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Dealing with the effects of ocean acidification on coral reefs in the Indian Ocean and Asia

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A B S T R A C T

Shallow coral reefs provide food, income, well-being and coastal protection to countries around the Indian Ocean and Asia. These reefs are under threat due to many anthropogenic stressors including pollution, sedimentation, overfishing, sea surface warming and habitat destruction. Ocean acidification interacts with these factors to exacerbate stress on coral reefs. Effective solutions in tackling the impact of ocean acidification require a thorough understanding of the current adaptive capacity of each nation to deal with the consequences. Here, we aim to help the decision-making process for policy makers in dealing with these future challenges at the regional and national levels. We recommend that a series of evaluations be made to understand the current status of each nation in this region in dealing with ocean acidification impacts by assessing the climate policy, education, policy coherence, related research activities, adaptive capacity of reef-dependent economic sectors and local management. Indonesia and Thailand, are selected as case studies. We also highlight general recommendations on mitigation and adaptation to ocean acidification impacts on coral reefs and propose well-designed research program would be necessary for developing a more targeted policy agenda in this region.

Contents

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1. Background & status

Shallow-water coral reefs are widespread in the Indian Ocean and Pacific Asia (Fig. 1) where they provide food, income and livelihoods to the coastal communities. Coral species richness peaks in the 'coral triangle' of Southeast Asia and declines gradually towards the west across the Indian Ocean (Roberts et al., 2002; Burke et al., 2011). The coral triangle, which encompasses the waters of Malaysia, the Philippines, Indonesia and Papua New Guinea, has the highest marine biodiversity in the world with an enormous range of reef-associated organisms (Hoeksema, 2007; Burke et al., 2011). In addition to providing many ecological benefits including habitat for fish, high biodiversity, and shoreline protection from erosion, the reefs also provide goods and services for direct or indirect use in consumption and production processes. Moberg and Folke (1999) identify and categorize the most important goods and services that coral reef ecosystems provide. They divide goods into renewable resources and reef mining and classify ecological services into physical structure services, biotic services, biogeochemical services, information services, and social/cultural services.

Coral reef fisheries and coral reef related tourism are two important ecosystem services in this region. According to the International Coral Reef Initiative forum, the coral reefs of the South East Asia and the Indian Ocean, with a surface area of approximately 100,000 km^2, provide tangible benefits from fisheries and tourism sectors of at least US$ 12 billion annually to the economies of the region. Around 11,000 businesses employing at least 4.5 million people, depend directly or indirectly on coral reefs in this region. For the coral reef fisheries sector, there are 3.35 million fishers in Southeast Asia and 1.5 million fishers in the Indian Ocean (Teh et al., 2013). The annual catch from coral reefs in Southeast Asia is about 3.7 million tonnes per year, contributing about USD$ 11 billion per year to the economy (Pauly and Zeller, 2016). Shallow-water coastal systems in the Indian Ocean (including coral reefs, seagrass beds and mangroves) have an annual production of ca. 20 tonnes of fish per km^2 (Souter and Linden, 2005). In Kenya, for instance, small-scale fisheries support an estimated 60,000 coastal residents, employ 10,000 people and supply about 70% of the country's total marine catch in 2014 (Pauly and Zeller, 2016), generating an estimated US$ 3.2 million per year. While the revenues generated from fisheries may be a tiny fraction of the total Gross Domestic Product (GDP), benefits of coral reef fisheries to the small-scale fishers are substantial. Other than fisheries, coastal communities also thrive on revenues from tourists as they pour into the area for various recreational activities on or around the reefs (Spalding et al., 2017). Annually, around 36.5 million visitors pay to enjoy the beauty of the region's coral reefs. However, all coral reefs are impacted by these various activities including fishing in particular, although some are much less affected due to geographical isolation and low human populations, such as those coral reefs that occur around Iles Eparses in the Western Indian Ocean (Quétel et al., 2016).

Healthy coral reefs not only provide food, jobs and income for coastal communities, they are also important for providing protection from storms and coastal erosion. Property protection from erosion and flooding is a direct benefit of coral reefs. The coral reefs provide an estimated US$ 22 billion annually in coastal protection benefits in this region. Coral reefs are also of interest to biotechnology companies that are now turning to reef organisms in search of new genes and molecules for the development of pharmaceuticals (Hunt and Vincent, 2006). The estimated present value of all the services provided by the ocean's ecological assets approaches $1 trillion, with an estimated annual dividend value of around $300-400 million per annum accruing from the coral reefs (Hoegh-Guldberg, 2015; Hoegh-Guldberg et al., 2017). Table 1 presents gross regional data on available estimates of coral reef economic and social benefits for the Indian Ocean and the South East Asia as well as country specific data for Kenya, Indonesia and Thailand. While these numbers are small relative to the Gross Domestic Product (GDP) of individual countries in the region (less than 1% in most cases), the distributional effect of the benefits has great implications for poverty alleviation, income distribution and social justice.

Coral reefs in the Indian Ocean and Asia are in steep decline because of multiple stressors including pollution, sedimentation, overfishing and habitat destruction by coral mining and destructive fishing practices (Burke et al., 2011). On top of all that are the effects of carbon dioxide (CO_2) emissions which are causing surface waters to warm and become more acidic (Pendleton et al., 2016). About 25% of tropical coral reefs have already been destroyed worldwide due to warming since these reefs are amongst the most vulnerable of marine ecosystems as the corals are already near their upper thermal limits (Hoegh-Guldberg et al., 2009) with mass bleaching events in 2016 and 2017 around the world (Hughes et al., 2018a,b). In the Indian Ocean, coral reefs experienced large-scale bleaching and mortality because of high temperatures in 1998 and 2005 (McClanahan et al., 2007) and again in 2010 and 2015 (Kimura et al., 2014). Marine heat waves are now causing mass coral bleaching and subsequent mortality with increasing severity and frequency in the coral triangle (Wilkinson, 2004; Peñaflor et al., 2009).

Alongside warming, CO_2 emitted into the atmosphere from various anthropogenic activities is changing the carbonate chemistry of surface waters in a process called 'ocean acidification'. Ocean acidification (OA) and bioerosion are likely to block the northward colonization of coral reefs as the Pacific Ocean continues to warm (Chen et al., 2013; Agostini et al., 2018), and any northward movement of coral reefs in the northern Indian Ocean is impossible due to the Asian landmass. Currently, ocean acidification monitoring stations and coral restoration programs are being implemented for monitoring, mitigating and adapting to coral reef damage. The IOC Sub-Commission for the Western Pacific (WESTPAC) established by the Intergovernmental Oceanographic Commission of UNESCO (UNESCO-IOC) with the support from its member states, National Oceanic and Atmospheric Administration (NOAA), and the Global Ocean Acidification Observing Network (GOA-ON) is developing a network of ocean acidification monitoring stations. These monitoring stations are used to understand the spatial (within-reef, cross-shelf, latitudinal) and temporal (diel, seasonal, past historic and projected future) variability of the seawater carbonate system and their function is critical to assess the sensitivity of reef communities to future changes in ocean chemistry (Fig. 2). Establishing carbonate chemistry baselines and generating coupled hydrodynamic–chemical–biological models of coral triangle and Indian Ocean reefs would

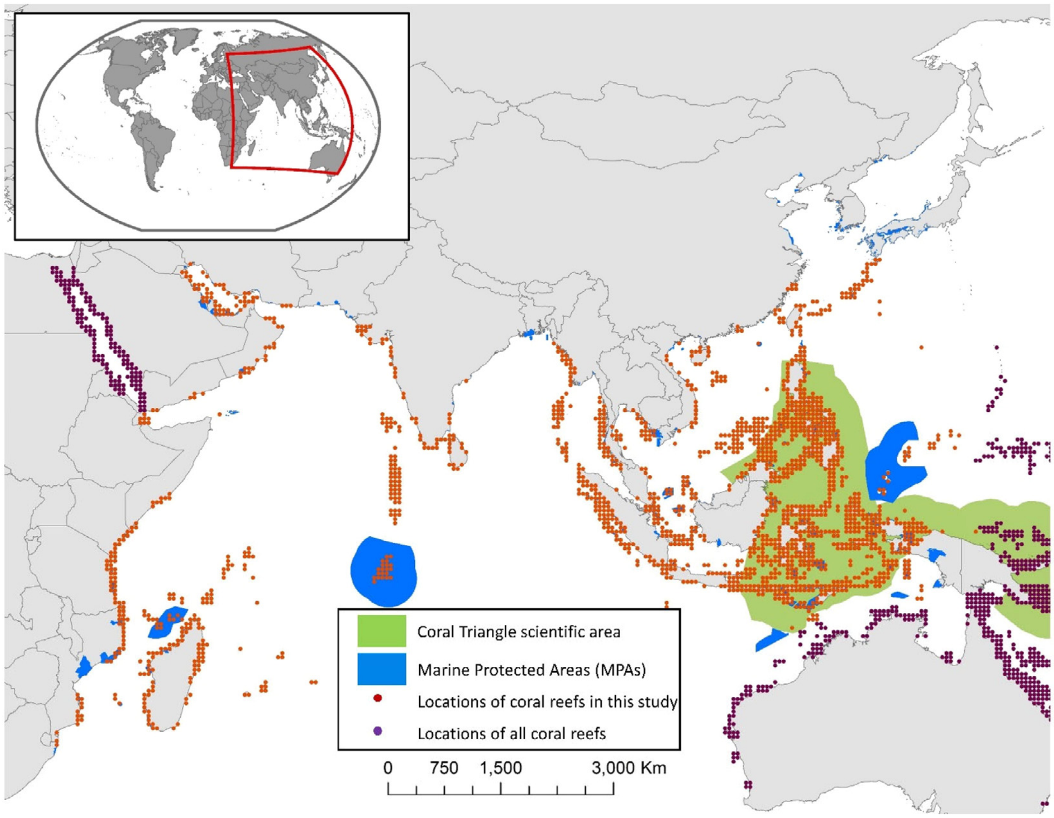

Fig. 1. Marine protected areas (blue), locations of Indo-Pacific shallow water coral reefs (orange dots) and the Coral Triangle area (green) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: UNEP World Conservation Monitoring Centre; www.marineregions.org.

Table 1
Gross Indicators of Coral Reef Economic and Social Benefits (2017) in Southeast Asia, Indian Ocean and three countries (Kenya, Indonesia and Thailand) in this region.
Source: http://www.icriforum.org/ compiled from various documents[b].

Region/ Country	Reef area (km^2)	Annual contribution of fisheries and tourism to GDP ($ million)	Percent contribution from		Total jobs depending on reefs	Total number of visitors	Total number of businesses	Value of coastal protection ($ million)
			Fisheries	Tourism				
SE Asia	69,637	10,619	45%	55%	3,168,050	35,100,044	7860	$19,099
Indian Ocean	27 960	2,037	28%	72%	1,510,690	1,353,000	2965	3,204
Kenya	630	146	66%	34%	13 538	34,000	200	
Indonesia[a]	39,538	4,126	55%	45%	1,663,757	19,000,000	2000	15,654
Thailand	2,130	1,792	20%	80%	105,687	958,000	1960	620

[a]The values here only include the reef area of Indonesia in Southeast Asia region (but excluding the reefs in Indian Ocean).
[b]https://www.icriforum.org/icri-documents/icri-publications-reports-and-posters/regional-fact-sheets-highlighting-importance-co.

inform the understanding of changes in carbon chemistry through time and help identify areas that are most vulnerable to OA. Indo-Pacific coral reefs have experienced acidification since the beginning of the industrial revolution (ca. 1750), and particularly during the past 50 years, following the post-1960s increase in anthropogenic CO_2 emissions. Boron isotope measurements show that ocean acidification is affecting the pH of the calcification fluid in *Porites* corals within the western North Pacific Subtropical Gyre (Kubota et al., 2017). It is not fully understood what ocean acidification has already impacted on coral reefs in the region, although evidence from areas off Japan with naturally low CO_2 indicate that much less coastal carbonate reef habitat is formed as CO_2 levels rise from 300–400 ppm (Agostini et al., 2018).

The decrease in pH and associated changes in the carbonate chemistry may be placing more stress on the reefs in this region and further increasing their susceptibility to warming and other stressors. However, there is a lack of local data for bridging the gap between chemistry and biological impacts and understanding their interactions. Although the interactions between OA and other environmental stressors are still uncertain, OA and warming are known to be the two critical drivers for reducing coral resilience, reducing coral growth rates and survival (Anthony et al., 2011; Viyakarn et al., 2015). Higher temperature, which leads to massive bleaching and is the predominate factor among other stressors, exacerbates and accelerate the OA-induced declines in calcification, survival, growth and development of corals (Anlauf et al., 2011; Pandolfi et al., 2011). The combination of temperature and acidification generally has catastrophic effects on corals (Anlauf et al., 2011; Anthony et al., 2011; Pandolfi et al., 2011), The 2030 Agenda for Sustainable Development adopted by world leaders also target towards minimizing and addressing the impact of OA and enhancing scientific cooperation at

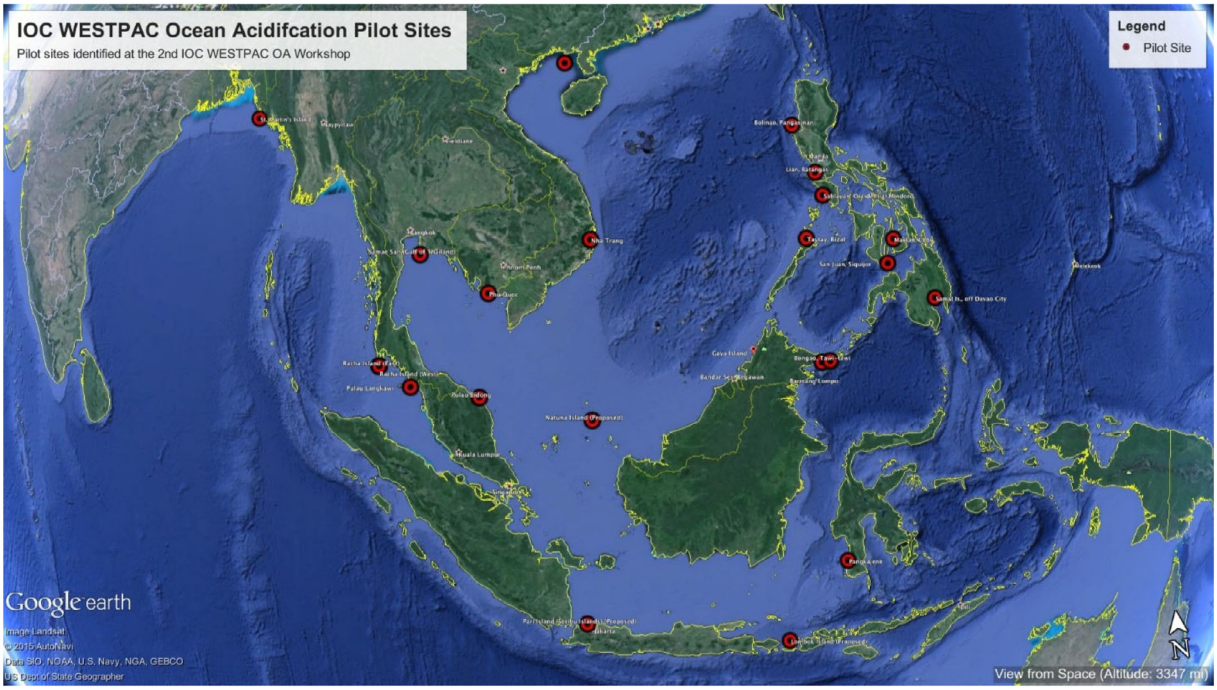

Fig. 2. Pilot network of ocean acidification monitoring stations in the Western Pacific region. This map aims to show the locations of the OA pilot sites. The details of each pilot site can be found at http://www.iocwestpac.org.
Source: UNESCO-IOC/WESTPAC.

all levels (SDG 14.3) (United Nations, 2019). Thus, it is a high priority for researchers to collaborate with local communities, non-governmental organizations (NGOs) and policy makers to identify solutions to monitor, mitigate and adapt to the impact of ocean acidification on coral reefs. In this paper, we evaluate the current adaptive capacity of society and highlight potential solutions that may reduce the impact of OA on coral reefs from both ecological and socio-economic perspectives. Our aim is to help the decision-making process for policy makers when dealing with these challenges.

2. Ecological and socio-economic impacts of ocean acidification in the Indo-Pacific

Reefs in the coral triangle are projected to become continuously adversely impacted and become "marginal" within the period 2020–2050 unless CO_2 emissions are curbed (Hoegh-Guldberg et al., 2009). A decline of the coral reefs in the coral triangle is having growing impacts on a large number of reef associated species, and this is degrading ecosystem services, such as food provisioning and coastal protection by the reefs (Pendleton et al., 2016). Laboratory tests and field experiments show that although many corals and other reef forming organisms are able to calcify and grow in acidified conditions, reefs are weakened and erode in waters that are periodically corrosive to carbonates (Fabricius et al., 2011; Rodolfo-Metalpa et al., 2011; Comeau et al., 2014; DeCarlo et al., 2017; Agostini et al., 2018). Much of what we know about the ecological effects of ocean acidification on coral reefs comes from volcanic seep studies where clonal coral colonies can be exposed to acidified conditions for hundreds of years. At such analogues for ocean acidification off Japan (Inoue et al., 2013), Maug (Enochs et al., 2015), Indonesia and Papua New Guinea (Fabricius et al., 2014) there are consistent patterns of coral reef degradation along gradients of increasing CO_2. Alongside a loss in coral diversity, fish behavior is impaired (Munday et al., 2014; Wang et al., 2017). Acidification causes a decline in shellfish and fisheries species and an overall loss in carbonate habitat structure, decreasing the ability of reefs to reduce erosion and storm wave impacts (Agostini et al., 2018). Laboratory, mesocom and CO_2 seep research shows that extra carbon availability can be a resource for microalgae and fleshy seaweeds which can then damage reefs (Kim et al., 2016; Agostini et al., 2018; Sahu et al., 2018) However, many of the countries which are highly dependent on coral reef ecosystems, such as Indonesia, lack robust data on ocean acidification (Pendleton et al., 2016). Future increases in extreme monsoon rainfall are considered to be very likely in East, South, and Southeast Asia: with all models projecting an increase in both the mean and extreme precipitation in the Indian summer monsoon (Hijioka et al., 2014). Coastal coral reefs around India and Southeast Asia are affected by periods of low carbonate saturation due to heavy rains which worsen the effects of ocean acidification on Asian reefs (Zhai et al., 2015; Dong et al., 2017), as does eutrophication caused by the use of fertilizers on land (Duprey et al., 2016). These can be coupled with acidic terrestrial soil runoff and an increase in sulphate and nitrogen aerosol loadings over the northwestern Bay of Bengal (George et al., 1994; Sarma et al., 2015). Many of the heavily populated harbors of the Indo-Pacific region (e.g. Mumbai, Hong Kong, Tokyo) have sediments that are contaminated with metals. Although some studies show that a decrease in pH may not necessarily increase coral uptake of metals such as copper and cobalt (Bielmyer-Fraser et al., 2018; Biscéré et al., 2015), other studies reveal that ocean acidification is expected to increase the toxicity of many metals (Millero et al., 2009; Wang et al., 2015). Some metals are essential to corals such as magnesium but the interaction of the uptake of these essential metals and ocean acidification has not yet been investigated (Biscéré et al., 2018).

Land use–coastal interactions continue to increase the degradation of coral reefs in the region, and reduce fisheries landings and food for local communities. These impacts are particularly important for the communities and countries that are highly dependent on coral reef ecosystems for their food, income and livelihoods. Many shell-forming species are negatively affected by OA (Kroeker et al., 2013). Reduced production of shellfish due to OA is expected to adversely affect the economy and food production in shellfish producing countries such as China and United States. Countries which have low adaptability are highly dependent on molluscs for nutrition and have rapidly growing populations are the most vulnerable to reductions in mollusc production driven by ocean acidification (Cooley et al., 2012). Regions with a rapidly increasing rate of demand for molluscs are also in the regions with high OA (Cooley et al., 2012). At the global level, the economic costs due to OA driven reductions in fisheries production from coral reef habitats were estimated to be $5.4 to $8.4 billion (present value) annually under high emission scenario (Speers et al., 2016). Although fisheries production in coral reef habitats is declining due to the impact of various factors, including OA, seafood demand in many countries is increasing. This may drive fishers to fish harder and increase their effort to exploit resources that are already overexploited. For example, they may increase the use of destructive fishing gears, as seen in Tanzania and Sri Lanka, and shifts to previously unimpacted fishing locations. These adaptation strategies have negative feedbacks on coral reefs and increase conflicts among fishers, communities and different countries (Souter and Linden, 2005). Degrading coral reefs due to OA may also have an adverse impact on the tourism associated with those reefs and, coupled with rising sea levels and storminess, increase coastal erosion. The cost of replacing shoreline protection services provided by coral reefs range from around £2M/km for a simple earth embankment with a stone revetment to £20M/km for concrete structures (Hedges, 2018) which contribute to 'ocean sprawl' whereby nearshore habitats are damaged by construction (Firth et al., 2016; Bishop et al., 2017).

The Indian Ocean and Asia contributed about 90% of global marine aquaculture production in 2016 (FAO, 2018). This provides considerable trade, employment and food security to some of the densest coastal populations of the world (Sriskanthan and Funge-Smith, 2011). The responses of farmed species to OA are species specific with shellfish and other calcifying organisms of the highest concern in an increasingly acidic ocean (Gazeau et al., 2013) whereas many macroalgae are resilient (Porzio et al., 2011). At this stage, there is not much knowledge and information on how OA will impact on regional aquaculture and more research is required.

3. Assessing adaptive capacity to the impact of ocean acidification

Before designing effective policy to deal with ocean acidification, it is important to understand the current adaptive capacity of society to the impact of ocean acidification on coral reefs by assessing different indicators including the current climate policy, management measures, education level and research intensity. We propose that it is necessary to develop a framework that should be considered when preparing for comprehensive and effective policies for the impacts of ocean acidification. Here, we use Indonesia and Thailand as case studies and use a conceptual framework to demonstrate how to assess their current efforts with respect to dealing with the effects of ocean acidification on coral reefs under the current status. Both Indonesia and Thailand are member countries (a total of 60) of the International Coral Reefs Initiative of the United Nations.

Indonesia

Indonesia is the world's largest coral reef nation, with over 51,000 square kilometers of reefs (almost 18 percent of the world total), extending nearly 5000 km from east to west, and harboring over 17,000 islands (including rocks and sandbanks) (Spalding et al., 2001). The majority of its coastal area is heavily utilized, particularly in the west, and considerable areas are under increasing stress from human activities. About 6000 of Indonesia's islands are inhabited, and marine and coastal resources and activities generate 25 percent of the country's gross domestic product (Table 1) (Dahuri and Dutton, 2000).

The total net economic losses of reef fisheries from reef degradation associated with various threats such as poison fishing, blast fishing, coal mining, sedimentation and overfishing were estimated at US$ 410,000 per square km of coral reef destruction per year using productivity change method on Indonesian coral reefs (Cesar and Chong, 2004). The same method was used to estimate the total net economic losses of tourism from reef degradation in Indonesia and it was found to be US$ 201,000 to 1,592,000 per square km of coral reef degradation per year associated with poison fishing, blast fishing, coral mining and sedimentation (Cesar and Chong, 2004). For each activity, reef degradation causes a decrease in potential tourism revenue. Also, the total net economic losses for indirect use of coral reef such as coastal protection was estimated to be US$ 21,000 to 453,000 per square km of coral reef degradation associated with blast fishing and coral mining using productivity change method (Cesar and Chong, 2004). For each activity, reef destruction reduces the protective capability of the reef. The reef's loss of protective capability is linked linearly to its protective value.

To better manage the marine and coastal resources, Indonesia designated seven marine protected areas (MPA) under the authority of Ministry of Environment and Forestry (MOEF) (ICRI, 2017). To monitor the decline in coral reef health due to global bleaching events, these seven MPAs aim to achieve several targets including capacity building for the marine park management authorities, supporting alternative livelihoods, and implementing effective management and law enforcement to increase food security of local people. All of these activities also support the strategies for mitigating and adapting the impact of ocean acidification on coral reefs. The adaptive capacity of a country is assessed through seven dimensions including local management, adaptive capacity of reef-dependent sectors, research development, policy coherence, area-based management, education and current climate policy (Table 2). Different levels of each indicator for understanding the adaptive capacity and preparedness of Indonesia in coping with ocean acidification is then estimated based on this information and opinions from the Indonesian local experts, who attended the 4th International Workshop on Ocean Acidification,[1] and their levels are illustrated in a radar diagram as shown in Fig. 3. The level ranges from no alignment (score = 0) to very high alignment (score = 3). The education, training, research and adaptive capacity on the impacts of OA on the coral reef systems are ranked at relatively low levels in Indonesia at the time of our assessment, however, Indonesia may probably be at the stage of drafting plans or having plans but have not yet been implemented. Although the estimated level of each indicator was resulted from a quick assessment, this assessment framework can act as an important tool for researchers to understand the adaptive capacity and further explore solutions for OA impacts. The findings of this kind of assessment will be targeted to disseminate to local community members and government institutions that manage coastal and marine ecosystems to enable them to implement the necessary management strategies. Also, there are some caveats in our preliminary assessment as we did not have any representative from the government of Indonesia in our workshop, so we could not get the most up-to-date information about the current status of these indicators in this country. As

[1] The 4th International Workshop on Ocean Acidification was organized by Monaco Scientific Centre in partnership with the IAEA's Environment Laboratories from 15th to 17th October 2017.

Table 2
Indicators and descriptions for each dimension for assessing the adaptive capacity and preparedness for each country on the impact of ocean acidification.

Dimension	Indicator	Description
Local management	Stress reduction	Measures to reduce the impacts on coral reefs by different stressors
	Coastal management	Management plans to defend against threats such as flooding, pollution and erosion on the coastal areas.
Current adaptive capacity	Adaptive capacity of reef-dependent sectors	• Exposure and sensitivity of the reef-dependent sectors to OA; • The existing of capital and sector-specific strategies to help them to adapt to the changes; • Relevant technologies to help the people in the sectors to adapt to the changes; • Social networks and organizations to assist the sectors to adapt to warming and OA.
Research development	Training	The existing of training programs for management authorities on OA.
	Research	The existing of research programs and research funding to support studies on the impact of OA on coral reefs and reef-associated species.
Policy coherence	International policies	National policies are consistent with the targets set by the intergovernmental organizations such as SDGs of UNEP.
	Internal policies	Policies across of different government departments in a country are coherent with the national policies.
	Science	National policies are consistent with the best available knowledge from science-based studies.
Area-based management	Area-based management	The existing of Marine Protected Areas (MPAs) to protect critical habitats and biodiversity.
Education	Education and public dialogue awareness	The existing of education program to educate the public on OA and climate change.
Climate policy	Climate policy	The existing of climate policies to mitigate and adapt the impact of OA and climate change on marine ecosystem.

Fig. 3. Conceptual framework showing the current status of climate policy, local management, adaptive capacity of reef-dependent sectors, research and development, policy coherence, area-based management and 'education-public-dialogue-awareness' of coral reef systems in Indonesia based on expert's opinions present at the 4th International Workshop on OA.

such, the information of these indicators will be further validated in the next stage of our assessment and the main idea here is to propose this assessment framework that can be used for assessing the adaptive capacity of each country under the OA impacts.

Thailand

Thailand has an area of 2,130 square kilometers of reefs (around 0.75% of world total).

An economic analysis of coral reefs in the Andaman Sea of Thailand (Seenprachawong, 2003; Kimura et al., 2014) estimated the direct use value of coral reefs in this region using Travel Cost Method. The study estimated the annual benefit from the recreational services of Phi Phi Islands at US$ 205.41 million, which is about US$ 6,243 per ha per year.

The total economic value of coral reefs in terms of utility values associated with coral reef biodiversity was estimated using Contingent Valuation Method (CVM) at Phi Phi Islands (Seenprachawong, 2003). The mean willingness to pay (WTP) per visit was estimated at US$ 7.17 for domestic visitors and at US$ 7.15 for international visitors. The total value of Phi Phi's coral reefs was estimated to be US$ 147,000 a year for domestic visitors and US$ 1.24 million a year for international visitors. The CVM study also estimated the total value (use and non-use) of the reefs to be US$ 497.38 million a year, averaging US$ 15,118 per ha per year.

Although the Intended Nationally Determined Contributions (INDC) of Thailand did not obviously mention about the marine ecosystems and coral reefs, they showed interest to join an Ad Hoc committee to develop guidelines to integrate coral reefs in the INDC. To address the impact of climate change and ocean acidification on coral reefs, Thailand has implemented a series of projects to manage marine and coastal resources to cope with these adverse impacts. For example, the Thailand National Plan for Marine Environmental Management (20 years plan from 2017–2036) has included climate change and ocean acidification as one of the threats to marine ecosystems. The reef status maps and coral reef resilience maps were updated and used for management planning. Under these projects, a large area of marine and coastal resources including important marine ecosystems is expected to be successfully managed. Thailand also focuses on monitoring coral recovery and management of coral reefs in and outside Marine National Parks following the coral bleaching event. The project aimed to monitor the impacts of coral bleaching event on coral reef ecosystem and the potential of coral recovery in and outside in marine national parks. It also enhanced the capacity building of young researchers in Thailand. These projects that related to climate change and ocean acidification mitigation covered the areas of integrated management, science and monitoring, capacity building and periodic assessment (ICRI, 2016). In addition, to prepare for mitigation and adaptation of impact of OA, a monitoring program under UNESCO-IOC/WESTPAC has been established in Thailand. The program increases the knowledge and capacity building of OA not only among Thai scientists but also among governmental sectors.

4. Ecological and socio-economic solutions to the impact of OA on coral reefs

4.1. Ecological solutions for the region

4.1.1. Network of marine protected areas (MPAs)

Marine protected areas (MPAs) are one of the most widely used management tools in the Indian Ocean and Southeast Asia; however, they tend to be scattered and most of them do not cover coral reefs (Figure 1, White et al., 2014). For example, only 17.8% of the coral reef habitat in the coral triangle lies within MPAs (White et al., 2014). In addition, because of failure of effective management, 69% of MPAs in Southeast Asia are rated as ineffective (Burke et al., 2011). Therefore, it is crucial to have a network of effectively locally-managed MPAs for protecting coral reefs. For example, in Iles Eprases, marine park of Glorieuses established in 2011, adjacent to that of Mayotte, help to sustainably manage biodiversity and fish resources associated with coral reefs. Although MPAs may not be able to address all the conservation goals, they increase the resilience of coral reefs to different stressors, including OA, slow the recent decline in coral cover, and also increase the resilience of the marine communities to the impacts of natural disasters (Makino et al., 2014; Mellin et al., 2016).

4.1.2. Strengthen inter- and intra- national collaborations

Both coral reef restoration programmes and monitoring of ocean acidification and coral condition require the scientific cooperation at all levels. Coral reef restoration can help the recovery of deteriorated coral reefs and this has become one of major tools for reef rehabilitation in Southeast Asia (Edwards, 2010; Williams et al., 2018). Although the long-term effectiveness of coral restoration on the ecological, socio-cultural and economic aspects still needs to be further explored, its short-term effectiveness on the growth and survival of coral reefs has been better studied (Hein et al., 2017). Many different coral reef restoration (rehabilitation) methods have been developed at the local, national and international levels with varying degrees of success. New scalable methods are emerging and being scientifically validated (Edwards, 2010; Chavanich et al., 2014; Williams et al., 2018) (Fig. 4).

Inter- and intra-national collaborations are important for coral reef restoration to improve the conditions of various dimensions of healthy corals reefs, such as biodiversity and resilience, while considering the local and national interests, e.g. food provision and coastal defense. A major reef restoration programme in Indonesia has shown that coral rehabilitation is achievable over large scales where coral reefs have been severely damaged by blast fishing and coral mining (Williams et al., 2018). A follow up 4-year restoration experiment of similar size on a nearby island hopes to scientifically answer questions related to the other dimensions of coral reefs as noted above in 2021.

In accordance with the target of Sustainable Development Goal (SDG) 14.3 (IOC-UNESCO, 2019), it is necessary to strengthen inter- and intra-national collaborations to adopt science based best practices for monitoring ocean acidification and coral condition. Methodology (for SDG Indicator 14.3.1) is prepared by Intergovernmental Oceanographic Commission (IOC-UNESCO) and International Oceanographic Data and Information Exchange Programme (IODE) for providing guidance to scientists and countries on what, where and how to conduct ocean acidification measurements and related parameters (GOA-ON, 2019). This methodology is particularly important for Least Developed Countries (LDCs) and Small Island Developing States (SIDSs) as they have less capacity in this area. It also stresses the importance of data transparency and the importance of open accessed data which allow the data and information to be shared within and among nations.

4.1.3. Promote non-destructive use of marine resources

Illegal and destructive fishing practices, such as dynamite and cyanide fishing, still occur in many countries in Southeast Asia and the east coast of Africa (McClanahan and Arthur, 2001; Allen and Werner, 2002; Kimura et al., 2014). The use of destructive fishing gears can be prevalent in poor fishing communities (Cinner, 2009). Dynamite fishing destroys coral reef habitat and the removal of large adult fish from populations leads to reductions in catch biomass and diminishing economic returns in a cycle that leads to further blast fishing on reefs. Therefore, promoting non-destructive use of marine resources such as reducing Illegal Unreported Unregulated (IUU) fishing, and banning the use of dynamite and cyanide fishing is of high importance in reducing stress to coral reefs to increase their resilience to the impact of OA.

(a)

(b)

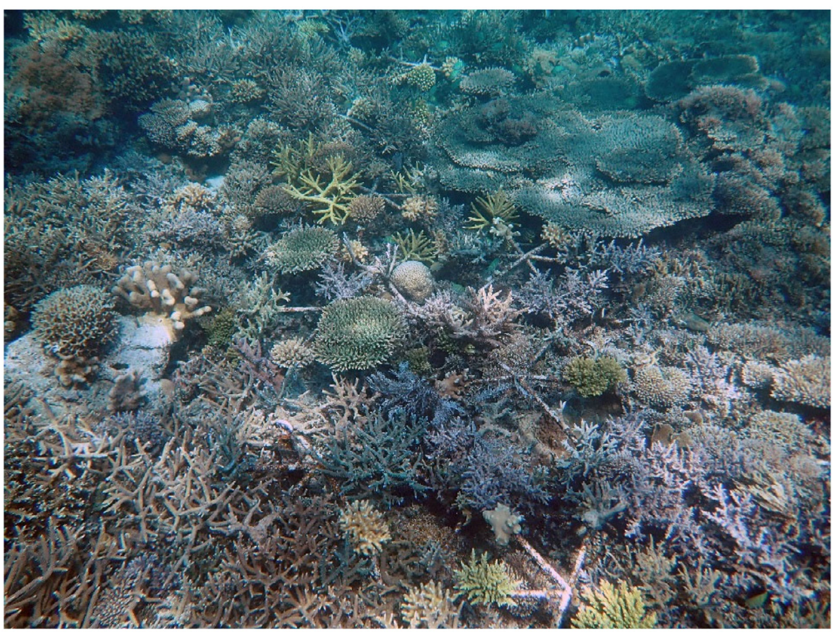

Fig. 4. (a) Mars Accelerated Coral Reef Rehabilitation System (MARRS) at Pulau Badi, Sulawesi, July 2015 — showing new installation on the left alongside 1 year old rehabilitation on the right. (b) Growth and restore of coral reef area under the rehabilitation program. This picture was taken in August 2018, at Pulau Bontausa by Professor David Smith, University of Essex during the Peer Review of the MARRS program. The restored area shown is approximately 14 months old.

4.2. Socio-economic solutions for the region

4.2.1. Commit to reducing carbon dioxide emissions

It is crucial for all the countries to commit to reducing their carbon dioxide emissions. There are many different ways, with differing costs, to curb emissions. For example, reducing demand for emission-intensive goods and services and encouraging lower-carbon technological use of power, heat and transport. It is necessary for researchers to implement a proper cost benefit analysis to make sure that the cost of proposed alternatives is lower than the cost of inaction. More specifically, it is important to have economic estimates of the cost of mass extinction of Asian coral reefs and the adverse impacts on the livelihoods they support, in order to use the price mechanism to curb the destruction of corals.

4.2.2. Increase public and political awareness on the value of coral reefs' services and its risk under OA

It is essential to determine and promote the value of the goods and services provided by coral reefs, such as their role in food provisioning, ecotourism and coastal infrastructure protection. Insurance companies and politicians are only just beginning to assess the societal and economic risk of OA to the benefits that the general public currently gains from intact and healthy coral reefs.

4.2.3. Education

Educational courses at schools, universities and adult learning fora need to incorporate up-to-date knowledge on the societal benefits of sustainable use of marine resources, for example, marine renewables, low carbon food production and sustainable fishing practices. Also, involving communities in the formulation of policy and decision making about the use of their marine resources can help Indo-Pacific nations manage their coral reef habitats in a more sustainable way.

5. Conclusion

Ocean acidification is projected to amplify the adverse effects of warming on the growth, development, calcification, survival and abundance of coral reef species at 1.5 °C of warming and even further at 2 °C, with high confidence (IPCC, 2018). When combining with other stressors on the coral reefs and associated marine species, ocean acidification will aggravate adverse impacts on coral reefs. These impacts are particularly important for Indian Ocean and Asian countries as most of them are dependent on coral reefs for supporting well-being through both direct and indirect ecosystem services. We propose a framework for assessing the current adaptive capacity of countries to deal with the impacts of acidification on coral reefs, and highlight the potential ecological and socio-economic solutions to deal with the impacts. Although our proposed solutions seem to be plausible, there is still a lack of scientific data that would allow us to develop a more targeted approach in this region. Particularly, locally measured data enable the scientists and researchers to characterize drivers and impacts and hence can help to mitigate the impacts of OA (Gattuso et al., 2018). Hence, a well-designed research program on monitoring OA and coral condition is necessary for each nation. Indeed, the most effective way for reducing or reversing OA impacts is to sustain negative CO_2emissions in the atmosphere and/or further reduce the non-CO_2 radiative forcing (IPCC, 2018). This requires all countries to cooperate and follow the targets they committed in the Paris Agreement. Also, it is crucial to increase the resilience of coral reefs by minimizing the impacts on coral reefs from other stressors, such as having a pollution reduction strategy and well-managed fisheries that eliminate destructive fishing practices.

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References

Agostini, S., Harvey, B.P., Wada, S., Milazzo, M., Inaba, K., Hall-Spencer, J.M., 2018. Ocean acidification drives community shifts towards simplified non-calcified habitats in a subtropical—temperate transition zone. Sci. Rep. 8, 11354.

Allen, G.R., Werner, T.B., 2002. Coral reef fish assessment in the 'coral triangle' of southeastern Asia. Environ. Biol. Fishes 65, 209–214.

Anlauf, H., D'croz, L., O'Dea, A., 2011. A corrosive concoction: the combined effects of ocean warming and acidification on the early growth of a stony coral are multiplicative. J. Exp. Mar. Biol. Ecol. 397 (1), 13–20.

Anthony, K.R., Maynard, J.A., Diaz-pulido, G., Mumby, P.J., Marshall, P.A., Cao, L., Hoegh-Guldberg, O.V.E., 2011. Ocean acidification and warming will lower coral reef resilience. Global Change Biol. 17 (5), 1798–1808.

Bielmyer-Fraser, G.K., Patel, P., Capo, T., Grosell, M., 2018. Physiological responses of corals to ocean acidification and copper exposure. Mar. Pollut. Bull. 133, 781–790.

Biscéré, T., Ferrier-Pagès, C., Gilbert, A., Pichler, T., Houlbrèque, F., 2018. Evidence for mitigation of coral bleaching by manganese. Sci. Rep. 8.

Biscéré, T., Rodolfo-Metalpa, R., Lorrain, A., Chauvaud, L., Thébault, J., Clavier, J., Houlbrèque, F., 2015. Responses of two scleractinian corals to cobalt pollution and ocean acidification. PLoS One 10 (4), e0122898.

Bishop, M.J., Mayer-Pinto, M., Airoldi, L., Firth, L.B., Morris, R.L., Loke, L.H., Hawkins, S.J., Naylor, L.A., Coleman, R.A., Chee, S.Y., Dafforn, K.A., 2017. Effects of ocean sprawl on ecological connectivity: impacts and solutions. J. Exp. Mar. Biol. Ecol. 492, 7–30.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at Risk Revisited. World Resources Institute, Washington DC, p. 114.

Cesar, H., Chong, C.K., 2004. Economic valuation and socioeconomics of coral reefs: Methodological issues and three case studies. In: Economic valuation and policy priorities for sustainable management of coral reefs. pp. 14–40.

Chavanich, S., Gomez, E., Chou, L., Goh, B., Tan, L.T., Tun, K., Chong, T., Cabaitan, P., Guest, J., Omori, M., Thongtham, N., Viyakarn, V., Zhu, W., 2014. Coral Reef Restoration Techniques in the Western Pacific Region. UNESCO-IOC/WESTPAC Bangkok Office, p. 8.

Chen, T., Li, S., Yu, K., 2013. Macrobioerosion in porites corals in subtropical northern south China Sea: a limiting factor for high-latitude reef framework development. Coral Reefs 32 (1), 101–108.

Cinner, J., 2009. Poverty and the use of destructive fishing gear near east African marine protected areas. Environ. Conserv. 36, 321–326.

Comeau, S., Carpenter, R.C., Nojiri, Y., Putnam, H.M., Sakai, K., Edmunds, P.J., 2014. Pacific-wide contrast highlights resistance of reef calcifiers to ocean acidification. Proc. R. Soc. Lond. B 281 (1790), 20141339.

Cooley, S.R., Lucey, N., Kite-Powell, H., Doney, S.C., 2012. Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. Fish Fish. 13 (2), 182–215.

Dahuri, R., Dutton, I.M., 2000. Integrated coastal and marine management enters a new era in Indonesia. Integr. Coast. Zone Manag. 1, 11–16.

DeCarlo, T.M., Cohen, A.L., Wong, G.T., Shiah, F.K., Lentz, S.J., Davis, K.A., Shamberger, K.E., Lohmann, P., 2017. Community production modulates coral reef ph and the sensitivity of ecosystem calcification to ocean acidification. J. Geophys. Res.: Oceans 122 (1), 745–761.

Dong, X., Huang, H., Zheng, N., Pan, A., Wang, S., Huo, C., Zhou, K., Lin, H., Ji, W., 2017. Acidification mediated by a river plume and coastal upwelling on a fringing reef at the east coast of Hainan Island, Northern South China Sea. J. Geophys. Res.: Oceans 122 (9), 7521–7536.

Duprey, N.N., Yasuhara, M., Baker, D.M., 2016. Reefs of tomorrow: eutrophication reduces coral biodiversity in an urbanized seascape. Glob. Change Biol. 22 (11), 3550–3565.

Edwards, A.J. (Ed.), 2010. Reef Rehabilitation Manual. In: Coral Reef Targeted Research & Capacity Building for Management Program, St Lucia, Australia, p. ii + 166.

Enochs, I.C., Manzello, D.P., Donham, E.M., Kolodziej, G., Okano, R., Johnston, L., Young, C., Iguel, J., Edwards, C.B., Fox, M.D., Valentino, L., 2015. Shift from coral to macroalgae dominance on a volcanically acidified reef. Nature Clim. Change 5 (12), 1083.

Fabricius, K.E., De'ath, G., Noonan, S., Uthicke, S., 2014. Ecological effects of ocean acidification and habitat complexity on reef-associated macroinvertebrate communities. Proc. R. Soc. B 281 (1775), 20132479.

Fabricius, K.E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M.S., Lough, J.M., 2011. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. Nature Clim. Change 1 (3), 165.

FAO, 2018. - Fisheries and Aquaculture Information and Statistics Branch online queries http://www.fao.org/fishery/statistics/global-aquaculture-production/en (accessed- 14.11.18).

Firth, L.B., Knights, A.M., Bridger, D., Evans, A.J., Mieszkowska, N., Moore, P.J., O'Connor, N.E., Sheehan, E.V., Thompson, R.C., Hawkins, S.J., 2016. Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. In: Oceanography and Marine Biology. CRC Press, pp. 201–278.

Gattuso, J.P., Magnan, A.K., Bopp, L., Cheung, W.W., Duarte, C.M., Hinkel, J., Mcleod, E., Micheli, F., Oschlies, A., Williamson, P., Billé, R., 2018. Ocean solutions to address climate change and its effects on marine ecosystems. Front. Mar. Sci. 5, 337.

Gazeau, F., Parker, L.M., Comeau, S., Gattuso, J.P., O'Connor, W.A., Martin, S., Pörtner, H.O., Ross, P.M., 2013. Impacts of ocean acidification on marine shelled molluscs. Mar. Biol. 160 (8), 2207–2245.

George, M.D., Kumar, M.D., Naqvi, S.W.A., Banerjee, S., Narvekar, P.V., De Sousa, S.N., Jayakumar, D.A., 1994. A study of the carbon dioxide system in the northern Indian Ocean during premonsoon. Mar. Chem. 47 (3–4), 243–254.

GOA-ON, 2019. SDG 14.3.1 Indicator Methodology. http://goa-on.org/resources/sdg_14.3.1_indicator.php (accessed 20.02.19).

Hedges, E.T., 2018. Climate Change and Coastal Defence. Research Centre for Marine Sciences and Climate Change, Department of Engineering University of Liverpool 2008, accessed via: https://www.liverpool.ac.uk/media/livacuk/climate-research/docs/RCMSCC_Climate_Change_{and}_Coastal_Defence_PDF_version.pdf.

Hein, M.Y., Willis, B.L., Beeden, R., Birtles, A., 2017. The need for broader ecological and socioeconomic tools to evaluate the effectiveness of coral restoration programs. Restor. Ecol. 25 (6), 873–883.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, R.D., Lindgren, E., Surjan, A., 2014. Asia. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327–1370.

Hoegh-Guldberg, O., 2015. Reviving the Ocean Economy: the Case for Action - 2015. WWF International, Gland.

Hoegh-Guldberg, O., Hoegh-Guldberg, H., Yeron, J., Green, A., Gomez, E.D., Ambariyanto, A., Hansen, L., 2009. The Coral Triangle and Climate Change: Ecosystems, People and Societies at Risk.

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S., 2017. Coral reef ecosystems under climate change and ocean acidification. Front. Mar. Sci. 4, 158.

Hoeksema, B.W., 2007. Delineation of the Indo-Malayan Centre of Maximum Marine Biodiversity: The Coral Triangle. Biogeography, Time, and Place: Distributions, Barriers, and Islands. Springer.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., Heron, S.F., Hoey, A.S., Hoogenboom, M.O., Liu, G., McWilliam, M.J., 2018b. Global warming transforms coral reef assemblages. Nature 556 (7702), 492.

Hughes, T.P., Kerry, J.T., Simpson, T., 2018a. Large-scale bleaching of corals on the Great Barrier Reef. Ecology 99 (2), 501-501.

Hunt, B., Vincent, A.C., 2006. Scale and sustainability of marine bioprospecting for pharmaceuticals. AMBIO: J. Hum. Environ. 35 (2), 57–64.

ICRI, 2016. Member's Report of the 31st General Meeting of International Coral Reef Initiative. IGRI GM 31 – Thailand. 2-4 2016, Paris, France.

ICRI, 2017. Member's Report of the 32nd General Meeting of International Coral Reef Initiative. IGRI GM 32 – Indonesia. 7-9 2017, Nairobi, Kenya.

IOC-UNESCO, 2019. Measuring progress on SDG 14 indicators. http://www.unesco.org/new/en/natural-sciences/ioc-oceans/single-view-oceans/news/measuring_progress_on_sdg_14_indicators/ (accessed 20.02.19).

IPCC, 2018. Global warming of 1.5c – summary for policymakers. In: Intergovernmental Panel on Climate Change. WMO & UNEP, http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf.

Kim, J.H., Kang, E.J., Edwards, M.S., Lee, K., Jeong, H.J., Kim, K.Y., 2016. Species-specific responses of temperate macroalgae with different photosynthetic strategies to ocean acidification: a mesocosm study. Algae 31 (3), 243–256.

Kimura, T., Tun, K., Chou, L.M., 2014. Status of Coral Reefs in East Asian Seas Region: 2014. Global Coral Reef Monitoring Network. Ministry of the Environment, Japan.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob. Change Biology 19 (6), 1884–1896.

Kubota, K., Yokoyama, Y., Ishikawa, T., Suzuki, A., Ishii, M., 2017. Rapid decline in pH of coral calcification fluid due to incorporation of anthropogenic CO 2. Sci. Rep. 7 (1), 7694.

Makino, A., Yamano, H., Beger, M., Klein, C.J., Yara, Y., Possingham, H.P., 2014. Spatio-temporal marine conservation planning to support high-latitude coral range expansion under climate change. Diversity Distrib. 20 (8), 859–871.

McClanahan, T.R., Arthur, R., 2001. The effect of marine reserves and habitat on populations of East African coral reef fishes. Ecol. Appl. 11 (2), 559–569.

McClanahan, T.R., Ateweberhan, M., Graham, N.A.J., Wilson, S.K., Sebastián, C.R., Guillaume, M.M., Bruggemann, J.H., 2007. Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. Mar. Ecol. Prog. Ser. 337, 1–13.

Mellin, C., Aaron MacNeil, M., Cheal, A.J., Emslie, M.J., Julian Caley, M., 2016. Marine protected areas increase resilience among coral reef communities. Ecol. Lett. 19 (6), 629–637.

Millero, F.J., Woosley, R., Ditrolio, B., Waters, J., 2009. Effect of ocean acidification on the speciation of metals in seawater. Oceanography 22 (4), 72–85.

Moberg, F., Folke, C., 1999. Ecological goods and services of coral reef ecosystems. Ecol. Econ. 29 (2), 215–233.

Munday, P.L., Cheal, A.J., Dixson, D.L., Rummer, J.L., Fabricius, K.E., 2014. Behavioural impairment in reef fishes caused by ocean acidification at CO 2 seeps. Nature Clim. Change 4 (6), 487.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., Cohen, A.L., 2011. Projecting coral reef futures under global warming and ocean acidification. Science 333 (6041), 418–422.

Pauly, D., Zeller, D., 2016. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat. Commun. 7, ncomms10244.

Peñaflor, E., Skirving, W., Strong, A., Heron, S., David, L., 2009. Sea-surface temperature and thermal stress in the coral triangle over the past two decades. Coral Reefs 28, 841.

Pendleton, L., Comte, A., Langdon, C., Ekstrom, J.A., Cooley, S.R., Suatoni, L., Beck, M.W., Brander, L.M., Burke, L., Cinner, J.E., Doherty, C., 2016. Coral reefs and people in a High-CO2 World: Where can science make a difference to people?. PLoS One 11 (11), e0164699.

Porzio, L., Buia, M.C., Hall-Spencer, J.M., 2011. Effects of ocean acidification on macroalgal communities. J. Exp. Mar. Biol. Ecol. 400, 278–287.

Quétel, C., Marinesque, S., Ringler, D., Fillinger, L., Changeux, T., Marteau, C., Troussellier, M., 2016. Iles Eparses (SW Indian Ocean) as reference ecosystems for environmental research. Acta oecol. 72, 1–8.

Roberts, C.M., McClean, C.J., Veron, J.E., Hawkins, J.P., Allen, G.R., McAllister, D.E., Mittermeier, C.G., Schueler, F.W., Spalding, M., Wells, F., Vynne, C., 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295 (5558), 1280–1284.

Rodolfo-Metalpa, R., Houlbrèque, F., Tambutté, E., Boisson, F., Baggini, C., Patti, F.P., Jeffree, R., Fine, M., Foggo, A., Gattuso, J.-P., Hall-Spencer, J.M., 2011. Coral and mollusc resistance to ocean acidification adversely affected by warming. Nature Clim. Change 1, 308–312.

Sahu, B.K., Pati, P., Panigrahy, R.C., 2018. Impact of Climate Change on Marine Plankton with Special Reference to Indian Seas.

Sarma, V.V.S.S., Krishna, M.S., Paul, Y.S., Murty, V.S.N., 2015. Observed changes in ocean acidity and carbon dioxide exchange in the coastal Bay of Bengal–a link to air pollution. Tellus B 67 (1), 24638.

Seenprachawong, U., 2003. Economic valuation of coral reefs at Phi Phi Islands, Thailand. Int. J. Glob. Environ. Issues 3 (1), 104–114.

Souter, D., Linden, O., 2005. Coral Reef Degradation in the Indian Ocean: Status report 2005. CORDIO.

Spalding, M., Burke, L., Wood, S.A., Ashpole, J., Hutchison, J., zu Ermgassen, P., 2017. Mapping the global value and distribution of coral reef tourism. Mar. Policy 82, 104–113.

Spalding, M.D., Ravilious, C., Green, E.P., 2001. World Atlas of Coral Reefs. University of California Press, Berkeley, USA.

Speers, A.E., Besedin, E.Y., Palardy, J.E., Moore, C., 2016. Impacts of climate change and ocean acidification on coral reef fisheries: an integrated ecological–economic model. Ecol. Econ. 128, 33–43.

Sriskanthan, G., Funge-Smith, S.J., 2011. The Potential Impact of Climate Change on Fisheries and Aquaculture in the Asian Region. FAO Regional Office for Asia and the Pacific, RAP Publication 2011/16, Bangkok, Thailand, p. 41.

Teh, L.S., Teh, L.C., Sumaila, U.R., 2013. A global estimate of the number of coral reef fishers. PLoS One 8 (6), e65397.

United Nations, 2019. Goal 14: Conserve and sustainably use the oceans, seas and marine resources. https://www.un.org/sustainabledevelopment/oceans/ (accessed 20.02.19).

Viyakarn, V., Lalipattarakit, W., Chinsak, N., Jandang, S., Kuanui, P., Khokiattiwong, S., Chavanich, S., 2015. Effect of lower pH on seetlement and development of coral, *Pocillopora damicornis* (linnaeus, 1758). Ocean Sci. J. 50 (2), 475–480.

Wang, X., Song, L., Chen, Y., Ran, H., Song, J., 2017. Impact of ocean acidification on the early development and escape behavior of marine medaka (oryzias melastigma). Mar. Environ. Res. 131, 10–18.

Wang, Z., Wang, Y., Zhao, P., Chen, L., Yan, C., Yan, Y., Chi, Q., 2015. Metal release from contaminated coastal sediments under changing ph conditions: implications for metal mobilization in acidified oceans. Mar. Pollut. Bull. 101 (2), 707–715.

White, A.T., Aliño, P.M., Cros, A., Fatan, N.A., Green, A.L., Teoh, S.J., Laroya, L., Peterson, N., Tan, S., Tighe, S., Venegas-Li, R., 2014. Marine protected areas in the Coral Triangle: progress, issues, and options. Coast. Manag. 42 (2), 87–106.

Wilkinson, C.C., 2004. Status of Coral Reefs of the World: 2004. Australian Institute of Marine Science (AIMS).

Williams, S.L., Sur, C., Janetski, N., Hollarsmith, J.A., Rapi, S., Barron, L., Heatwole, S.J., Yusuf, A.M., Yusuf, S., Jompa, J., Mars, F., 2018. Large-scale coral reef rehabilitation after blast fishing in Indonesia. Restoration Ecol..

Zhai, W.D., Zang, K.P., Huo, C., Zheng, N., Xu, X.M., 2015. Occurrence of aragonite corrosive water in the North Yellow Sea, near the Yalu River estuary, during a summer flood. Estuar. Coast. Shelf Sci. 166, 199–208.