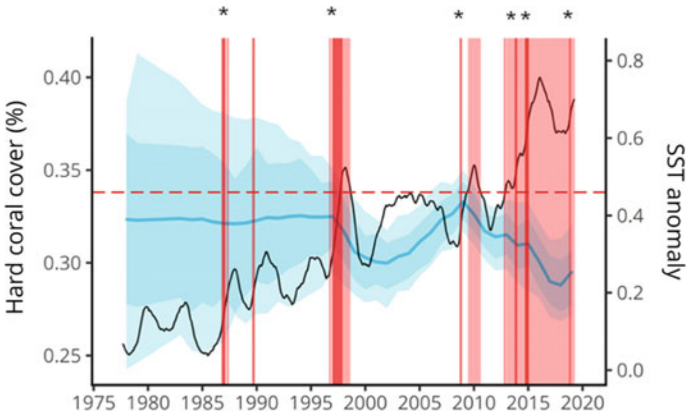

Fig. 2.6 The estimated global average hard coral cover (lighter sold line starting around 33% in 1977) is overlaid with the sea surface temperature (SST) anomaly from 1977 to 2020 (darker line starting at about 0.25 in 1977). The 80% (darker area) and 95% (lighter area) confidence intervals of coral cover estimates are shown. Periods of rapid increase in SST anomaly are indicated by asterisk [*] marks (*Source* GCRMN [2021])

Table 2.1 Values of coral reef ecosystem services quantified in the literature, from a global perspective

Statement	References
More than 275 million people worldwide live within 30 km of reefs (and <10 km from the coast), and ~850 million people live within 100 km of coral reefs	Burke et al. (2011a, b)
At least 500 million people rely on coral reefs for food, coastal protection, and livelihoods	Wilkinson (2004)
In developing countries, coral reefs contribute about one-quarter of the total fish catch, providing food to an estimated one billion people in Asia alone	Moore and Best (2001)
More than 150,000 km of shoreline in 100 countries and territories receive some protection from reefs	Burke et al. (2011a, b)
Globally, coral reefs provide 130 billion USD of flood protection from 100-year storm events	Beck et al. (2018)
Some 30% of the world's reefs are of value in the tourism sector, with a total value estimated at nearly US$ 36 billion, or over 9% of all coastal tourism value in the world's coral reef countries	Spalding et al. (2017)
There are at least 6 million reef fishers in 99 countries worldwide, accounting for about 25% of small-scale fishers	Teh et al. (2013)

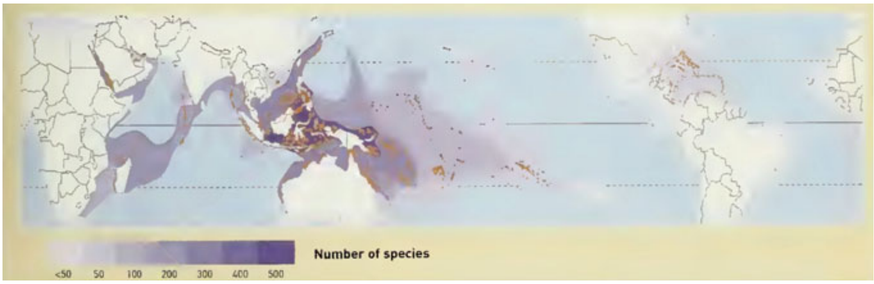

Fig. 2.7 Patterns of biodiversity of the coral reefs (*Source* Spalding et al. [2001])

produce many different classes of marine natural products that could serve as models for compounds useful for medicine, agriculture, and other purposes (see Sect. 2.5.3).

2.4.2 Coastal Protection

Coastal protection is an economically important ecosystem service provided by coral reefs, especially to island nations. Reefs shelter coastal settlements, and mangrove and seagrass areas, from waves, winds, and other ocean-related hazards though dissipation of wave energy by friction on reef structures (Goulay et al. 1996; Lugo-Fernandez et al. 1998; Sheppard et al. 2005). Protection of coastal settlements from storm damage reduces economic losses and loss of life. Mangroves and seagrasses offer additional protection from storms, serve as nursery areas for important fish species, and help process nutrients and other wastes from land to the ocean (see next section). Coastal protection value (CPV) has been defined to recognize the economic value of coastal protection and inform coastal management policies (Cesar et al. 2003; Burke and Maidens 2004). The annual global coral reef CPV was estimated as 9 billion USD by Cesar et al. (2003).

2.4.3 Blue Carbon

Blue carbon ecosystems play an important role in CO_2 sequestration and storage in the form of organic matter, and coral reefs can help protect these systems. Chapter 3 on Mangroves and Seagrasses provides a more detailed description of the benefits provided by these ecosystems. Blue carbon has gained much attention in efforts related to reducing atmospheric CO_2. For example, recent studies have shown that intact reefs can increase the capacity of seagrass meadows to store carbon by promoting carbon accumulation and avoiding erosion and export of carbon (Guerra-Vargas et al. 2020). These economic valuations are considered as “indirect use value”

(De Groot et al. 2010) or “hidden value” (Van Beukering et al. 2007; Sarkis et al. 2010) because these services are not visible in daily life.

2.5 Blue Economic Sectors

2.5.1 Tourism

Coral reef-associated tourism is one of the most prominent eco-tourism activities in tropical coastal countries. Coral reefs are very attractive destinations for tourists from all over the world, leading to the significant generation of foreign income for many developing country economies. Components of reef-related tourism include attractive beach sites and sheltered waterfronts with panoramic views, and underwater activities such as SCUBA diving and snorkeling (Hasler and Ott 2008). Approximately 30% of the world’s coral reefs are sites of tourism-related income generation, contributing nearly US$36 billion annually, or more than 9% of all coastal tourism value in the world’s coral reef countries (Spalding et al. 2017). See Chaps. 6 and 13 for more details on the relation of tourism and blue economies.

2.5.2 Fisheries

Coral reefs provide habitats for enormous biomass, including finfish and shellfish resources that are the basis for reef fisheries. A well-managed reef can provide 0.2–40 tons of seafood per km^2 annually (UNEP 2004), with an average of about 5 tons of seafood per km^2 per year. This translates to an annual yield of 1.42 million tons of seafood from coral reefs worldwide. Coral reef-associated fisheries are a source of income for many coastal communities, mainly in the developing world (Burke et al. 2011a, b). In terms of nutritional value, reefs supply half of the protein requirement of the people in some areas, and reef fish are important sources of vitamins A, B, and D, calcium, iron, and iodine. Across reef nations and territories, people consume an average of 29 kg of fish and seafood each year (Newton et al. 2007), with consumption of reef fish being the highest in the Maldives (180 kg/person/year). Reef fish and shellfish are also harvested for aquaria and curio exports. The economic importance of coral reef products varies by region. Southeast Asian countries generate $2.4 billion per year in products, and in the Caribbean $395 million per year is derived from reef-related fisheries (Teh et al. 2013). Reef-associated exports are valued at more than 1% of total exports in 21 countries and territories, and more than 15% of total exports in six other countries (Burke et al. 2011a, b). See Chap. 4 for more information about fishery contributions to blue economies.

2.5.3 Marine Biotechnology

Marine biotechnology (or blue biotechnology) is a rapidly developing field and applied to the areas of public health, human disease, and seafood safety, with new discoveries of promising products being made continually from marine organisms such as algae, sponges and mollusks. Due to their unique bioactive and structural diversity, natural products from marine organisms are a potent source of therapeutics that exhibit structural and chemical features not present in terrestrial organisms (Horta et al. 2015). During the last 50 years, about 20,000 novel compounds have been isolated and identified from marine organisms (Simmons et al. 2005), and more than 300 patents related to marine natural products have been approved (Blunt et al. 2013). Coral reefs—including coral-associated microorganisms and marine invertebrates—are the source of about 245 potent bioactive compounds identified so far, including substances with anti-inflammatory, cytotoxic, antimicrobial, antiviral, and antifouling properties (Bruckner 2002). It is noteworthy to mention that the development of marine natural products does not necessarily lead to the widespread harvesting of the organism producing the products, as the products often can be synthesized in the laboratory after the structure and activity of bioactive compounds have been determined.

2.6 Threats and Their Impacts

Coral reefs are adapted to thrive in a stable environment and are therefore easily affected by sudden changes of abiotic factors, such as decreased salinity and pH, increased temperature, hurricanes and wave action, nutrient pollution, and siltation. Human threats include overfishing, destructive fishing practices, damage by tourists, and destruction as part of coastal development. Over the last four decades, catastrophic events have affected coral reef systems globally, resulting in their destruction over vast areas.

A combination of increased seawater temperatures and food availability promote devastating outbreaks of the predatory crown-of-thorn sea stars that feeds exclusively on scleractinian corals and has caused extensive damage on the Great Barrier Reef and in other areas of the tropics (Uthicke et al. 2015).

In addition to such natural threats, various human activates are responsible for reef degradation. Tourism and recreational activities, and use of explosives (dynamite fishing), poison and destructive gear for reef fisheries are examples for destructive human activities. Impact from these activities, coupled with land-based activities such as shore development, farming, mining, deforestation, reclamation, sewage disposal exert tremendous stress on the ecological balance of reefs. Segel and Ducklow (1982) found that most corals are weakened by stress, particularly due to diseases caused by bacteria as a result of anthropogenic activities (see next paragraph). Changes in the extent of biotic and abiotic stressors are likely to be further compounded by the slow decrease in seawater pH, commonly referred to as ocean acidification (Hoegh-Guldberg et al. 2017; Cornwall et al. 2021) (see Sect. 2.6.3 and Chapter 11).

2.6.1 Coral Bleaching

Coral reefs support numerous blue economy activities and global warming is a challenging and emerging threat to the survival of coral animals. Tropical coral species generally live close to their upper temperature limits (Berkelmans and van Oppen 2006) and an increase in sea surface temperature of 0.5 °C can exceed a species' heat tolerance, which causes corals to expel their endosymbionts, leading to a phenomenon known as "coral bleaching". Because corals depend on algae for the majority of their energy requirements, prolonged coral bleaching frequently results in disease, reduced growth and reproduction and often large-scale coral mortality (LaJeunesse et al. 2018; Hughes et al. 2019; Sully et al. 2019). The mechanisms related to bleaching and subsequent mortality of different taxa are still not well understood (Hughes et al. 2018) and thermal tolerance of the symbiotic relationship can vary greatly between and within species as well as across different geographical areas (e.g., Cunning et al. 2021).

In order to mitigate the effect of coral bleaching, it is important to understand the underlying physiological mechanisms responsible for the dissociation between both symbiotic partners. Although coral reefs may be largely eliminated worldwide by the end of this century as a result of coral bleaching (Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2007; Veron et al. 2009; Bay et al. 2017; Heron et al. 2017), recent studies also suggest that many species are able to adapt and increase their resilience to reoccurring heat exposure (Matsuda et al. 2020).

2.6.2 Coral Diseases

Over the past few decades, there has been a marked rise in coral diseases (Rohwer et al. 2002) and epizootics of coral disease have resulted in significant losses of coral cover (Aronson and Precht 2001; Walton et al. 2018), The most notable disease outbreak was reported from Florida reef tracts from 2014 and it is ongoing to date (Precht et al. 2016; Walton et al. 2018). Although there is still a lot of uncertainty surrounding specific pathogens and/or their vectors, disease prevalence has been linked to an array of environmental disturbances pertaining to water quality such as nutrient load and sewage (Redding et al. 2013), as well as increases in seawater temperature (Maynard et al. 2015). Determining the drivers of disease outbreaks is an ongoing area of vigorous research aiming to disentangle the relative effects of host resilience and destabilized homeostasis within the holobiont on disease outbreaks (Burge et al. 2014; Thompson et al. 2014; Peixoto et al. 2017).

2.6.3 Ocean Acidification

Ocean acidification threatens many ocean ecosystems including coral reefs (see Chap. 11 for details on ocean acidification and its economic impacts). Economic impacts of ocean acidification are difficult to predict because the biological effects of acidification are not yet fully known or predictable. Pelagic organisms that live in the open ocean and benthic animals that live in shallow habitats or in deep waters are threatened by ocean acidification, but corals and pteropods appear to be most at risk (Caldeira and Wickett 2003; Fabry et al. 2008).

In the late 1980s, it was inferred from the geologic record that the chemical condition of the ocean controls the rate of production of carbonate shells and skeletons in the marine environment over geologic time scales (Veron 2000). Experiments performed on tropical corals showed coral growth rates slowing dramatically as seawater CO_2 concentrations increase (Gattuso et al. 1998). Soon after, a groundbreaking study combined model predictions of future ocean chemistry with results from laboratory experiments on corals. This study concluded that coral growth would be severely impeded later this century and that tropical reefs are likely to be most vulnerable (Kleypas et al. 1999).

The scientific and policy needs for coordinated, worldwide information gathering on ocean acidification and its ecological impacts, recognized by the United Nations General Assembly (UNGA 2013), and by many governmental and non-governmental bodies, resulted in the creation of the Global Ocean Acidification Observing Network (GOA-ON) (Newton et al. 2015) and inclusion of ocean acidification monitoring as a goal of Sustainable Development Goal 14. The methods of monitoring and research for ocean acidification are interdisciplinary, including carbon chemistry, meteorology, oceanography, biogeochemistry, ecology, and biology. Basic data collection includes temperature, salinity, water depth, oxygen concentration and carbon-system parameters, plus fluorescence, and irradiance. Benthic status (e.g., coral and coralline algae cover) is also included in monitoring coral reef habitats to correlate with the physical and chemical variations in the water column that correspond to those specified for the Global Coral Reef Monitoring Network (GCRMN), a program of the International Coral Reef Initiative. These methods will detect ocean acidification as more acidic conditions erode dead carbonate structures in coral reefs (Campbell et al. 2014; Hoegh-Guldberg et al. 2017).

2.7 Importance of Global Observing Systems for Coral Reefs

Several international projects and activities contribute data on ocean and marine biodiversity parameters, including data related to coral reefs. The following are among the notable high-level activities:

- The Global Ocean Observing System (GOOS) is a platform of the United Nations Education, Scientific and Cultural Organization's Intergovernmental Oceanographic Commission, UNESCO-IOC, along with other co-sponsors (Miloslavich et al. 2018b). GOOS established a new panel in 2015 to extend Essential Ocean Variables (EOVs) to the biological and ecosystem components of the ocean. The Biology and Ecosystems Panel identified a set of biological EOVs and is working on strengthening and developing coordinated observing networks around each of these (Miloslavich et al. 2018b) in response to identified global needs. See also Chap. 14.
- The Marine Biodiversity Observation Network (MBON) of the Group on Earth Observations Biodiversity Observation Network (GEO BON) (Mueller-Karger et al. 2018) was established to develop a global community of practice for the collection, curation, analysis, and communication of marine biodiversity data. This requires coordination and collaboration among countries, organizations and individuals involved in the Group on Earth Observations (GEO) and many other organizations.

These groups provided leadership in developing EOVs and Essential Biodiversity Variables (EBVs) for biological and ecological parameters (Table 2.2) and to promote the integration of regional datasets shared among scientific communities through global systems such as the Ocean Biogeographic Information System (OBIS).

Hard coral cover and composition was identified as one of the leading biological EOVs (see specification sheet at www.goosocean.org/eov), partly due to the two decades of coordinated coral reef monitoring already undertaken by the GCRMN (e.g., Wilkinson 2000, 2008). The GCRMN has been the unofficial global observing system for coral reefs since 1997 with the publication of the first global status of reefs report (Wilkinson 2000) that was motivated by the first global coral bleaching event of 1997–1998. After that, several reports on coral reefs on global and regional levels, including research methods, were published. These reports were incorporated into the Convention on Biological Diversity (CBD) (e.g., https://www.cbd.int/; Tittensor et al. 2014) and global assessments (GRID-Arendal and UNEP 2016).

2.7.1 The Global Coral Reef Monitoring Network (GCRMN)

The GCRMN was established by the International Coral Reef Initiative (ICRI) in 1995, initially with the primary task of reporting on the condition of the world's coral reefs in the context of the development of the ICRI "Call to Action" (Dight and Scherl 1997). Since then, the GCRMN has produced a range of global, regional and thematic reports on coral reef status and trends, with the support of regional coordinators and managers of marine parks.

The GCRMN has recognized that coral reefs in more than 100 countries are under significant pressure from human activities, and are uniquely vulnerable to climate change, as well as ocean acidification. This makes coral reefs a sensitive indicator

Table 2.2 Essential Ocean Variables (EOVs) important for monitoring and reporting coral reef health, and levels proposed to assist in assessing data quality by the Global Coral Reef Monitoring Network (GCRMN)

EOV name	Description and notes	Levels 1, 2, and 3*
Hard coral cover and composition	Hard corals are the architects of coral reefs, justifying this as the most important indicator of coral reef presence and health. Three-dimensional reef structure is strongly determined by the growth form of coral colonies. For the GCRMN, the growth (functional) form and genus-level identification provide sufficient detail for monitoring	1-total hard coral cover (%) 2-cover by functional group/growth form 3-cover by genus or species
Fleshy algae cover	Different algal groups serve unique functional roles in reef communities. In general, fleshy, macro and turf algae are primary competitors to corals for occupying reef substrates; some also release dissolved organic carbon into the water which fuels microbial activity that inhibits corals. Crustose coralline algae (CCA) are key contributors to reef building. Fleshy algal cover is the aggregation of fleshy, macro and turf algal forms	1-total fleshy algal cover (%) 2-cover by functional group (turf, fleshy/macro, CCA, and calcareous) 3-cover by genus or functional group, with canopy height
Fish abundance and diversity	Fish are highly diverse, occupy a range of functional roles, are mobile, and their size matters. The selection of target fish for monitoring is challenging and highly variable. Monitoring programs are therefore encouraged to focus on a subset of fish families and to record all species within them, though in many cases target species/taxa are more manageable	Assigning levels for fish data is premature. The most basic is abundance of key taxa, the most complex is biomass of all species in key families' status

*Data levels rank from Level 1 (minimum requirements) to Level 3 (maximum requirements) See additional details below from 2000 to 2008

system for coastal ocean health, climate change and ocean acidification impacts, and their implications for society.

The GCRMN Implementation and Governance Plan (Obura et al. 2019) identifies four goals for the GCRMN, with subsidiary objectives:

- Goal 1: Improve understanding of coral reef status and trends, globally and regionally.
- Goal 2: Analyze and communicate coral reef biophysical, social and economic trends, providing science-based recommendations in support of raising awareness, management and policy development.
- Goal 3: Enable and facilitate greater utilization of coral reef data, including in research.
- Goal 4: Build human and technical capacity to collect, analyze and report biophysical and socio-economic data on coral reefs.

Tracking and reporting on coral reef status and trends is needed to understand the extent and rate of change, and to design appropriate responses. As coral degradation is taking place at the global level, driven by global as well as local processes, systematic coral reef observation is required. These observations directly support planning and tracking coral reef health in relation to sustainable development, climate change and biodiversity conservation, and have broad application in awareness raising and outreach. High-quality coral reef data will also support research, including in relation to ecology and ecosystem service provision, and observational data are needed for modelling to better predict future reef responses to climate stress.

The role of the GCRMN is to provide these coral reef data, aggregating from national to regional levels, and then to a global level. The EOVs proposed by the GCRMN are important for monitoring and reporting coral reef health (Table 2.2).

2.7.1.1 Revitalizing the GCRMN

Greater precision and consistency in how data are measured and reported is a priority focus for the GCRMN in the coming years. The GCRMN is adopting the Essential Variable approach (Obura et al. 2019) and a data quality model (Table 2.2) that enables (a) effective submission of minimum data required to monitor and assess reef health (hard coral cover and composition), and (b) procedures for strengthening and extending the data to additional key variables (e.g., algae and fish), and improving the resolution and "quality" of each variable.

The data quality model scores three levels of data, from minimum requirements (Level 1) to maximum (Level 3), providing specific guidance on how to improve data quality from Level 1 to 3, and incentivizing monitoring teams to improve quality. The key method for ensuring data quality is the preparation and submission of appropriate metadata (GCRMN 2018a, b) that include information on sites and sampling, variable precision and replication, and any data processing or transformations applied after data collection. This approach enables two objectives: first, to maximize submission of data that meet a minimum standard from all parts of the globe, and second, to provide a pathway for capacity building to improve data quality to the highest levels possible.

2.8 Science and Technology Measures

For developing countries, there are specific needs related to observational monitoring and ecosystem-based management approaches at local levels (Obura et al. 2019). Awareness and access to available new technologies and capacity building are among some of the priorities, including for personnel at the science-policy interface. These aspects are discussed in detail in Chaps. 14 (Ocean Observations) and 15 (Capacity Development). This section presents a description of the science and technology options to better manage reef ecosystems in order to avoid threats to sustainable blue economies and discusses some of the latest studies on improving our understanding of coral reefs.

A large body of literature shows that the major threat to coral reefs globally is the series of unprecedented coral bleaching incidents that have occurred in various parts of the world. The major cause of this coral bleaching is global warming, caused by increased sea surface temperature. Research on coral physiology and adaptive capacities may help in devising approaches to mitigate the impacts of global warming.

2.8.1 Research on Coral Symbiosis and Coral Bleaching

Stony corals owe their success as reef builders to their symbiosis with endosymbiotic dinoflagellate algae of the genus *Symbiodinium*. These algae live in coral tissues in extremely high densities (greater than 10^6 cm^{-2}) and provide up to 90% of a coral's nutritional requirements (Muscatine and Porter 1977). Researchers have studied the connections between loss of endosymbionts, the global incidence of coral bleaching, and the loss of coral cover in recent decades. The effects of thermal stress on corals over the last century (Lough 2000) yield clues to the future of coral reefs in the context of global warming in the future (IPCC 2021).

Coral-*Symbiodinium* symbiosis is temperature sensitive; increased sea surface temperature can disrupt coral symbiotic complexes to cause coral bleaching resulting from the expulsion of symbiotic algae from the coral tissues due to the thermal stress. It is sometimes possible for the algae to recolonize coral tissues after the temperature returns to normal. This situation is called temporary bleaching and corals can recover within a couple of days. However, if elevated temperatures last for a longer period, bleaching can become permanent and there is no chance for the coral to maintain the symbiotic system (Muscatine 1990).

Recent research to understand coral bleaching and to improve knowledge of the effects of temperature on the breakdown of coral symbiosis also includes microbial ecology, to integrate into a larger explanation of status of the reef coral health (Dove and Hoegh-Guldberg 2006), as explained in the following section.

2.8.2 Coral Reef Microbiology

Coral reef microbiology is an emerging field that integrates existing knowledge of the coral endosymbiosis, with new studies of other organisms within the holobiont, such as endolithic algae, bacteria, protists, fungi and viruses (Rosenberg et al. 2007; Peixoto et al. 2017; Tong et al. 2020) (Fig. 2.8).

Bacteria are assumed to contribute to coral holobiont biology primarily in terms of stress tolerance and adaptation to disparate environments (Voolstra et al. 2021). Recognition of the importance of bacteria as part of the coral holobiont led to the proposal of several hypotheses of coral reef processes. For example, the coral probiotic hypothesis states that microbes support coral biology through selection of the most advantageous holobiont configuration in a given environment. This was also referred to as the "microbiome flexibility" hypothesis to include the notion that the potential and likelihood for microbiome change differs among host species (Peixoto et al. 2017). These concepts might help in attempts to select and manipulate specific microbes to aid the heat stress tolerance and resilience of the coral

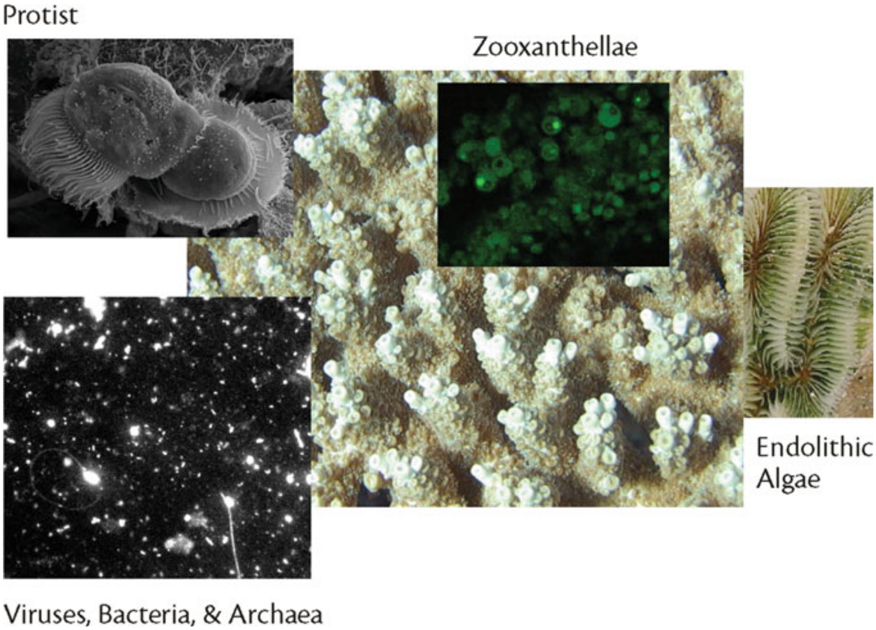

Fig. 2.8 The coral holobiont consists of symbiotic zooxanthellae, the coral animal and associated viruses, microbes (both bacteria and archaea), and endolithic organisms. Most of the viruses are bacteriophages, which attack the microbes. The endolithic organisms include algae, fungi, sponges, and microbes that bore into the coral skeleton. The holobiont likely occupies different coral reef niches by mixing and matching different components (i.e., the Probiotic Hypothesis). Zooxanthellae and protist micrographs by Linda Wegley and Ian Hewson, respectively (*Source* Rosenberg et al. 2007; Attribution 4.0 International [CC BY 4.0])

holobiont. Microbes included in the coral holobiont are also described as "beneficial microorganisms for corals" (BMCs) (Santoro et al. 2021). These coral-associated beneficial microbes generally fix atmospheric nitrogen, maintain sulfur cycling, scavenge reactive oxygen species (ROS) that otherwise harm coral tissues, and produce antibiotics to thwart pathogens (Robbins et al. 2019). The functional changes and host association of BMCs are largely unknown.

Knowledge gained from coral reef microbial ecology studies has been applied to explain the large-scale ecological status of coral reefs. Dinsdale et al. (2008) characterized microbial communities from pristine to human-populated atolls in the Pacific Ocean, including four coral atolls in the Northern Line Islands located in the central Pacific Ocean. The differences in microbial communities across atolls reflected the variation in the oceanographic conditions and direct and indirect human impacts, such as fishing and land use (Dinsdale et al. 2008; Sandin et al. 2008). Data from this study could serve as a baseline for future studies on reef microbes and the association of microbes on degradation of coral reef systems worldwide. Techniques used in this study represent a combination of methods from metagenomics, microscopy, microbial culture methods, and water chemistry.

2.8.2.1 Microbiome Studies

Another study was conducted of coral reefs at 11 Line Islands in the central Pacific Ocean that together span a wide range of biogeochemical and anthropogenic influences to examine coral microbiomes (Kelly et al. 2014). The percent cover of major benthic functional groups were significantly correlated with particular microbial taxa. Reefs with higher coral cover had a coral microbiome with higher abundances of Alphaproteobacteria (such as Rhodobacterales and Sphingomonadales), whereas microbiomes of algae-dominated reefs had higher abundances of Gammaproteobacteria (such as Alteromonadales, Pseudomonadales, and Vibrionales), Betaproteobacteria, and Bacteriodetes. In contrast to taxa, geography was the strongest predictor of microbial community metabolism. Microbial communities on reefs with higher nutrient availability (e.g., equatorial upwelling zones) were enriched in genes involved in nutrient-related metabolisms (e.g., nitrate and nitrite ammonification, total nitrogen transport). On reefs further from the equator with lower nutrient levels, microbes had more genes encoding chlorophyll biosynthesis and photosystems I/II.

2.8.2.2 Application of Environmental Genomics

Another approach to coral reef research has involved the application of metagenomics in coral reef studies to obtain a comprehensive view of microbial ecology of coral reefs. Metagenomics is the study of genetic material recovered directly from environmental samples, such as seawater. This is a broad field also referred to as environmental genomics, ecogenomics and community genomics. A detailed metagenomics study from Japanese reefs (Meirelles et al. 2018) suggest that synergistic effects among several regional stressors are driving coral decline. In a highly hydrodynamic reef environment, high algal/turf cover, stimulated by eutrophication and low fish abundance due to overfishing, promote water column microbial activity, together with crown-of-thorns sea star outbreaks and climate changes impacts; these coral reefs are likely to collapse.

2.8.2.3 Global Microbialization of Coral Reefs

Global coral reef status shows that coral-dominated reefs are becoming algal-dominant reefs worldwide, recognized as a "phase shift" (Hass et al. 2006). This shift in coral ecosystems was explained as "global microbialization" of coral reefs, an observed shift in ecosystem trophic structure towards higher microbial biomass and energy use. On coral reefs, the primary causes of microbialization are overfishing of herbivorous fish and eutrophication, both of which enhance the growth of fleshy algae, allowing it to out-compete calcifying corals and coralline algae. Haas et al. (2016) propose that the "DDAM (Dissolved organic carbon [DOC], Disease, Algae, Microorganism) positive feedback loop" gives fleshy algae a competitive advantage. The DDAM feedback loop involves ungrazed fleshy algae releasing DOC, supporting pathogenic bacteria that harm corals. Observations from three ocean basins were used to demonstrate the prevalence of DDAM processes. Besides promoting growth of fleshy algae, microbialization of reefs can also increase hypoxia and decrease pH from the microbial respiration of DOC. Following the explanation of microbialization in coral reefs, interest has increased regarding microbial metabolism and the microbiome over reefs and its connectivity to local environmental factors. Microbiome studies explain the maintenance and adaptation of microbiomes to local conditions, facilitated by the horizontal transfer of genes responsible for specific metabolic capabilities from one microbial species to another. The core microbiomes are determined by holobiont macroorganisms as explained above in this chapter.

2.8.3 Modelling and Monitoring for Threat Alert Systems

Global-scale coral bleaching risk alerts have been generated for the past 20 years based on satellite observations of sea surface temperature (SST), through detection and mapping of high positive SST anomalies relative to long-term averages. Bleaching alert products were developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch Program (http://coralreefwatch.noaa.gov/satellite/; Liu et al. 2014). Other regional forecast models of coral stress due to heat, extreme cold winter anomalies, and coral disease have been implemented, such as in Australia (Maynard et al. 2011). These models, combined with volunteer-based ground-truth monitoring networks (e.g., Gudka and Obura 2017), help generate awareness of the threat of coral bleaching, and build interest and capacity in management responses to mitigate the effects of these events and promote resilience and recovery from the events (Marshall and Schuttenberg 2006). A typical major bleaching event occurs over 2–4 months, and monitoring an event requires different approaches at its start, during the event, and afterward to track long-term impacts. Improved quantitative data helps to target management and policy responses more effectively.

Fixed buoys for monitoring aerial and subsurface biophysical properties of coral reef waters are used for monitoring in some locations, notably the NOAA Coral Reef Early Warning System (CREWS). Starting in 1997, this system combined software and sensor platform development to automatically detect conditions thought conducive to coral bleaching (Hendee et al. 2007). Buoys in this network of stations around the Caribbean and in Saipan (in the Pacific Ocean) relay data by satellite to the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, USA.

2.8.3.1 Remote Sensing and GIS

Satellite-based remote sensing enables the monitoring of shallow-water tropical coral reefs over a broad range of spatial and temporal scales (meters to global and from near-daily to decadal). Satellite images and other data, such as measures of the roughness of the sea surface and sea level can cover large areas, such as, hundreds to thousands of square kilometers, quickly and synoptically, frequently and repeatedly, over long periods of time (Eakin et al. 2010; McCarthy et al. 2017).

In recent decades, application of remote sensing and tools of image processing on coral reef ecological data have increased understanding of the status of reefs. Habitat mapping is a foundation for marine spatial planning and to detect changes of coral cover, reef heath, and ecosystem dynamics (Hamylton 2017; Purkis et al. 2019). Machine-learning algorithms are now embedded into image classification routines to map coral reef habitat at large geographic scales (see next section). For the global Allen Coral Atlas, “random forest” learning algorithms classify groups of image pixels (objects) into habitat maps from a collection of covariate data layers, including satellite image reflectance (e.g., from Landsat, Sentinel2, Planet Dove, and Worldview-2 satellites), bathymetry, slope, seabed texture and wave data (Lyons et al. 2020). Multiple decision trees were trained from known occurrences of bottom type (“ground truthing” data) to classify unknown objects from the mode of the individual tree classes. Working with covariate data and desired results, a machine learning classifier uses calibrated values to identify bottom type using the mode of individual tree classes. These data are applied at a global scale using Google Earth Engine to provide a repository of high-resolution Earth observation imagery using a remote supercomputer (Gorelick et al. 2017). Resulting habitat maps have clear potential management applications, for example, in evaluating reef connectivity for the dispersal of coral and crown-of-thorns sea star larvae, modeling water quality, and evaluating reef restoration sites (Roelfsema and Phinn 2010; Roelfsema et al. 2020). While machine-learning algorithms offer a reliable means of habitat classification,

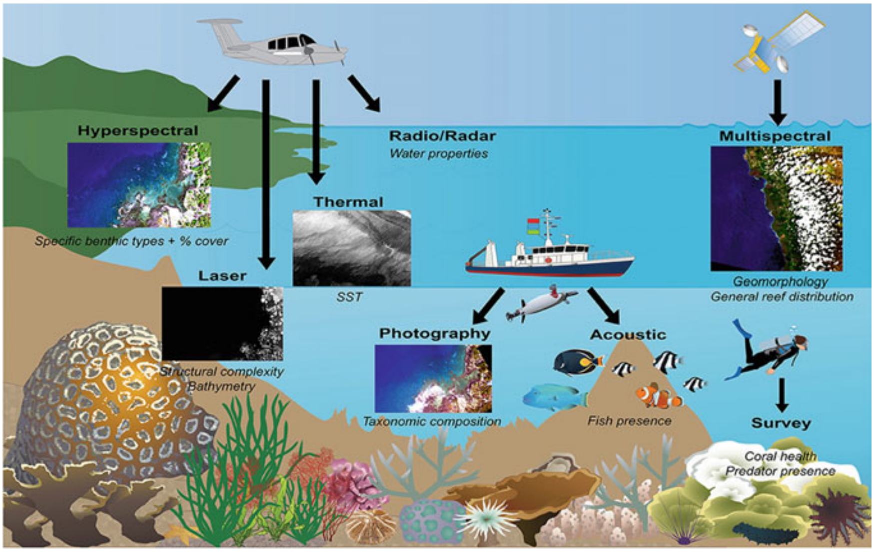

Fig. 2.9 Application of Remotly sensed measurements to coral reef restoration examples by the Carnegie Airborne Observatory [Asner et al. 2012]. Symbols are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/) (*Source* Foo and Asner [2019] Attribution 4.0 International [CC BY 4.0])

their use for mapping relies on input of covariate biophysical data. Feature extraction provides an alternative application of machine-learning algorithms to coral reef imagery.

Remotely sensed measurements can be useful for coral reef restoration activities (Fig. 2.9). Key criteria considered by restoration practitioners are paired with the current platform and sensing technology that is most mature and developed, for the criterion at the required resolution to inform fragment collection, coral out-planting, and monitoring efforts.

2.8.3.2 Machine Learning for Detecting Features in Coral Reef Environments

Discrete features visible within images can be directly detected as recurring patterns across multiple pixels. This is commonly achieved through a family of multi-layered deep-learning algorithms known as convolutional neural networks (CNN) that were initially developed for facial and handwriting recognition. These algorithms define a series of mathematical convolutions to generate the output from the input, allowing all instances of a feature falling within an image to be located based on a predefined set of features (LeCun et al. 2015). On sand cay islands and reef flats, features that are amenable to detection include fallen trees, particularly on narrow beaches, which signify erosion of sand cay shorelines (Lowe et al. 2019) and individual mangrove

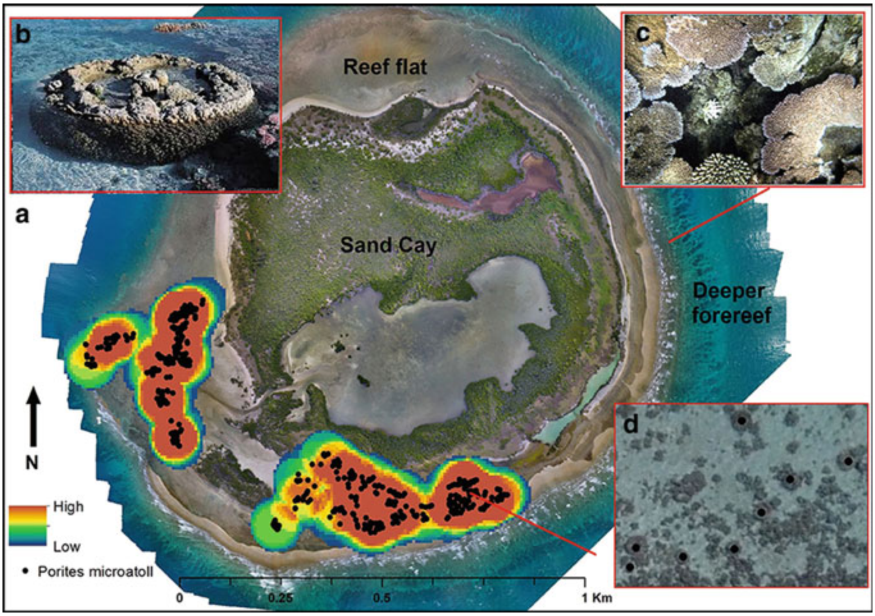

Fig. 2.10 Example of mapping possible by drone, showing a composite picture composed from 1400 UAV images of Nymph Island on Australia's Great Barrier Reef. Panel A shows the photomosaic, which Panel C that the detail available can show individual corals (*Source* Hamylton et al. [2020] Attribution 4.0 International [CC BY 4.0])

trees, from which forest expansion and contraction can be monitored over time (Hamylton et al. 2020). Individual corals are now clearly visible in drone images acquired above reefs (Fig. 2.10) and machine-learning algorithms hold good potential for detecting reef features, opening up a wealth of potential management applications for monitoring coral restoration and bleaching. For example, on degraded reefs, restoration activities include planting tens of thousands of juvenile corals (Lirman and Schopmeyer 2016), whose planting sites can be optimized by analysis of existing coral distributions.

2.8.3.3 Citizen Science and Coral Reef Monitoring (www.citizenscience.org/)

Community-based monitoring is important to gather information for reef management and involve local communities in protecting the reefs on which they depend. Many programs have arisen to monitor reef conditions in local areas involving local communities, with limited expert support, including Reef Life Survey (Stuart-Smith et al. 2017) and Reef Check (Hodgson 1999, 2001). The need of this type of program and training opportunities are described by Miloslavich et al. (2018a).

2.8.3.4 Data Collection and Analysis

Human observation in underwater environments is limited due to the harsh seawater environment and the large geographic scales involved, but it has been possible to begin new observations of coral reef environments in some areas, using new technologies for coral research and monitoring. Ideally, autonomous systems can be deployed to collect physical, chemical, and biological data to overcome in-person observation limitations. Environmental data such as oxygen concentrations, temperature, chlorophyll levels, and seawater turbidity and salinity help scientists interpret biological features and trends. Besides moored instruments, automated underwater vehicles (AUVs) and unmanned aerial vehicles (UAVs) (Gasmueck et al. 2006; Chirayath and Earle 2016; Koparan et al. 2018; Levy et al. 2018; Monk et al. 2018) can be used to survey reef areas.

Passive acoustic monitoring of the sounds of organisms on coral reefs is an emerging field (Servick 2014) that can complement visual methods and make continuous observations during day and night regardless of weather or storm conditions. It is becoming possible to calculate measures of acoustic diversity (Kaplan et al. 2015; Mooney et al. 2020) and efforts are underway to create an international library of underwater biological sounds to make automatic detection of animals possible (Parsons et al. 2022). Passive acoustic monitoring may make it possible to monitor reef health with less personnel required, and making it possible to observe rarely seen species and provide information about daily and monthly variation in reef ecosystems as well as to record isolated acoustic events (Staaterman et al. 2014; Parsons et al. 2016; Lillis and Mooney 2018).

Photographic reef surveys can be conducted using automated image capture and analysis tools. This type of monitoring can be conducted using images collected by platforms navigated underwater by a diver (e.g., the XL Catlin Seaview Survey http://catlinseaviewsurvey.com/) or using remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) (Beijbom et al. 2015), with some caveats (Lesser and Slattery 2021). There are rapidly developing technologies to both acquire and process 3-dimensional photomosaic imagery using structure-from-motion (SfM) photogrammetry (Burns et al. 2015).

Studies of marine benthic and microbial biodiversity have been conducted using one square foot structures called Autonomous Reef Monitoring Structures (ARMS) (https://naturalhistory.si.edu/research/global-arms-program) by the Smithsonian Institution, U.S. National Oceanic Atmospheric Administration, and others (Pearman et al. 2019). Deployment of ARMS has demonstrated rates of colonization by reef-related species, including cryptic and invasive species (Ransome et al. 2017; Palomino-Alvarez et al. 2021), and the feasibility of using artificial structures to assist in rehabilitation of reef areas.

2.8.4 Coral Ecosystem Restoration and Conservation Tools

2.8.4.1 Coral Mitigation/Restoration Research

As pointed out in Chap. 11 on Ocean Acidification, managers of coral reef areas can do little to slow the global increase in ocean acidification due to increasing CO_2 in the atmosphere. However, there are some potential means of mitigating ocean acidification at local levels, or perhaps repair damage to coral reef ecosystems due to ocean acidification and other stresses. Albright and Cooley (2019) described a variety of passive and active approaches to help protect coral reefs or to help them recover if damaged. Passive measures are those that reduce controllable stresses on coral reefs and increase the resilience of reef areas. Examples of passive approaches include more conservative management of fisheries and coral reef areas to make them more resilient, implementation of marine spatial planning to separate conflicting uses from reef areas, protecting reef areas as part of marine protected areas, factoring reef health and sustainability into national blue economy plans (Andersson et al. 2019), and improving wastewater treatment to decrease eutrophication and other coastal pollution (Guan et al. 2020). Active measures to reef protection and mitigation mentioned by Albright and Cooley (2019) include using aquatic plants such as seagrasses to remove CO_2 from seawater, chemical balancing of pH in reef areas, reef restoration from coral nurseries, and "assisted evolution" for both corals and the dinoflagellates they host. Application of these passive and active approaches will require significant research, technology transfer, and capacity development.

2.8.4.2 Coral Reef Arks

Restoration efforts that target ecosystem-level processes, such as nutrient cycling, structural complexity and herbivory, are necessary to restore balance to these ecosystems and the services they provide. The success in colonization of ARMS deployed in various locations led to the development of Coral Reef Arks as a potential reef restoration technique. Coral Reef Arks were conceived to address a global need for new technologies that can help mitigate widespread coral reef degradation. The Arks concept has been tested by building miniature Ark models and deploying them in a coral mesocosm system. Arks are midwater structures that can be weighed in place to determine if the corals residing on them are growing (i.e., getting heavier). By moving corals up into the water column—distancing them from degraded substrates and providing improved access to light, flow, and nutrients—and by moving corals alongside the surrounding reef organisms that support coral health, Coral Reef Arks could create thriving "mini-reef" communities to support conservation and restoration goals. Arks could support the economic development of reef fisheries and tourism, and enhance coastal protection and carbon sequestration. They can also support research on marine natural products. This new tool can support restoration of reef-associated marine life as a potential option for preserving coral reefs of the world. Arks will create an entirely new way to study coral reefs and allow for the continued discovery of new marine natural products. Arks could serve as midwater nurseries and reservoirs for restoration projects, providing flora and fauna to restore reef communities following damage or degradation, and critically preserving coral reefs of the world.

2.9 Conclusions

Coral reef ecosystems provide critical services and products that are foundations of several conventional (tourism, fisheries) and emerging blue economic sectors. Intact reef ecosystems also provide protection against or reduce threats from natural hazards and extreme events. Climate change and other human activities have led to a decline in coral reefs globally, limiting their ability to provide products and services. This decline in live coral cover over the last two decades has been due to coral bleaching, coral diseases, and mechanical destruction from uncontrolled tourism and destructive fishing methods. In many regions, there have been regime shifts due to impacts of complex natural and anthropogenic factors still under investigation, where coral cover is being replaced by algal cover. There is strong evidence-based research on mechanisms explaining why corals die. However, research and monitoring are needed to continue to better understand and observe coral ecosystem dynamics and reef behavior in support of ecosystem-based management of resources. New scientific understanding could lead to new methods of conservation and launch coral restoration initiatives. Shallow-water corals are mostly bordered by developing countries in the tropics with specific local needs for observational monitoring and management approaches. Awareness and access to available new technologies and capacity building, including for personnel at the science-policy interface, are among some of the priorities.

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