7 Synthesis and Future Perspectives on the Coral Reefs in the Western Pacific Region

Jing Zhang, Gi Hoon Hong, R. John Morrison, and Thamasak Yeemin

Abstract

Being one of the older marine organisms, corals have existed on this planet for more than several hundreds of millions of years and serve as an important component in global marine ecosystems. Coral reefs provide services covering a variety of social and economic aspects affecting the life and welfare of millions of people in the Western Pacific Region. Coral reefs also protect marine environments in low latitude zones that help to reduce the impacts from global climate changes. However, the future of coral reefs in the Western Pacific Ocean and particularly tropical and subtropical areas relies on the behavior of human beings at regional scales, as well as the interactions with changes in global climate. Uncertainty exists in the predictions on how coral reefs will cope with the complex interactions between various external forcings on this planet over the next century.

Keywords

Western Pacific Ocean · Coral reefs · Multiple stressors · Ecosystem sustainability · Future development

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7.1 Introduction

The oceanic waters adjacent to the low latitude member states of the sub-commission of the UNESCO International Oceanographic Commission for the Western Pacific Region (IOC/WESTPAC) are characterized by the extensive development of shallow coral reefs. The coral reefs in the region cover about 300 × 10^6 km^2 of ocean surface area and have been estimated to provide, annually, ecosystem services ranging from 570 billion to ~33 trillion US dollars (Wilkinson 2000; Veron et al. 2009). Thus, the coral reefs in the Western Pacific Region are of paramount importance in the regional economies and welfare of human society. These coral reefs have developed in the oceans of this planet over hundreds of millions of years, starting from early Mesozoic Era (250–220 Mya). The term "Anthozoa" (i.e., corals) include three classes, Octocorallia, Hexacorallia, and Ceriantharia, in which Hexacorallia is composed of coral reef builders, the stony corals (Scleractinia), sea anemones (Actiniaria), and zoanthids (Zoantharia) (https://en.wikipedia.org/wiki/Anthozoa). The modern corals include ca. 6323 species worldwide (Appeltans et al. 2012). In the Indo-Pacific Region, reef building corals have more than 600 species, and the number of coral species that form symbiosis with zooxanthellae accounts for >75% in the world (Veron et al. 2009 and 2015; DeVantier et al. 2020), most of which are distributed in shallow waters of tropical and subtropical regions of the global ocean. In the Western Pacific Region, coral reefs can be found between 40° N and 40° S, where they contribute to ecosystems as individual reefs making archipelagoes, groups of atolls/lagoon-islands spreading all over the tropical waters, and reef flats adjacent to the coasts and/or islands (Chin et al. 2011).

Coral reefs have been incorporated into the entire range of anthropogenic activities since the beginning of human settlements. For example, coral reef ecosystems have been exploited for food items such as fish, holothurians, and seaweeds; they have been mined for use as construction

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materials, such as road fill sand, bricks, house-building and/or making cement, etc. These activities can be traced back to thousands of years ago, well before the modern era. Skeletons of some rare coral species have been used historically for decoration, jewelry, and/or currency for trade and industry. This may have accelerated their disappearance and extinction on this planet. Pearls were harvested from pearl-rearing oysters inhabiting in the coral reefs (http://www.sustainablepearls.org/pearl-farming/ecology/coral-reefs/). In modern societies, coral reefs have become even more valuable resources as sustaining pillars of regional economies, through tourism and fisheries. However, anthropogenic perturbations super-imposed by the large magnitude of climate variability have impaired the functions of coral reefs in many low latitude maritime countries over the last 500 years worldwide, including the tropical Western Pacific Ocean (Bellwood et al. 2004; Hoegh-Guldberg et al. 2007). Although detailed discussions of the anthropogenic forcings on the coral reefs would include a lengthy list of human activities, some of the more important issues are commented on below:

- In coastal areas, coral reefs serve as protection and buffering zones against damage caused by the oceans, such as tropical storms and strong waves (e.g., surges). They help to minimize serious coastal erosion on the adjacent land mass. This nearshore land is often the best agricultural area in these tropical locations.
- Coral reefs help to maintain the high level of biodiversity of marine ecosystems, particularly in the Western Pacific Region, where they provide habitats for many precious and rare biological species with rich genetic resources located close to both coastal and open ocean waters through system connectivity. Damage to coral reefs has induced an irredeemable impact on the function of marine ecosystems.
- Coral reefs play an important economic role for maritime countries that can be linked to the wealth of society. The most direct benefits include tourism and fisheries. The renewable resources in tropical areas rely on the health of coral ecosystems. In many tropical and subtropical countries, deterioration of coral reefs has become a barrier to economic progress.

Sound and sustainable management strategies should start from a comprehensive scientific understanding of the coral reef ecosystems. Here our purpose is intended to serve as a reference guide for college students, postgraduate fellows, coral reef park managers, and relevant administrators in the Western Pacific Region. In the broad Western Pacific Region from north to the south, six tropical countries (i.e., Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste) are of concern in the Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security (CTI = CFF, http://www.coraltriangleinitiative.org/), where nearly 30% of the world's coral reefs and 75% of all known coral species are found (Burke et al. 2012).

In this monograph, we try to revisit the major issues resulting from changing climate and anthropogenic perturbations on coral reefs in the Western Pacific Region. As in other tropical and subtropical marine environments, coral reefs in the Western Pacific Ocean have suffered from increased external forcings, such as global warming, sea level rise, and surface ocean acidification, which together with the land-use changes and direct (e.g., coral mining) and/or indirect (e.g., illegal fishing) exploitation activities have created much uncertainty regarding the fate and destiny of coral reefs. Based on an understanding of the nature and impact of the identified changes, plus an analysis of existing data and knowledge, we summarize the major findings of coral reef studies in the Western Pacific Region and raise a number of issues for consideration in future developments.

7.2 Function of Coral Reefs in a Sustainable Anthropocene

Large-scale environmental perturbations caused by the changes in climate and prolonged anthropogenic activities may shift coral reefs from healthy symbiotic coral regimes to barren rocky surfaces (Fig. 7.1). There exist synergistic and antagonistic effects with regard to the situation of multi-stressors (driving forces) and interactions of external forcing and coral reef, which amplifies the uncertainty of prediction for the responses of coral ecosystem to the changing external pulse. The synergistic effect can impair the resilience of coral reefs against the external forcings, while antagonistic character will visually make the systems not sensitive to the environmental changes. For example, removal of herbivores (e.g., fish and sea urchins) via overfishing, through diseases, or through excessive nutrient loadings allows macro-algae to overgrow the reef, and the coral symbiont zooxanthellae became unable to synthesize food for corals. Thus corals eventually die and the coral reefs became barren rock. Such "regime and/or phase shifts" have been observed in coral reefs in the Atlantic, Indian, and Pacific Oceans (Kleypas and Yates 2009). In fact, the so-called regime/phase shifts occur in processes of a multiple-step fashion, and the ecosystem may undergo several quasi-stable stages where each transit condition with resistance as resilient ability of system can be regarded as separate "regime" and/or "phase" for a given time and at specific space dimensions.

In a natural ecosystem, coral reefs rely on the food and energy from autotrophic endo-symbiotic zooxanthellae (e.g., dinoflagellates) and capturing planktonic prey through heterotrophic feeding. In coastal waters adjacent to human

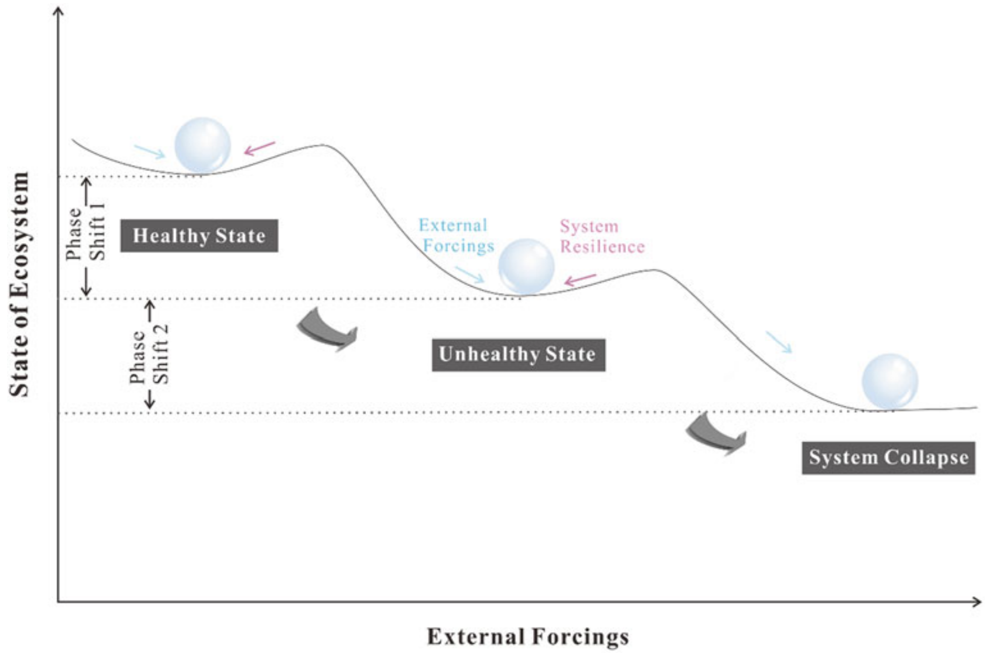

Fig. 7.1 Conceptual illustration of regime and/or phase shifts for coral reefs under the perturbation of combined external forcings and system resilience, with illustrations of different and/or intermediate phases/ regimes of state of ecosystem along with the combined stressors. In reality, there exist several/different intermediate phases/regimes between original state and system collapse, for example, the regime/ phase shifts from a dominance by hard corals to turf and macro-algae and even to rocky landscape, while the figure shows a simplified case. In the case of interactions among multi-stressors, the synergistic effects can amplify the impacts of external pulses, while antagonistic behaviors tend to increase visually the resilience of coral reefs. Note that in the figure, temporal scale is not included

settlements, over-enrichment of nutrients often occurs, and this promotes blooms of macro-algae to outcompete reef building corals for habitats and other limiting micronutrients (e.g., trace elements). The proliferation of macro-algae favors herbivorous swimmers and benthos over omnivorous species. The species compositions of swimmers and benthos (e.g., fish) are consequentially followed. Some of the sea urchins, such as black long-spined species (*Diadema antillarum*), can eat coral-smothering algae in reef systems (https://www.sciencedaily.com/releases/2001/07/010730081053.htm), but incursion of sea urchins due to overfishing (i.e., removing sea urchin predators) facilitates rapid grazing of crustose coralline algae (O'Leary and McClanahan 2010). This can remove and/or retard coral recruits and erode the coral surface and hence push the coral-zooxanthellae symbiosis towards bleaching and rocky collapse. Incursion of coral-eating starfish (e.g., crown-of-thorns starfish, *Acanthaster* sp.) due to pollution and agricultural runoff may occur (Pratchett et al. 2017). Coral diseases often occur in nearshore and eutrophic coastal waters, resulting in coral bleaching and reproductive system and genetic damage, driving the whole system from an autotrophic to a heterotrophic status.

In the coastal environment, land resources-related drainage of pollutants is usually the critical factor that initiates water quality deterioration and promotes eutrophication and, in certain circumstances, the hypoxia and even anoxia of benthic systems. Coastal eutrophication can be characterized by changes in turbidity, nutrients as well as dissolved organic carbon in the water column, and an increase in harmful algal blooms with accumulation of some kinds of biotoxins in organisms. The blooms of algae can be either indigenous through competition for limiting nutrients or invasive species that are related sometimes to shipping activities (e.g., discharge of ballast water and leach of ship hull coatings).

Although large-scale changes such as global warming, sea level rise, and surface ocean acidification are considered as the important (negative) external forcings on the sustainability of coral reefs in the Western Pacific Ocean and in other oceanic tropical and subtropical sectors, they all are of large/worldwide, slow, and persistent nature. For example, the rate of sea level rise is a few millimeters per year in the tropical Western Pacific Region countries; pH of surface seawater has been reduced by 0.1–0.2 units over the last several hundreds of years. On the other hand, anthropogenic perturbations, such as eutrophication and dumping of wastes, are local or regional in nature with small areal scale and high temporal frequencies. In the coastal environment, sea level, surface temperature, and seawater pH experience large-scale daily as well as seasonal variability. Sea level in coastal areas can be a difference of several meters between high and low tide periods, and sea water pH values can differ by 0.5–1.0

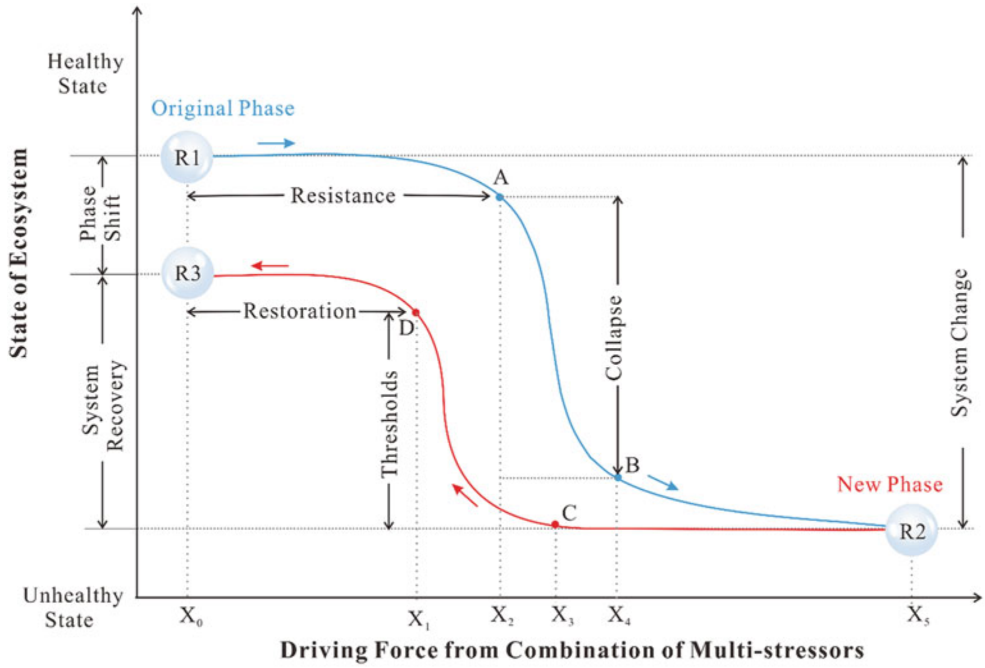

Fig. 7.2 Resistance, hysteresis, and threshold of system transformation of coral reefs. Under the impact of driving forces, original coral reefs (R1) may illustrate resilience (X_0–X_2) before collapse (X_2–X_4) to a new phase (R2). While recovery of coral reefs may be more difficult and suffering, there is threshold (X_1–X_3) before the reefs can reach the observed recovery and system stability (i.e., restoration in X_0–X_1). It is unexpected that the changes in coral reefs are irreversible, and hence there is still phase/regime shift between original status (R1) and system recovery (R3). Note that in the case of combination of multiple stressors, there exists lag/delay of system response, such as X_5–X_3. In the stage X_2–X_4, the synergistic effect can induce cascading consequences of system response. In the stage of X_3–X_1, the system response can be delayed and/or there is a lag related to the antagonistic effects

unit between day (photosynthesis dominance) and night (respiration dominance) time. These magnitudes in changes are far greater than those of the slow warming and surface ocean acidification in the ocean basin scale. Thus, the fringing reefs may have adapted to higher variability of the change in sea level, sea surface temperature, and seawater pH and hence be more resistant to the external perturbations than the coral reef ecosystems (e.g., atolls) in the open ocean situation.

Another important aspect of coral reefs is the hysteresis effect in the structure and function of ecosystems. Between different regimes, there are usually barriers and/or obstacles, because of the nature of system resilience (Fig. 7.2). In this case, release of external forcings and/or removal of anthropogenic perturbations does not necessarily mean that the ecosystems will immediately return and/or shift back to its original state. Sometimes, the full recovery of a damaged ecosystem will never happen (Wilkinson et al. 2005). What is more common is that changes in ecosystems can be slow and often irreversible, and the consequences can be delayed (lag) and even unexpected based on state-of-the-art knowledge. Therefore, new regimes/phases often emerge due to the complexity of interactions among the constituents of the coral reef system that we do not yet fully understand. Moreover, it should be kept in mind that the complex interactions between driving forces and system behaviors include synergistic and antagonistic effects of external pulses and cascading consequences of coral reefs, which in combination will result in a lag of recovery of coral reefs (Ellis et al. 2019). In the case of synergistic effect, the impact of individual stressors is amplified, while antagonistic behavior will make the system more resilient against the combined external pulses. For example, increased levels of ultraviolet radiation can damage photosynthetic cells, which in combination with thermal stress can accelerate and exacerbate the coral bleachings (Radice et al. 2020). Nevertheless, elevated pCO_2 and low pH associated with upwellings are considered stressors with negative effects on the reef metabolism; coral calcification is autotrophy-enhanced process with photosynthetic drawdown of seawater CO_2 concentrations that elevates Ω_{ar} and hence favorable for organismal $CaCO_3$ deposition (Yeakel et al. 2015).

7.3 Coral Reefs in the Western Pacific Region and Comparison to Other Areas

Coral reefs are found in the low latitude zones of the Western Pacific Ocean and the adjacent coastal seas, covering wide areas in tropical and subtropical climate (i.e., between 40 °N and 40 °S), and illustrate a spectacular landscape on this plant, in comparison to Indian Ocean and Atlantic Ocean (Fig. 7.3). As coral reefs are increasingly important for the human society in the broad Indo-Pacific Region in terms of economic value, cultural heritage, and aesthetic status, wise management is urgently needed in the current phase of climate change response and rapid expansion of various economic activities centered around the coral reefs (e.g., tourism).

Globally, the total area of coral reefs has decreased by almost a half from 62 million hectare (ha, 1 ha = 10^{-2} km^2) in 1977 to 28 million ha in 2001 that is equivalent to 280×10^3 km^2, i.e., a reduction of ca. 50% in the last quarter of the twentieth century (Spalding et al. 2001; De'ath et al. 2012). The unit ecosystem service value of coral reefs has been estimated to be on average US $352,249 per ha/year (i.e., $36,794 to $2,129,122/ha/year) in 2007 dollar value (Costanza et al. 2014). The services provided annually by coral reefs include food (e.g., 5–15 tons of sea food/km^2), 150×10^3 km long shoreline protection from storms and erosion, about 15% of gross domestic product (GDP) in the world, and largely untapped sources of natural products with enormous potential as pharmaceuticals, nutritional supplements, enzymes, pesticides, cosmetics, and other novel commercial products. The total area of coral reefs in the Western Pacific Region is more than 134,860 km^2 and accounts for close to the half of the world area of the coral reefs. Moreover, the Indo-Pacific Region as a whole accounts for more than 90% of the global shallow coral reefs as shown in Spalding et al. (2001) and also in Table 7.1. It should be noted, however, that most of coral reefs are claimed within the Economic Exclusive Zones (EEZs) of individual countries, one or another, in the tropical and subtropical climate region. Given the fact that the claimed EEZs by different countries in the Western Pacific Ocean have conflicts of political interests and differences in economic demands, the reef areas and associated populations shown in Table 7.1 may have overlaps, and hence interpretation should be with caution.

Tropical and subtropical areas of the Western Pacific Region include a human population of ca. 1 billion of people, including mainland and island countries (Spalding, et al. 2001). Most maritime countries in this region rely on the services provided by coral ecosystems (e.g., coral reefs) as an important component of their GDP and national treasuries, based on fishery, tourism, pharmacology and manufacturing industry (e.g., natural products), and richness in biodiversity due to the structural complexity of their habitats (hotspots) generating multiple ecological niches for thousands of associated biological species, from microbial communities to the top predators (Roberts et al. 2002). This biodiversity (species) richness and heritage favor reef stability and provide benefits to human society (Rabosky et al. 2018). Such services have become indispensable to the daily life of millions of people in the coastal areas of the Western Pacific Ocean.

It has been reported that about 727 hermatypic coral species in 13 families are found in the Western Pacific Ocean (Bellwood et al. 2005), as the area is the most important on this planet for coral ecology and landscape (Roberts et al. 2002). In particular, East Indies Triangle (i.e., Indonesia, Malaysia, New Guinea Island, and the Philippines) is known to be the area of a global maximum for species diversity for several marine taxa, including fishes, corals, lobsters, and snails, and those species diversity is found to be decreased away from the triangle (Reaks et al. 2008). In most areas of the Western Pacific Region, coral reefs have exhibited various impairment symptoms depending on the type of external perturbations, locations, and temporal scales. Some important and negative impairment syndromes of coral species which hence lead to loss of ecosystem function in the Western Pacific Ocean can be summarized as below:

- Coral bleaching can be related to different forcing factors, such as changes in sea surface temperature, UV radiation and inhibition, overloading of sediments and change in turbidity, and nutrient (sewage) dumping by the local population.
- Coral diseases caused by bacteria and viruses are usually related to the deterioration of water quality, such as drainage of pollutants from adjacent land sources as well as the changes in seawater thermal conditions (e.g., temperature).
- Change from healthy corals to macro-algae-dominated systems and then rocky landscape can be a result of either over-enrichment of terrestrial nutrients (i.e., bottom-up) or overfishing of herbivores (i.e., top-down), or both.
- Release of predation pressure could decimate the coverage of live corals on the reef and consequently free space for algal growth (i.e., outbreaks of coral tissue-feeding crown-of-thorns sea stars).
- Loss of habitats provided by the coral reefs can also be a consequence of illegal fishing, mining and coral reclamation, as well as the damage by natural factors, such as the typhoon and tsunami and bleaching under high sea-surface temperature (SST).

In the Western Pacific Region, climate variability and anthropogenic perturbations have been recorded in the coral bands of reefs. For example, coral samples from Guam illustrate an increase of more than two orders of magnitude in the levels of $^{239+240}Pu$ since the 1950s, resulting from atomic bomb tests in the subtropical Pacific Ocean. Moreover, the accumulation of radionuclides in corals showed a similar pattern to the worldwide $^{239+240}Pu$ depositions from global fallout (Lindahl et al. 2011). In the subtropical Western

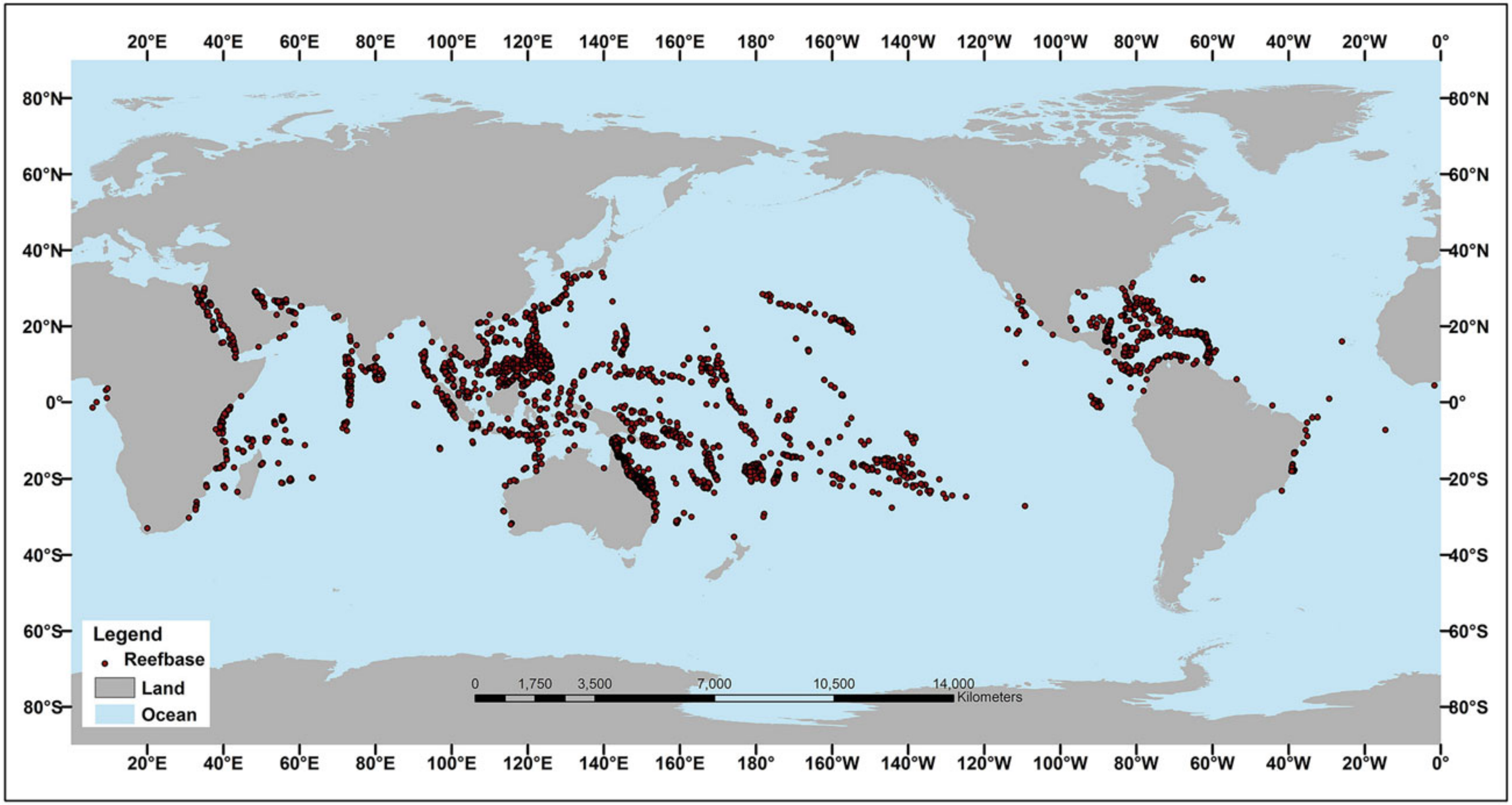

Fig. 7.3 A global view of the distribution of coral reefs in the region of 40 °N to 40 °S, seen from space. The figure is a composite image based on the data of satellite. In the figure, distribution of coral reefs in the Western Pacific Ocean is outstanding in comparison to other tropical and subtropical areas, such as Atlantic and Indian Oceans. This figure is from NOAA: "In what types of water do corals live? National Ocean Service website, web-site at https://oceanservice.noaa.gov/facts/coralwaters.html, renewed on 01/07/2020"

Table 7.1 Reef area (km^2) and population protected by coral reefs in the wider Western Pacific Ocean. Data are from Spalding et al. (2001) and Pendleton et al. (2016) with update from Burke et al. (2012)

Western Pacific Region	Reef area (km^2)	Population protected by coral reefs (inds.)
Australia	48,960	316,027
Bangladesh	50	1318
China	2450	1,212,378
Fiji	10,020	383,845
Indonesia	39,358	12,198,508
Japan	2900	623,273
Malaysia	2935	1,142,333
Philippines	22,484	12,963,66
Samoa	490	316,027
Singapore	13	78,342
Solomon Islands	5750	307,616
Thailand	2130	233,667
Tonga	1500	84,729
Vietnam	1270	1,581,789
Kiribati	2940	110,000
Marshall Islands	6110	65,000
New Zealand	150	No data
Palau	1150	6000
Papua New Guinea	13,840	750,000
Timor-Leste	350	15,000
Vanuatu	4110	42,000
American Samoa	220	1500
Commonwealth of Northern Marianas	88	33,000
Federated States Micronesia	4340	65,000
French Polynesia	6000	125,000
Guam	220	55,000
New Caledonia	5980	95,000
Wallis and Futuna	940	5000
Western Pacific Region Total	208,398	18,669,683

Note: According to Davey (2015), New Zealand in the strict sense does not have any coral reefs—rather it has coral colonies located in the northernmost islands (i.e., Kermadec Islands, Bay of Islands, etc.)

Pacific Ocean, anthropogenic lead concentrations in the reef-building corals have increased by more than fivefold in the twentieth century, and stable isotope ratios of lead (e.g., $^{206}Pb/^{207}Pb$ vs $^{208}Pb/^{207}Pb$) in corals provide clues as to the different sources, i.e., Australian mining Pb, Chinese loess, and lead deposition from gasoline exhausts via atmospheric depositions (Inoue and Tanimizu 2008).

In coastal areas of Thailand, coverage of hard corals (%) and related fish abundance are negatively correlated with the quality of ambient seawaters. Particularly, a reduction of coral coverage is observed when the area is affected by nutrient sewage inputs from adjacent land use (Reopanichkul et al. 2009). Along the coast of Thailand, corals are replaced by macro-algae where influx of nutrients and turbidity are both increased, and dissolved oxygen contents decrease due to the enhanced (high) level of sewage discharges from adjacent land-based sources.

In the Great Barrier Reef off the eastern Australia, it has been found that coral bleaching is regulated by a combination of thermal stress (i.e., sea surface temperature) and surface runoff from adjacent land-based activities, such as pollution (Furnas et al. 2005). In areas affected by flood plumes from river with higher nutrients and *Chl-a* levels (i.e., inshore), temperature and exposure time of thermal bleaching of corals have lower resistance compared to reef systems further off-shore, and a reduction of 1 °C–2 °C of bleaching threshold was observed for the inshore reef systems affected by the surface runoff (Wooldridge 2009). Reduction of nutrient input (i.e., dissolved inorganic nitrogen, DIN) from adjacent land sources was reported to induce an increase of resistance of coral reefs to thermal bleaching (i.e., higher threshold) again.

7.4 External Forcings and Systems Response Threats to Coral Reefs in the Indo-Western Pacific Region

Threats to the health of coral reefs range from the sudden increase of sediment and nutrient loads to coastal areas resulting from human activities, surface ocean warming, and acidification due to the emission of greenhouse gases through industrial activities, to the underlying climate change resulting from the periodic orbital variations (e.g., Milankovich Cycle).

The deterioration of coral reefs is manifested by the suppressed growth and survival of hard coral colonies, coral reproduction and recruitment, and disturbance of the previous interactions of coral populations with other organisms (e.g., coralline algae, bioeroders, macro-algae and heterotrophic filter feeders, pathogens, and coral predators), which has been recognized an impact with negative consequences, for example, coverage and mortality, fecundity and recruitment, photosynthesis, symbiont, and calcification (Jones et al. 2015). An increase in nutrient supply (i.e., eutrophication) from the coastal cities and tourist industries may induce the blooming of crustose coralline algae and/or even macro-algae, forming mucous sheets enveloping the colony's surface and trigger or aggravate coral diseases (Bessell-Browne et al. 2017). This results in consequences of calcification, fecundity, and larval survival to decrease (Szmant 2002; Fabricius 2005; Costa et al. 2008). Increase in terrestrial sediment load to the adjacent coral reefs can increase water turbidity and reduce the underwater light field (e.g., photosynthetically available radiation and quantum yield), which can lead to declining coral cover and diversity and decreased recruitment of juveniles (Fabricius 2005; Cooper and Fabricius 2007). Drainage of pollutants, including sub-marine ground sources and discharge of ballast waters, may also induce lower symbiont zooxanthellae density, reduced recruitment, and increased possibility of infection by diseases (Laporiade 1997). Furthermore, eutrophication modifies the interactions between microbial loop and the main food chain in the reef areas, which alters the pathway of material flow and energy partitioning in the system, with proliferation of heterotrophic bacteria. In the case when hypoxic water develops, benthic system can be also negatively affected.

Coastal reclamation, including construction of airfields and resorts, as well as lime production using corals, can significantly damage and/or even destroy the whole adjacent coral reef (Maragos et al. 1996). Furthermore, different fishing activities, such as selective fishing on top-predators vs herbivores, may also affect the habitats through changing competition among corals, macro-algae, and turf algae (Walsh 2011). All the stressors mentioned above are related to human-designed/intended activities within the adjacent watersheds and/or even in the marine environment itself (e.g., overfishing and illegal fishing activities). Nevertheless, changes in food-web structure of coral reefs can affect the coral coverage and symbiont relationships, for example, an increase in biomass of filter feeders and grazers, resulting from land to sea gradients (i.e., inshore–offshore) created by the land-based human activities (Fabricius 2005; Kleypas et al. 2006).

Last but not the least, climate variability and a slow but consistent trend of warming/sea level rise and ocean acidification also have negative but not to be underestimated impacts in the Western Pacific Region. For example, calcification and growth rates of coral communities all decrease along with the increase of pCO_2 and reduction of Ω_{arag}, i.e., the saturation of aragonite in surface seawater (Kleypas et al. 2006; Kleypas and Yates 2009). In the high CO_2 and SST oceanic waters, the combined effects of thermal and pH stressors make the system calcification more difficult because extra energy is required to maintain the function of H^+ and Ca^{2+} gradients in the cell. At the same time, respiration can be higher than the rate of system photosynthesis. Using pCO_2 and SST as independent variables, the model prediction indicates that at $pCO_2 = 450$ ppm (v/v), the calcification rates of corals in the Western Pacific Ocean can be reduced by 50% (Kleypas and Yates 2009).

7.5 Summary and Main Conclusions of This Study

The present book is composed of five cross-linked chapters based on the digestion of research data that is focused on the Western Pacific Ocean, covering broad interests and including anthropogenic environmental impacts on coral reefs, coral biology and reef ecology, biogeochemical cycle of coral systems, proxies to understand climate and anthropogenic processes, and tracers embedded in coral skeletons that can explain various aspects of research results in the science of coral reefs (Fig. 7.4). Although the mission of this monograph is largely scientific in nature and is contributed by the research community of the Western Pacific Ocean, the knowledge summarized within is equally applicable to the Indian and Atlantic Oceans and thus helpful in configuring research and designing management in other parts of the world. In this section, the major findings of this monograph will be discussed and synthesized below based on the snapshot of individual chapters.

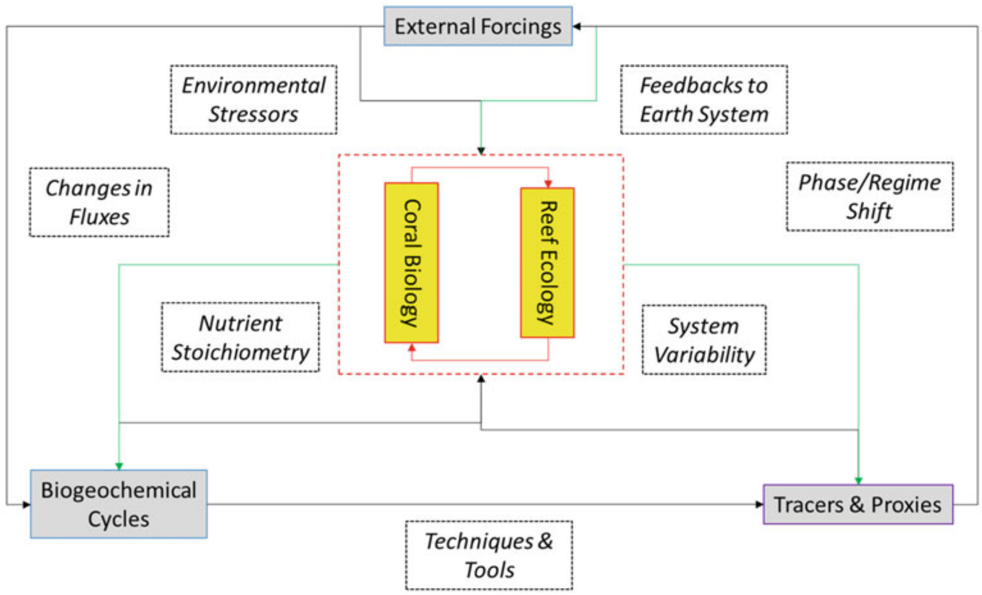

Fig. 7.4 Structure of present monograph, illustrating the cross-link of individual chapters that cover the major aspects of coral reefs study and challenges of coral reefs of Indo-Pacific Oceans. In the figure, five cross-linked chapters are indicated by shadow boxes; box with italic words illustrates the potential interactions between different chapters. Green arrows emphasize the impacts of coral reefs; otherwise, black color is used in the figure

7.5.1 Anthropogenic Impacts Become Dominant Issues for the Sustainable Development of Coral Reef Systems

Coral reefs are among the most important ecosystems globally. They provide food and construction materials for millions of people living in the tropics, but this use of the reef by humans comes at a cost. The major drivers of the many anthropogenic impacts on the coral reef environments in the Southeast Asia and Pacific Island region include increasing overall populations, increasing migration of people from inland to coastal areas, and issues relating to subsistence and low-income community's response to the global economic situation through their changing use of reef resources, e.g., increased reef gleaning. Pollution from small-scale and/or local developments can be linked to, for example, urbanization and industry, as well as impacts from other human activities including agriculture and aquaculture, tourism such as construction of resorts and diving facilities, mining, commercial fishing including marine and coastal mariculture. Relevant issues like land-use changes, coastal erosion, sedimentation, and eutrophication are recognized as being of major importance. Related impacts caused by coastal city expansion (e.g., building of ports and marinas, roads, industrial areas, waste management—including location of "landfills" and sewage treatment facilities) have received a good deal of attention, and we now have a reasonable understanding of the nature of their impacts. The significant impacts of shipping and trade activities (e.g., oil spills, reef collisions, waste disposal, antifouling materials) are also considered. The problem of plastics has come to the fore in recent years (Law 2017), with substantial quantities of plastic materials being found near most coastal population centers, and they are found in the bodies of a large number of coral reef organisms (Reichert et al. 2018). A comprehensive listing of the anthropogenic activities impacting on coral reefs, together with a review of the impacts from each type of activity, shows that the influence of anthropogenic activities can be dramatic in the absence of good legislation, management planning, and the effective implementation of both.

These direct impacts of humans can be enhanced by indirect effects of climate change (e.g., temperature, rainfall, acidification, sea level rise, and tropical storms) that are superimposed on the direct anthropogenic impacts. Hydrodynamic patterns around coral reefs are also altered by anthropogenic activities. The driving forces based on the impact types (e.g., hydrodynamics changes, sediment fluxes, nutrient flows, contaminant mobilization/transport/transformation) and the consequences for coral reefs of changes in these driving forces are discussed in the previous sections of this monograph.

Pollution can occur from many sources. These include small-scale developments, e.g., tourism and local industry (e.g., diving, construction of resorts and harbors), as well as impacts from large (watersheds)-scale human activities including agriculture, urbanization, extraction of resources (mining), commercial fishing, and marine and coastal mariculture. Pollution can also be from marine sector itself, such as those related to shipping activities, oil platforms and oceanic trade, for example, discharge of ballast waters may introduce alien species and external nutrients. Issues like land-use change, sedimentation, and eutrophication cause serious problems over wide areas of the region. Throughout the Western Pacific Region, coastal city expansion (e.g., building of ports, roads, industrial areas, housing and sites for waste management—including location of "landfills" and sewage treatment facilities) is problematic, often leading to pollution, sediment mobilization, displacement, and burial of reefs. Another problem for most governments in the Western Pacific Region is the significant impact of shipping activities and ship repairing in yard, including oil spills, reef collisions, waste disposal, and antifouling material handling and management, particularly in the Southeast Asia.

A comprehensive listing of the activities impacting on coral reefs, together with a review of the impacts from each type of anthropogenic activity, has been developed (Table 2.1 in Morrison and Aalbersberg, Chap. 2). This list, when complemented by commentary on the effects of climate change that are superimposed on the direct anthropogenic impacts, such as temperature, rainfall, acidification, sea level rise, and storms, provides a mechanism for developing a comprehensive picture of human impacts in any selected area. This information will assist environmental decision-makers in determining a priority order of actions that need to be addressed given local political and economic conditions.

7.5.2 Coral Biology Is Critical in Our Knowledge of Tropical and Subtropical Environments

Understanding coral biology is crucial for coral reef management under the crisis of global change. This monograph provides updated knowledge on several important aspects of coral biology with focus on the Western Pacific Ocean. The aspects include coral bleaching, coral diseases, coral genetics and sexual reproduction, developmental biology, and recruitment in corals. Studies on coral bleaching have focused on spatial and temporal variations of bleaching events, causes, mechanisms, and consequences of coral bleaching impacts. The severe coral bleaching events were observed in the years 1998 and then 2014–2017. Due to global warming and the transition to Anthropocene, coral bleaching is occurring more frequently in all El Niño–Southern Oscillation phases, increasing the annual coral bleaching in the next decades. The mechanisms in which the coral and its zooxanthellae are impacted by high temperatures and the initial cellular responses to the stress are intensively examined. Effects of coral bleaching on coral reef ecosystems include a decrease in net rates of calcium carbonate accretion and changes in primary productivity.

Coral diseases have the potential to significantly affect corals and their community structures. Several studies illustrated coral disease prevalence in Indo-Pacific reefs which is linked to local anthropogenic disturbances, such as eutrophication, sedimentation, land-based pollution, marine debris, and increased ocean temperatures. Several case studies of the identification and transmission of coral diseases are documented. Plastic waste can enhance microbial colonization by pathogens implicated in outbreaks of disease in marine ecosystems. The proposed prevention of coral diseases includes policy, management and good practice, technical methods, and coral genetic selection. The methods for the prevention and therapy of coral diseases are recently proposed.

Coral genetics have been intensively examined, particularly for research applications in molecular taxonomy and systematics as well as coral population genetics. The proposed integrative classification system will form the framework for more accurate biodiversity estimates and guide the taxonomic placement of extinct species. Molecular studies have been instrumental in refining species boundaries in the coral species complex and revealing hidden species diversity. Mitochondrial molecular phylogenies are congruent with groups based on gross morphology, therefore reflecting species-level differentiation. Population genetic studies based on genotypic information using molecular markers have clarified genetic diversity and connectivity, clonality, and species diversity, particularly cryptic species and coral population adaptations. Gene flow is also useful for investigating the expression of population dynamics. Population genetic studies are useful for estimating reproductive features and past events based on the extent of genetic differentiation in populations from different locations.

Advances in coral sexual reproduction, fertilization, hybridization, development, and recruitment are highlighted in this study. Coral spawning is often presented as synchronized phenomena. The important controlling factors include temperature, solar irradiance, wind, lunar cycles, and sunset times. Several coral species from some reef sites have lost their reproductive synchrony. Ultimately, such a synchrony breakdown reduces the probability of successful fertilization, resulting in the reduction of new recruits, which may drive coral populations to extinction. The *Acropora tenuis* had a mixture of gametes from more than six intraspecific colonies and could achieve stable fertilization rates of greater than 95%. Synchronous spawning occurs among many *Acropora* species, and crossing experiments have shown that some species can hybridize in vitro. Some products of interspecific hybridization may persist as the offspring of self-fertilizing F1 hybrids. The developmental biology of corals reveals that there are two major groups, the "complex" and the "robust." One apparent difference between these two major groups is that before gastrulation the cells of the complex corals thus far described spread and flatten to produce the so-called prawn chip, which lacks a blastocoel. Understanding coral recruitment patterns for effective coral reef management is very important. Recruitment rates and juvenile abundance were lower on the more degraded reef. These patterns are likely a consequence of differential pre-and post-settlement mortality as a result of the high sedimentation rates and degraded conditions and possibly reduced larval supply.

7.5.3 Coral Reef Ecology Bridges System Functions and Adaptive Management Towards a Sustainable Development

The important information on coral reef biodiversity decline and extinction risk, coral reef recovery after disturbances, coral reef resilience, coral reef connectivity, coral reef bioerosion, coral reef refugia under global change, marine protected area networks, and passive and active restoration of degraded coral reefs is synthesized in this monograph. Coral reefs are critically important to the economic development of most tropical and maritime countries. The loss of vulnerable species from coral communities is occurring at an accelerating rate, particularly in the Western Pacific Region. Many coral species are impacted by anthropogenic perturbations, especially those in the coastal waters which are at risk. Coral reef recovery following severe disturbances depends on several complicated factors, including resistance and tolerance to external forcings, recruitment rate, reef connectivity, and local stressors. Some resilience factors have the potential to operate within the predicted annual frequency of thermal stress events, whereas others act over longer timescales. The resilience assessment involves assessing ecological factors that contribute to resistance and recovery, particularly bleaching-resistant coral species and coral recruitment and anthropogenic stressors that reduce resilience. Managers can use the resilience index to compare coral reef resilience levels among reef sites and times for global coral reef resilience assessment. The main goal of resilience-based management is to identify and prioritize management actions that enhance system resilience. Maintaining reef framework is also very important, particularly taking into consideration the bioerosion rate at a degraded reef. Reef-derived carbonate and organic matter, for example, in sediments, may dissolve chemically, at a rate correlated with the aragonite saturation state of the overlying seawater column. The biologically driven erosional processes are associated with the grazing activities of various fish and sea urchins, as well as the activities of various endolithic (internal substrate living, borers), including sponges, bivalves, worms, and microorganisms, such as cyanobacteria and fungi.

As global climate change potentially causes more frequent and severe coral bleaching events, identifying and conserving coral reef refugia is critically important. Coral reef refugia should be able to buffer regional changes in stressors related to environmental change, particularly seawater temperature (SST) and ocean acidity (pH) over decades while providing other conditions conducive to coral growth and reproduction, for a large complement of corals and associated species. Most coral reefs are in a type of marine protected areas (MPAs) that intensively require scientific data for management. Fifteen principles for integrating fisheries, biodiversity, and climate change objectives into MPA network design simultaneously were proposed. The establishment and management of MPAs and MPA networks should be based on adequate scientific information particularly to identify which areas serve as spawning, feeding, and nursery grounds and sink/source of juvenile fish/corals.

The achievements of passive and active coral reef restoration projects in the Western Pacific Region are necessarily considered for the improvement of coral reef management plans. Community involvement is very important to the success of coral reef restoration efforts, and it has the added benefit of raising awareness. The most effective and widely used method for active coral reef restoration is coral gardening. The coral gardening concept is a two-step process, i.e., the nursery phase dedicated to the development of large stocks of coral colonies in mid-water floating nurseries and the transplantation phase where nursery-farmed coral colonies, which have reached suitable sizes, are out-planted onto degraded reef areas. Integrating functional considerations into transplantation acts, such as in the use of allogenic and autogenic engineer species, could improve the impacts of restoration on coral reef biodiversity. The active coral reef restoration toolbox provided seven classes of novel avenues and tools, which include the improved gardening methodologies, ecological engineering approaches, assisted migration/colonization, assisted genetics/evolution, assisted microbiome, coral epigenetics, and coral chimerism. The guidelines for maximizing the adaptive potential of restored coral populations aimed to re-establish populations that are capable of sexual recruitment and genetic exchange. Coral larval enhancement also has the potential for increased scales of restoration on damaged reefs.

7.5.4 Biogeochemical Processes of Coral Reefs Play a Key Role in Understanding the Element Cycles and Connectivity Between Different Systems

Coral reefs in the Western Pacific Region are distributed over a wide range of different biogeochemical provinces. The coral systems can be found along water quality gradients including from reef flats in coastal (inshore) environments with, generally, a eutrophic character to the offshore barrier reefs and atolls which tend to be more oligotrophic in character. In coral reef systems, biogeochemical processes play a critical role in material flow and energy distribution among different compartments and for the maintenance of different metabolic functions. The successful symbiont relationship between coral (consumer) and zooxanthellae (producer) relies also on the sustainable provision of macro- and micronutrients. Many corals also have the ability to use heterotrophic pathways for food resources (i.e., dissolved and particulate organic matter), and hence the partitioning of material flow (nutrition) between autotrophic (i.e., photosynthesis by zooxanthellae) and external food uptake have a dramatic impact on the sustainable development of coral reefs in a changing marine environment. The influence of changing biogeochemical pathways induced by physical (i.e., hydrography and circulation), biological (e.g., food-web structure), and other factors (e.g., external forcings) on coral reefs can be in various aspects, for example, different concentrations for nutrients and their species ratio in autotrophic process, availability of dissolved and particulate organic matter in the water column as for heterotrophic food sources, and other pollutants and toxic materials with side effects such as pathogens and diseases. The responses of coral reefs to the abovementioned biogeochemical impacts include, but are not limited to, changes in the ratio between autotrophic and heterotrophic food resources for corals, calcification and growth rate, fecundity and coverage, as well as the connectivity between different reef systems (e.g., recruitment of juveniles). In the Western Pacific Region, degradation of coral reef systems has been observed almost everywhere across biogeochemical gradients (e.g., water quality as proxy) at low and mid-latitudes, from eutrophic coastal environment to oligotrophic open ocean waters (Williams et al. 2015).

In the oligotrophic waters from open and deep ocean, offshore coral reefs are facing low primary production, limited by nutrients and/or trace elements, where external forcings are linked to large-scale climate variability, such as warming and acidification. The sustainability of coral reefs in the offshore and open oceanic areas is heavily dependent on the biogeochemical processes (e.g., via upwellings) that regulate availability and supply of limiting chemical elements and the variability between new vs recycled nutrients and trace elements.

On the other side, in the nearshore environment, fringing reefs live in a condition affected by the human perturbations driven by land-based and in situ processes, imposed on the climate variability that is sometimes difficult to distinguish and separate, but together make the living situation more harsh than in the open and offshore systems. In this area, the challenge is how coral reefs can cope with the increased pollution and changes in habitats that both can be the driving forces for biogeochemical dynamics.

In addition to observations and laboratory simulations, a rather simple biogeochemical model can be developed to understand the behavior of coral and zooxanthellae symbiosis under the external forcings, such as availability of nutrients and increased temperature. The model outputs indicate that carbon transfer between zooxanthellae and the coral host and coral feeding rates both can be affected by the external nutrient concentrations and the temperature gradient. The implications include that changes in limiting nutrient species and global warming can have dramatic impacts on the sustainability of coral reefs. The potential of coupling a biogeochemical module into the 3-D hydrographic model is that responses of the coral ecosystem to environmental changes, such as the ocean warming, acidification, and coastal eutrophication, can be analyzed with fine resolutions in time and space.

7.5.5 Proxies Embedded in Coral Skeletons Are Powerful Tool to Track the Impact of Environmental and Climate Variabilities

Human pressures on coral reefs are reported to have increased significantly worldwide in recent decades, and their impact on the coral reefs are more pronounced in the Western Pacific Ocean including the Southeast Asia. For example, the Coral Triangle Region indicated that the level of threat from local activities (e.g., overfishing, destructive fishing, coastal development, watershed-based pollution) increased by about 40% from 1998 to 2007 (Burke et al. 2012). In addition to direct human activities, indirect environmental changes caused by global warming and surface ocean acidification together with low frequency natural climate variability and the associated changes arising from the consequences stemming from the species interactions among coral reef ecosystem constituents (e.g., proliferation of predators and diseases) also stress corals. Large-scale storm surges or tsunamis will, in some areas, physically destroy (e.g., kill corals, break corals, upturn corals) or disturb the health of coral reefs (e.g., partial bleaching, infestation with disease, silt-smothered live corals), for example, India, Indonesia, and Thailand after 2004 Indian Ocean earthquakes and tsunami (Kumaraguru et al. 2005; Wilkinson et al. 2005).

These environmental changes affect the chemical composition of the ambient seawater, where the coral grows. These seawater composition changes are often incorporated into the processes of calcium carbonate mineral aragonite precipitation as impurities or snapshots of isotopic variations within various constituents, since the entire processes of calcification are dictated by animal coral mediated thermodynamic principles. Therefore, deciphering environmental change indicators embedded in coral skeletons is dependent upon scientific reasoning and analytical capabilities. Many new tracers have been established recently, thanks to the advances in our understanding on the biology of aragonite skeletal formations in relation to the ambient seawater chemical and isotopic compositions and of the analytical instruments such as mass spectrometry and non-destructive analytical devices.

Corals generally precipitate their aragonite skeletons along the growth axis at a rate of about 1 centimeter a year. Therefore, a high-resolution sampling has to be made to provide signals at shorter than monthly intervals, which faithfully record seawater composition changes at the time of their growth. Dating of coral bands is available using visual or x-radiographs of annual growth bands; ^{14}C, ^{210}Pb, ^{228}Th, ^{230}Th, and artificial radionuclides of ^{90}Sr and ^{239}Pu isotopes; and amino acid racemization depending upon the purpose of the research project and amount of sample available. The exemplary tracers for long-term climate and environmental and short-term anthropogenic changes occurring in coral reefs ecosystem are Li, B, C, N, O, F, Na, Mg, P, S, Ca, V, Cr, Mn, Fe, Ni, Cu, Zn, Sr, Y, Mo, Cd, I, Ba, Nd and other rare earth elements (REEs), Pb, U, Pu, and their isotopes. As trace elements and their isotopes in the ocean receive major attention since 2010 through the ongoing GEOTRACES program (an international study of marine biogeochemical cycles of trace elements and their isotopes), the knowledge on the incorporation of trace impurities into coral skeletons will be greatly expanded in the coming decades. An extensive comparative study on the instrumental records and climate and environmental variabilities over the past 50–150 years led by another international program on the Future Earth Past Global Changes (PAGES 2k) for 2017–2020 will also greatly strengthen our ability to decipher climate and environmental changes that occurred in the ancient times before the modern instrumental records were available. This is particularly important for temperature estimation from a variety of geochemical proxies and their uncertainties, analytical issues associated with fossil corals, and novel proxies for global biogeochemical cycles (Zinke et al. 2018). Therefore, coral proxies will be very useful in coming decades for deciphering what happened in the past, and simultaneously they will provide us with critical knowledge and tools for the better stewardship of the fragile coral reefs facing multiple stressors both now and in the years to come. More detailed information embedded in coral skeletons will be added continuously to our knowledge base on the long-term variation in chemical composition of seawater and Earth climate as coral reefs were formed approximately 500 million years ago and continue to provide valuable information (Webby 1984).

7.6 Challenges for the Ecosystem-Based Management (EbM)

Given that the trends of increasing global warming, sea level rise, and ocean acidification will persist for the next century and/or even beyond, and various perturbations by human beings will also exert their influence on the coastal and terrestrial environment and adjacent marine waters, coral reefs in the Western Pacific Region will continue to face different external stressors in combination and will have to continue to cope with constraints arising from a changing environment (Fig. 7.5).

Managing coral reef ecosystems at the ecosystem level requires an integrated monitoring network and an operational strategy. Existing monitoring stations are usually confined to the coast, and the distribution of sites is limited to a few places covering the vast coral reef area. The data collection and transmission from monitoring stations to the home laboratory/office are often delayed. Moreover, in situ monitoring activity is limited to only a few relatively easily measured parameters, such as temperature, pressure (depth), salinity, and fluorescence of seawater. It is expected that the parameters of most interest in coral reef ecosystems, such as nutrients (index of eutrophication), dissolved oxygen (DO) (indicator of hypoxia), composition and abundance of pigments (information on the algae assembly and abundance), and turbidity (proxy of total suspended matter) in the water column will be designed, and monitoring stations will be added along the seawater chemical compositional gradients from nearshore to the offshore. Thanks to the advances in Internet and satellite communication technologies, more data transmission between monitoring sites and onshore laboratories will become two-way and real-time, which provides an opportunity for swift (response) actions to be initiated as required. The purpose of marine spatial planning (MSP) as a part of the integrated coastal zone management for a given community is to examine ecosystem services to the predetermined magnitude in terms of social, economic, and environmental benefits in a sustainable manner considering both current and future generations. Therefore, marine spatial planning should utilize an ecosystem-based approach (EbA). This marine spatial planning may be used to select the sites, their environmental variables, and frequencies of monitoring in a given coral reef ecosystem. The monitoring networks could be tied into an early warning observation system for marine disasters, including abrupt seawater compositional changes, algal blooms, storm surges, etc.

The observed data transmitted from the field to the onshore laboratory will need to be fed into numerical water circulation and/or biogeochemical models of a given coral reef ecosystem. In the past, observations on coral reefs usually included photographs and sampling for nutrients, alkalinity, pH, pCO_2, composition of pigments, and taxonomy, whereas observations towards understanding food-web structure and interactions between different trophic levels and physiological time series did not receive sufficient attention. Therefore, observations on such ecosystem level variables and parameters should be promoted. Incubation and

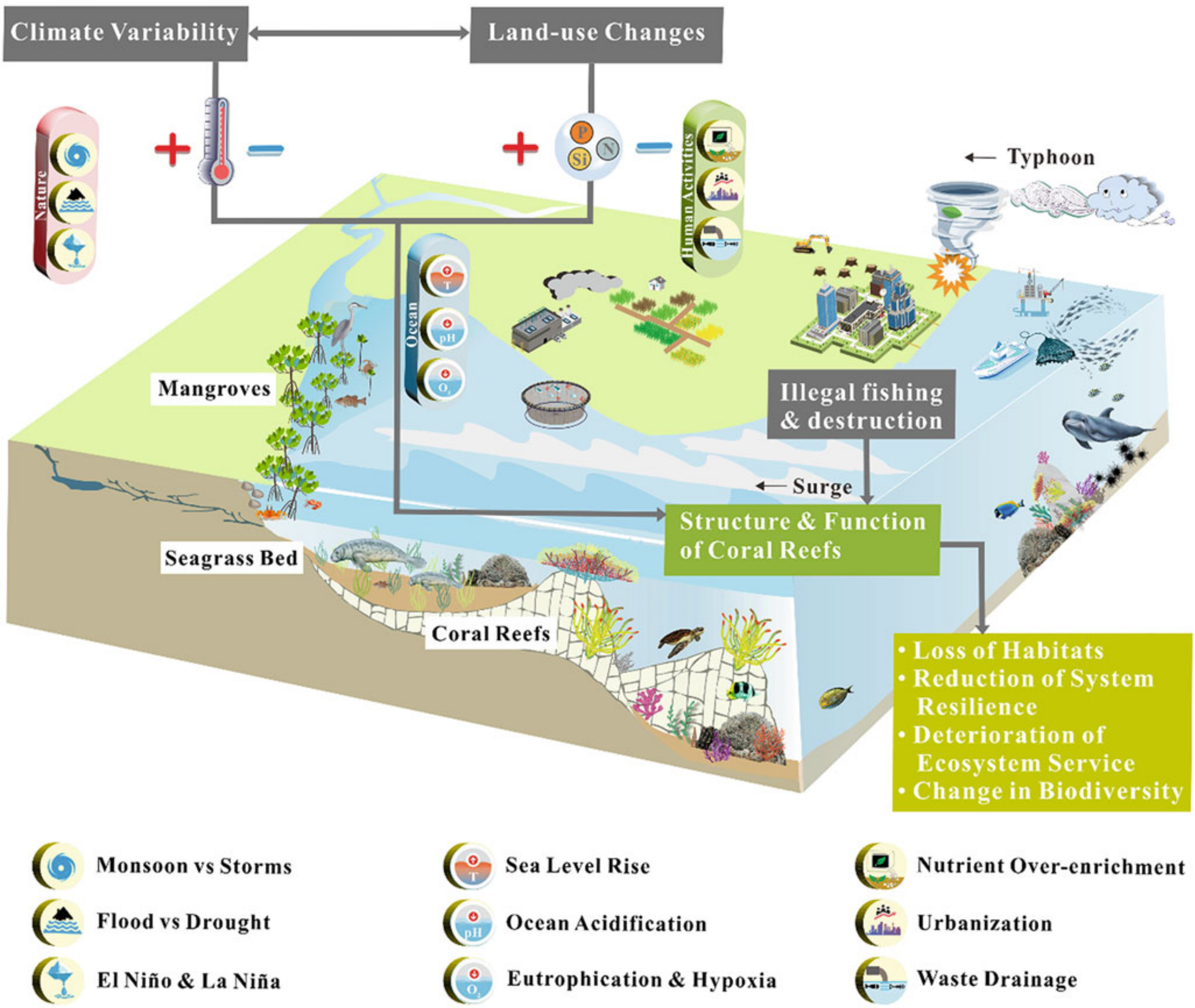

Fig. 7.5 Illustration of interactions between external forcings and responses of coral reefs, with applications for the Western Pacific Ocean at ecosystem management level. In the figure, the combined effects of natural and anthropogenic forcings may induce a number of syndromes from molecular to system levels, while responses of coral reefs are system specific

mesocosm experiments on the rate measurements and mechanism approaches should be encouraged in order to parameterize the biogeochemical processes and validate outputs of numerical simulations. Moreover, observations should be combined with continuous monitoring networks, and hence the spatial coverage of observational data can be integrated with the time-series information from monitoring sites in order to describe the biogeochemical field of targeted coral systems.

Currently, there is a gap in monitoring setups that allows understanding the relationship between examining external forcings (e.g., changes in water quality) and deciphering responses of coral reefs, for example, primary productivity and symbiosis between corals and zooxanthellae. In the landscape, resolution of satellite-based remote sensing is usually not high enough to collect and portray the patchy character of coral reefs, such as the temperature and distribution of pigments. There is also a challenge in remote sensing to examine the daily variability (e.g., day- and night-time differences) using the visible wavelength spectrum. In the tropics and subtropical areas, remote sensing using satellite data can be also a problem when the weather conditions (e.g., cloud coverage) are not suitable. Using the monitoring data, one can seldom extract information about the connectivity between different reef systems, such as the dispersal of larvae. At the molecular level, it is hoped that monitoring systems can provide information relevant to the studies on genetics and/or genomes of coral development.

Innovation of coral reef observing techniques is urgently required to address those challenges encountered by coral ecosystems in a changing climate, ranging from monitoring of multiple parameters in the field to the molecular and genetic studies in a well-equipped laboratory. In reality, the techniques currently used for in situ monitoring are limited to a few variables/parameters with limited precision and data logging. Therefore, new sensors for in situ monitoring are expected to be equipped with multi-sensor probes to observe coral physiological phenomena occurring in constituents of coral reef ecosystems and water quality with enhanced real-time data transmission capability (i.e., via satellites). The sensors are expected to become smaller in size, low energy consuming, more compact, and more robust for facilitating their use in harsh coastal environments. The question of what to "see" and what to "track" needs to be discussed when designing the monitoring network, and data transmission from sensors to shore laboratory should be warranted. In the onshore laboratory, biogeochemical variable/parameter determination (e.g., ICP-MS and HPLC-MS) needs to be closely coordinated with molecular/genetic analyses for samples of targeted biological species.

Numerical modeling is a powerful tool that allows diagnoses of condition of coral ecosystems and prediction of the response of reef ecosystems to external forcings, given that mechanisms are well understood and realized through parameterization. However, numerical models have been largely developed for hydrodynamics and sediment transport (cf. Storlazzi et al. 2011); biogeochemical models have recently become available to aid understanding of the causal relationship of essential key chemical elements and coral biology, which is affected also by the initial condition, boundary situations, as well as interactions with outside target ecosystems (Galli and Solidoro 2018). Developing numerical models requires comparison of model outputs with in situ observational/monitoring data to ensure validity of their parameterization of biogeochemical reactions occurring in corals and the ambient seawater. In the Western Pacific Region, application of numerical simulations to the biogeochemical processes occurring in the coral reefs is still in its infancy (Mayer et al. 2018), and upgrading this will need coordinate joint efforts of modeling as well as in process studies.

Study of marine ecosystems, including coral reefs, is usually multidisciplinary. The mission of a multidisciplinary research project in the Western Pacific Ocean is unlikely to overlap completely with the management needs of any specific country in this region. There is a need to match the scientific directions of projects with what is expected by any interested or concerned country in implementation. In the Western Pacific Region, there are several international research platforms to mobilize scientists from around the world to lend their expertise in research and educational facilities in their home laboratories or virtual team work, such as IOC/WESTPAC-CorReCAP Project established in 2008, Coral Triangle Initiatives, and NGOs among others. Such activities provide a collaborative environment in which regional scientists can come together to share and discuss research, as well as to get support for all steps of the research process, including designing, searching, writing, publishing, and even fundings. Publicly available high frequency and nonintrusive Earth observational information using electromagnetic waves (satellites) and data and knowledge produced by the existing projects supported by individual governments and/or inter-governmental organizations, e.g., Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI-CFF), can be coordinated by a team with a scientific advisory mechanism of the highest quality, with active participation of research scientists, educational agencies, management, and policy-making people. Any lack of research assets (e.g., a highly skilled academic work force, advanced research infrastructure, and a mature high-tech industry system) may be complemented by other participants through the network of distributed centers of excellences (Hellstrom 2018). The established international collaborations in this region will provide further opportunities for data sharing, exchange of expertise and research protocols, coordinating analytical facilities, etc. This kind of collaboration at the regional level will result in research networks on coral reefs across the whole Western Pacific Region, to face the need for capacity development to conduct multidisciplinary studies.

Finally, the successful and sustainable development of integrated coral reefs studies in the Western Pacific Ocean requires strong support from capacity building agencies in this region. National and international marine research initiatives require integrated multidisciplinary facilities with support for equipment and observations, as well as continued capacity building (Morrison et al. 2013). In addition to the infrastructure for research, the challenges of ecosystem-based management (EbM) in the Western Pacific Region include also the development of capability to synthesize the collaborative research results and to maintain the capacity built within the marine science community in the member countries. It is important to keep in mind that capacity building on the coral reef science should take into consideration technical and scientific skills and the ability to design research activities. This is particularly important in the Western Pacific Region, because capacity building needs to be developed for a wide range of religious belief and culture differences in this area. In order to reach the goal of high-quality coral reef studies in this region, the marine community, from the scientific to the social sectors, should reduce the overlap and duplication in capacity building activities and ensure to bring all efforts together with all existing relevant resources and infrastructure across the whole Western Pacific Region (Morrison et al. 2013).

7.7 Future Scientific Research Priorities on Coral Reefs

Coral reef ecosystems have developed over several hundreds of millions of years and are widely distributed in the tropical and subtropical marine environment and hence have survived episodes of climate variability and tectonic movements in geological time since Mesozoic Era. Coral reefs flourish in the tropical and subtropical ocean with very limited ranges of salinity, temperature, and sea level variability and are often exposed close to the thermal threshold of survival in the geological time. However, living in the current Anthropocene, coral reef stressors have been expanding due to global warming, with consequential sea level rise and ocean acidification. In urbanized coasts, coral reefs are subject to pollution (e.g., terrigenous and marine sediments, nutrients, heavy metals, organic contaminants, floating and submerged plastic litter, marine debris, and abandoned fishing net and gear, etc.) and human-made substrates, such as artificial rocky habitat, floating structures, piers and pilings, scoria deposits, and artificial islands (Heery et al. 2018). More than 20 million people in the Western Pacific Region depend on coral reefs for their livelihood (Pendleton et al. 2016). The future of coral reefs in the Western Pacific Ocean is largely subject to how human society in this area behaves in terms of protection of marine ecosystems and controls user communities against ambitions of exhausting marine resources.

Current major climate predictions indicate that in the very near future, greenhouse gas species (e.g., CO_2, CH_4, and N_2O) in the current atmosphere will continue to increase over the next several decades, suggesting that the global and large-scale climate trends, such as warming, sea level rise, and acidification, will continue. At the regional and local scales, superimposed perturbations may arise from urban activities and from open ocean operations. Effects of global climate change and CO_2 emissions, while relatively clear in trend direction, are quantitatively less certain at regional level, which makes it difficult to assess and predict the responses of coral reefs, often due to the lack of essential ocean observation and robust numerical models.

Over the last 10 years, several workshops and training courses have been conducted within the IOC/WESTPAC-CorReCAP Project by the participants from member countries in the Western Pacific Ocean. These activities have contributed to enhancing the knowledge and capacity of communities in this region on coral reef-related issues and to broadening the reach and scope of member countries' research programs. Some member countries are still experiencing numerous challenges in conducting scientific studies on coral reefs, ranging from limited material and financial resources, poor physical and communication infrastructure, and lack of scientific careers, scientific tradition, institutional support, and collaboration within the local scientific community due to economic constraints or small size of populations in some island states (Harris 2004). In this monograph, based on the multidisciplinary examination of current coral reefs of the Western Pacific Ocean, several priorities can be proposed for action that are also coming out from research experiences gained from activities at the regional level as well as through comparison with other global efforts. These include:

- Filling out of the knowledge gap with integrated monitoring and observational systems. Although studies on coral reefs are undertaken in most IOC-WESTPAC member countries, there is still lack of effective mechanisms for communication and data sharing in the Western Pacific Region. How to integrate local knowledge based on individual studies and update this kind of information to international forum and hence move forward coral sciences should be considered as one of the priorities in the future development.
- Innovation and updating of techniques and infrastructure in the network for coral science. Levels of research infrastructure are very different between countries of Western Pacific Region, hence updating and sharing the research facilities and exchange of expertise become a stumbling block in developing coral reef studies. It has been suggested that through coordinated research programs, people from different countries can have access to the state-of-the-art techniques and observational facilities, such as satellite observations, GIS, and molecular biology to match the growing research needs and update the laboratory facilities.
- Improvement of capacity building in coordinated coral reefs studies of Western Pacific Region. Sustainable development of coral reef studies to satisfy the requirement of ecosystem-based management is inseparable from the contribution of capacity building. There is a need to provide mechanisms for knowledge transfer, sharing the expertise, and updating the infrastructure within the network of coral reef studies. In this case, capacity building should strive to establish continuity and attract active PhDs and young scientists. Regionally targeted, mesocosm-level, or larger field experiments may be useful to study the combined effects of global stressors and local environmental stressors originating from human activities if funds are available. The future development of capacity building in this region should take into consideration differences in culture and language of the member countries.

We are quite optimistic noting that there are already a number of coordinated research programs on coral reefs in the Western Pacific Ocean, such as Coral Triangle Initiative (CTI) and IOC/WESTPAC-CorReCAP. Recent research data indicated the richness of coral biodiversity in the basin-wide biogeographic ranges of Western Pacific Ocean (Dietzel et al. 2021). Scientific evidences coming out from such research activities call for rethinking what declines in abundance mean for coral reef extinction risk in a global scale (Pennisi 2021). Because previous claims on coral extinction were based on studies from individual systems, there is a need to reexamine the actual status of coral reefs from perspective of biodiversity gradients taking into considerations classification for life history of species and population size in geographic ranges. Through the collaboration of existing regional and international level research programs and coordination of member countries in this region, coral reefs in the Western Pacific Ocean will be well maintained for the foreseeable future.

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