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Socio-economic tools to mitigate the impacts of ocean acidification on economies and communities reliant on coral reefs — a framework for prioritization

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ABSTRACT

Coral reef preservation is a challenge for the whole of humanity, not just for the estimated three billion people that directly depend upon coral reefs for their livelihoods and food security. Ocean acidification combined with rising sea surface temperatures, and an array of other anthropogenic influences such as pollution, sedimentation, over fishing, and coral mining represent the key threats currently facing coral reef survival. Here we summarize a list of agreements, policies, and socio-economic tools and instruments that can be used by global, national and local decision-makers to address ocean acidification and associated threats, as identified during an expert workshop in October 2017. We then discuss these tools and instruments at a global level and identify the key tasks for raising decision makers' awareness. Finally, we suggest ways of prioritizing between different actions or tools for mitigation and adaptation.

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0. Introduction

Tropical reef systems, like the policy and socio-economic frameworks directly or indirectly impacting them, are home to a diversity of species. Yet, despite this diversity, they are particularly vulnerable marine ecosystems. Approximately 25% of coral reefs have already been severely impacted worldwide due to warming in areas where corals have already reached their upper thermal limits (Hoegh-Guldberg et al., 2009). In the past two decades, mass coral bleaching events and related mortality have been observed in various regions where there have been elevated sea surface temperatures (SST) (Descombes et al., 2015). According to the 1.5 °C report of Intergovernmental Panel on Climate Change (IPCC), coral reefs would almost entirely disappear with 2 °C of warming, with just 10%–30% of existing reefs surviving at 1.5 °C (https://www.ipcc.ch/sr15/). Concurrently, pollution, sedimentation, large outbreaks of disease, storm impacts, competition from macro- and encrusting algae, overfishing and habitat destruction, such as coral mining and destructive fishing practices, are also contributing to the decline in abundance and diversity of coral reefs. Further compounding and exacerbating these threats, the pH of the ocean has been driven down at a global scale by about 0.1 from pre-industrial levels due to the absorption of excessive CO_2 emitted into the atmosphere primarily as a result of fossil fuel combustion. This process of Ocean Acidification places additional stress on coral reefs and the marine species associated with them, further increasing their susceptibility to other threats and reducing their resilience, and capacity to provide valuable and essential ecosystem services (Hughes et al., 2018).

Ocean acidification has been shown in laboratory studies, and from research in areas with naturally low pH, to cause decreased growth rates and increased mortality in hard corals (Anthony et al., 2011). Low pH also favors growth of seaweeds that compete with corals, while negatively affecting forms of algae that are important precursors for recruitment of many corals (and therefore reducing recovery potential of coral reefs after disturbances) (Anthony et al., 2015). These effects of ocean acidification on coral reefs compound, and are compounded by, the numerous other categories of anthropogenic pressure on the marine environment (Hoegh-Guldberg et al., 2007; Pendleton et al., 2016). Such pressures can be indirect and diffuse, such as global climate change, or direct and local, such as point-source pollution (Carpenter et al., 2008). Among the global threats, perturbations such as massive bleaching events caused by increased sea and ocean temperatures, are now observed worldwide (Heron et al., 2016). Among the most important local threats are pollution, overfishing, and destruction of habitat, including direct reef destruction due to the use of fishing gears, construction works and limestone exploitation (Zaneveld et al., 2016). Many studies now show that increasing populations are raising the anthropogenic pressure on ecosystems such as coral reefs (Cinner et al., 2009).

The combined effect of these respective pressures has been a slow-onset crisis for coral reefs. Regrettably the crisis facing coral reefs across the globe is now manifesting itself with disturbing clarity. The implications for the communities and economic sectors highly dependent on coral reefs are significant and potentially catastrophic. Economic development, safety and public well-being are all threatened by the decline of coral reef systems.

An estimated 3 billion people depend on marine and coastal biodiversity for their livelihoods (FAO, 2014). The disruptions to the delivery of marine ecosystem services caused by ocean acidification and climate change and pollution of the marine environment will seriously affect the economy of coastal communities and could also impact food security and could in turn result in increased poverty.

To proactively mitigate and adapt to the impact of ocean acidification on coastal communities, it is important for national governments to assess the economic value of their coastal resources, including the coral reefs. To accomplish such a task, national governments need to compile standardized statistics on variables such as percent of population living in coastal areas, percent of built property located along the coast, percent and type of business establishments along the coast, percent of labor force employed in businesses located along the coast, percent of tax revenues from business located on coastal areas, and total number of visitors and tourists to the coastal areas. They also need detailed information on the contribution of fisheries to their GDP.

Fig. 1 presents NOAA's estimates of the value of reefs by their different functions.

The Reef Resilience network states that more than half a billion people rely on reefs for food and livelihood and over 275 million live within close proximity (30 km) of the reefs. The fish catch around the reefs in Asia secure food to one billion people and the reefs protect more than 150,000 km shorelines in 100 countries.[1].

[1] http://www.reefresilience.org/coral-reefs/reefs-and-resilience/value-of-reefs/.

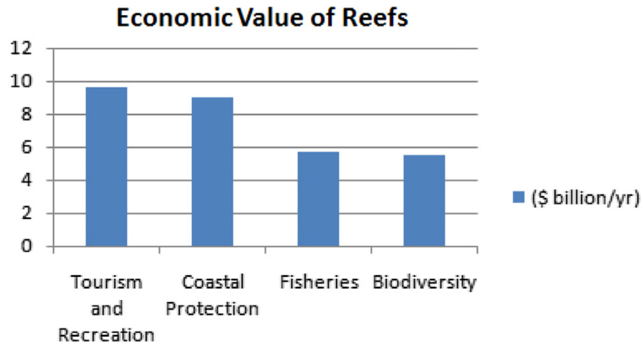


Fig. 1. Economic value of reefs.
Source: https://coralreef.noaa.gov/aboutcorals/values/.

Accurate and sustained data collection over time is key. Being able to measure damages/losses to environmental resources is crucial in bringing attention to the problems at hand. Different stakeholders could be involved in data collection (general public, high school pupils, researchers from local universities etc.) These national databases with local information on the state of coral reefs as well as on coastal economic activity would not only provide relevant information to governments but would also enable researchers to more accurately evaluate the socio-economic effects of different policy options/actions to protect corals. And joint data gathering might also generate the positive externality of having the local communities value reefs and have a sense of ownership over the resource.

This paper provides an overview of the agreements, policies, and socio-economic tools and instruments for international, national and local decision making to address ocean acidification, its impacts on coral reefs and societies, before presenting a framework for prioritizing actions.

1. Tools at the international level: Global policies and regional agreements

In view of the considerable number of existing regulatory instruments, the greatest challenge is not in developing new instruments, but to ensure that; (i) all States have sufficient knowledge and understanding of the overwhelming number of existing instruments and the synergies that exist between them, and (ii) they are, according to their capabilities, in a position to adopt the necessary measures to conform and implement all these legal texts or policy declarations at the national level.

1.1. Mitigation: agreements and protocols

The pH of the ocean, semi-enclosed seas and coastal waters across the globe is variable both spatially and temporally. However, ocean acidification is a ubiquitous and global phenomenon with potentially catastrophic consequences, caused primarily from increasing concentrations of atmospheric CO_2. It therefore demands mitigation responses at the international level. However, in order for mitigation measures to be successful, both decision makers and the public need to be aware of potential and occurring climate change impacts, including the effects of ocean acidification on coral reefs, and the existing benefits to people that will be lost from continuing coral reef degradation. Global initiatives should articulate and draw attention to the value of ecosystem services provided by coral reefs, such as their role in food provisioning, recreation and culture as well as coastal infrastructure protection, and stress the risks posed by ocean acidification to these services.

Mitigation has been identified as the most fundamental way to reduce climate change and ocean acidification risks. The Paris Agreement, the successor of the Kyoto Protocol, aims to strengthen the global efforts to reduce greenhouse gas emissions, including CO_2, the primary gas driving ocean acidification (UNFCCC, 2015). The effectiveness of the agreement, however, depends entirely on the sustained commitment and effectiveness of countries to reduce their CO_2 emissions. Current commitments, however, are most likely much too low to reach the internationally agreed 2 °C target (Rogelj et al., 2016).

In addition to the Paris Agreement, there exists a body of norms addressing threats to marine ecosystems, including coral reefs. Some are of a general nature, others deal with specific sources of pollution such as the pollution from vessels, from dumping or from land-based responsible for most of the contamination of the oceans and affecting the most productive areas of the marine environment (see Appendix for an exemplary list). The control of such sources of pollution could mitigate harmful damages to the marine environment such as preventing the increase of acidification affecting corals reefs.

At global and regional levels, a number of international agreements aim to combat different sources of marine pollution. In addition, a number of declarations or instruments of a voluntary nature, in which States have committed themselves to taking actions or meeting policy goals and targets, are also significant.

Ten years after the adoption of UNCLOS, the Rio Conference on Environment and Development (UNCED) adopted an ambitious program of action. It was designed to ensure the sustainable development of the resources of the planet. The outcome of the Conference was a comprehensive blueprint for action to be taken not only by governments and United Nations organizations but also by non-governmental organizations, independent sectors and groups in every area in which human activities have an impact on the environment. This blueprint known as Agenda 21 devotes its entire Chapter 17 to oceans and seas.

1.2. Economic instruments and tools

The environmental economics literature outlines two primary market-based instruments to mitigate greenhouse gas (GHG) emissions and thereby reduce ocean acidification stressors on coral reefs:

- Taxation (e.g. carbon tax) or subsidies (e.g. energy efficiency subsidies, subsidies for renewable energy technologies, feed-in tariffs for renewable energy); eliminating fossil fuel subsidies,
- Emissions trading systems (ETS), or cap-and-trade (CAT) programs, based on quota allocation.

Such market-based instruments are quite common. A price on carbon through Emissions Trading Systems (ETS) and taxes were in place for 39 national and 23 sub-national jurisdictions according to a World Bank Report, as of August 31, 2015. Together, these carbon-pricing instruments cover about 12 percent of the annual global GHG emissions. The combined value of the carbon pricing instruments in 2015 was estimated at just under US$ 50 billion globally, of which almost 70 percent (about US$ 34 billion) is attributed to ETS and the remainder (about 30 percent) to carbon taxes.

Environmental policy instruments, such as taxes and ETS, have their respective strengths and weaknesses. Tax-or-subsidy-based control mechanisms may cause rigidities between direct producers and end-users, and affect the decisions of market agents in a negative way. Still, effective carbon taxes have proven to cause significant reductions in GHG emissions in several countries in the world. Allocation of green taxes and fines aimed at marine protection could be considered in the policy mix, along with the removal of subsidies and other incentives that encourage the use of fossil fuels.

Along with market-based mechanisms, technological standards and associated restrictions pertaining to fuel oil, energy efficiency and GHG emissions may also be employed for climate change mitigation. Energy performance certificates and green bonds can also be cited among the instruments available for emissions reduction because mitigation is crucial to preserve coral reefs.

1.3. Ecosystem services

In addition to supporting fisheries and tourism, coral reef ecosystems also provide recreational, cultural, and aesthetic benefits. Various environmental economic studies calculate household willingness to pay to protect these sorts of services, either through the establishment of marine protected areas (MPAs), payments for ecosystem services, or climate change mitigation

Payments for ecosystem services (PES) and biodiversity offsets could provide financial incentives to property and business owners to enhance their environmental practices, either by subsidizing better practices through PES schemes or by requiring the purchase of offsets to balance carbon emissions or other negative externalities being generated by the business. Other instruments are related to social status. For example, certification incentives to identify businesses in different regions that have adopted environmental best practices, could provide an additional motivation for businesses to reduce their environmental impact and contribute to regional coral reef conservation.

Entrepreneurship activities must be developed in maritime and coastal tourism taking in consideration the Blue Economy conceptual framework as a valuable heuristic — not only to structure evaluations of practice, but also to help reveal missing ingredients necessary for the sustainable development of healthy oceans and to refine sustainable development models to better address ocean issues Keen et al. (2018). It needs also a strong political willingness, commitments, rigorous researches and promoting social awareness (Bari, 2017). Finally, another public policy tool can be to utilize market-based incentives for reef restoration, coral reef resource trading, and coral farms for medicinal purposes where future reefs can be partially protected through the resources generated by such enterprises.

2. National governance

2.1. Nationally determined policy combinations

In their respective efforts to protect and preserve coral reefs, every government is uniquely positioned to determine its own ways and means of contributing to global objectives of consequence for coral reefs, such as the Paris Agreement, Agenda 2030 and the SDGs, as well as domestic objectives that might go beyond the objectives and targets of multilateral commitments. In this context, the Paris Agreement provides a framework that requires individual countries to develop and communicate their domestic strategies, known as their Nationally Determined Contributions (NDCs).[2] Already, 180 parties have submitted their initial NDCs.[3]

[2] http://unfccc.int/focus/items/10240.php.

[3] http://www4.unfccc.int/ndcregistry/Pages/All.aspx.

2.2. Giving priority to human well-being

Oceans provide resources such as fish and other seafood, as well as supporting human well-being, in general. Presently, 850 million people live within 100 km of coral reefs and many of whom look to these marine ecosystems for food and livelihoods (Burke et al., 2011). The reef ecosystems protect coastal villages, businesses, and residents from wave action and storms, providing risk reduction benefits to an estimated 100 to 197 million people (Ferrario et al., 2014). Coral reefs support fisheries that are important for food, as well as income from tourism and recreation plus associated profits, taxes, and foreign income. (Bell et al., 2013; Brander and Beukering, 2013; Cruz-Trinidad et al., 2014; Deloitte Access Economics, 2013; Hoegh-Guldberg et al., 2014). Well-being is also imparted from coral reefs through the provision of cultural and recreational opportunities, a sense of security, and opportunities for empowerment through effective governance systems (Balmford and Bond, 2005). The extent to which human well-being should be prioritized in policy and adaptation planning processes, requires the evaluation of coastal resources, not only for their economic provisioning services, but also for the role that coral reefs play in contributing to human well-being.

2.3. Population density in coastal regions

Presently about 40% of the world's population lives within 100 km of the coast. As population density and economic activity in coastal areas increase, so do pressures on coastal ecosystems. Habitat conversion, land cover change, pollutant loads, and introduction of invasive species are among the most important pressures on coastal systems. These pressures can lead to loss of biodiversity, coral reef bleaching, new diseases among organisms, hypoxia, harmful algal blooms, siltation and reduced water quality. They can also threaten human health through toxins in fish and shellfish and pathogens such as cholera and hepatitis. To address these population density challenges, national governments can use zoning regulations to limit development activities along the coast. Governments can also attach premiums on licenses that develop both residential and commercial facilities. The proceeds from these licenses could be used towards conservation efforts. Harbor activity is an important aspect for the shipping industry, which national governments and economies rely on. To help preserve and restore damage to coral reefs, large and/or high-traffic vessels could be subjected to fees.

2.4. Promoting sustainable ecotourism, education and communication

To provide the best protection to coral reef ecosystems against ocean acidification and climate change, national governments need to adopt legal and economic tools that are adapted to their country's specific capabilities, particularly within marine-based industries such as tourism. To this end, tourism regulations should be focused on implementation at the local level, and complemented by economic and social initiatives that reinforce the regulations. This could include encouraging human activities that simultaneously promote education and conservation for the marine environment, which can be done through well-regulated tourism and small scale, sustainable fishing tourism managed under best practices. Tourists could be empowered to protect coral reefs by being involved in citizen science conservation and monitoring efforts.[4]

[4] One example is the Citizen Science Program in the US (https://sanctuaries.noaa.gov/involved/citizen-science.html). Another example is a study that evaluated the role of marine citizenship in UK marine governance (McKinley and Fletcher, 2010).

As part of overall development policies, national governments could use the following means to promote sustainable tourism in their respective countries:

- Test and certify tourism service providers (travel agencies, tour organizers, hotels, etc.) on the knowledge, understanding and interpretation of concepts of sustainable tourism and the principles of ecotourism.
- Require local governments to educate public sector employees to identify best environmental practices appropriate for their needs.
- Allocate funds for educating public sector employees as well as fishermen
- Require certification of tourism sector employees: divers and instructors, waiters and other employees.

In this regard, education programs such as literacy programs in schools, but also observations and experimentations in situ by pupils or students, may also raise awareness of the sustainable use of marine resources. For regions depending on coral tourism, various communication tools could be used to provide more information to tourists about protecting the environment.

2.5. Providing support to communities after extreme events

National governments should have emergency plans and procedures to respond to rapid-onset extreme events and their consequences for coral reefs. Extreme events, such as tsunamis, hurricanes and earthquakes, create material damages that may cripple reef-dependent-economies for a long time, undermining capacity to mitigate or adapt to slow-onset ocean acidification and climate change.

Temporary adaptation strategies, such as the banning of some fishing activities after natural disasters, such as hurricanes, may allow faster recovery of coral reef habitats and ecosystems. An effective adaptation strategy would also include developing an early warning system for extreme events to assist decision-makers to design and implement relevant adaptation strategies and responses.

2.6. Ocean literacy programs in schools

National governments help shape the curricular content of primary and secondary education. Introducing ocean literacy programs may motivate innovative conservation and enhance the desirable outcomes for a Blue Economy. The Marine Activities, Resources, and Education (MARE) Program is an example of a program that seeks to increase ocean literacy through informal and formal education. The Lawrence Hall of Science at University of California at Berkeley developed the MARE Program which is currently administered throughout the USA and Mexico through five Centers.[5]

2.7. Incentivizing sustainable consumption/production

National governments need to ensure sustainable consumption and production of goods and services, which is also required by the Sustainable Development Goal 12. Realizing SDG 12 will involve a variety of stakeholders, including businesses, consumers, policy makers, researchers, scientists, retailers, media, and development cooperation agencies, among others. Through the creative use of pricing signals discussed earlier, national governments can promote sustainable consumption and production that reduces pressure on coral reefs.

According to a UN Report, households consume 29 per cent of global energy and contribute to 21 per cent of CO_2 emissions. If people worldwide switched to energy efficient lightbulbs the world would save US$ 120 billion annually.[6] National governments could facilitate the transition to energy efficiency lightbulbs by providing companies and households with zero interest loans or allowing the expenses to be tax deductible.

The same UN report also states that each year about one third of all food produced – equivalent to 1.3 billion tonnes worth around $1 trillion – ends up rotting in the bins of consumers and retailers, or spoiling due to poor transportation and harvesting practices. Governments could help encourage businesses to invest in proper storage and transport facilities using price signals.

3. Local options

3.1. Adaptation and valuation of coral reefs

Building or improving the adaptive capacity of society to the impacts of ocean acidification and climate change can be framed according to five domains including, (i) the assets that people can draw on in the time of need, (ii) the flexibility to change strategy, (iii) the ability to organize and act collectively, (iv) learning to recognize and respond to the change, and (v) the agency to determine whether to change or not (Cinner et al., 2018). These key domains can assist decision makers to ensure that sufficient capacity exists within local communities and industries to design and implement socio-economic adaptation plans. If sufficient capacity exists, solutions for dealing with coastal area stressors, adopting sustainable fishing-related activities and improving resilience of coral reefs might be possible. Here, we highlight potential socio-economic tools in each of these realms for adapting to the impacts of ocean acidification and climate change on coral reefs.

3.2. Mitigate other stressors on coral reefs

The link between local pressures and overall vulnerability to ocean acidification highlights the importance of reducing other stressors, such as overfishing and pollution, through targeted local management actions (Anthony et al., 2015). For example, sediment and nutrient runoff from land leads to adverse impacts on coral reefs in various regions of the world including Australia, Africa, Pacific Islands, etc. (Golbuu et al., 2011; Uthicke et al., 2012; Van Katwijk et al., 1993). Pulses of suspended sediment concentrations following heavy rainfall can block the light for photosynthesis used by corals, reducing larval recruitment, inducing coral diseases, and causing a shift to the dominance of macroalgae, among other impacts (Bartley et al., 2014). In such instances, increases in investment on localized and targeted land-based management measures and actions are required to reduce runoff and sediment, including agricultural pollutants, into the ocean (Kroon et al., 2016). Land management measures with a wider coverage of the whole watershed system and long-term monitoring programs are required to effectively reduce chronic runoff and erosion (Wang et al., 2011; Wilkinson et al., 2014).

Small-scale threats such as destructive fishing, or direct extractions are considered to be more closely linked to developing countries (in particular, in the "Coral Triangle" in South-East Asia and in East Africa), whereas long-term stressors such as shifts in

[5] http://mare.lawrencehallofscience.org/partnerships/mare-centers See as well: Ocean School program http://www.oceanschool.ca/, from the Ocean Frontier Institute in Canada (with Wendy Watson, ex-director IOC/UNESCO).

[6] http://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/16-00055L_Why-it-Matters_Goal-12_Consumption_2p.pdf .

water quality or in species assemblage are more often associated with industrial developed countries. Coastal development and pollution are observed worldwide as soon as coasts get populated (WRI, 2011).

3.3. Enhancing well-managed fisheries and changing fishing practices

Overfishing, especially of species important to coral reef resilience, can exacerbate the effects of ocean acidification. Herbivorous fish, such as parrotfish (Scaridae), surgeonfish (Acanthuridae) and rabbitfish (Siganidae), play a key role in controlling seaweeds, which can readily overgrow corals or prevent new corals from colonizing after disturbance (Hughes et al., 2007). In many countries these fish are targeted by commercial and subsistence fishers, often using nets or traps. Fishers and fishery managers can help support reef resilience at local scales by ensuring that the harvest of herbivorous fishes is carefully managed to ensure that their important function in controlling seaweed biomass is not diminished. This can be accomplished through a range of measures, including closing sensitive areas to herbivore fishing, placing restrictions on the size or number of herbivorous fishes that can be caught, preventing types of gear that target important herbivores, banning sales of herbivorous fishes or facilitating a shift in target species through market incentives or other mechanisms (Bozec et al., 2016).

Another key adaptation strategy is to allow for greater flexibility of the fishers' behavior. This idea encompasses potentially switching to new fishing locations, changing to other alternative jobs or fisheries, shifting to other gear type, and targeting species with less negative impacts under ocean acidification and climate change. "Good" fisheries subsidies can allow fishers to have more capacity to move to new locations with larger boats and more advanced technology. Funding contributed to develop alternative livelihoods such as ecotourism may also increase the flexibility of coral reef fishers (McClanahan et al., 2015; McIlgorm et al., 2010). Fishers should also be provided with skill learning programmes to enable them to the acquire better knowledge of the local ecology of their fishery, knowledge of potential new fishing locations, techniques for using new gear and knowledge of potential new exploited species (Berkes et al., 2000).

When looking at fisheries, and especially subsistence fishing, resource managers need to combine ecological vulnerability and social vulnerability for local populations, and so consider social-ecological interdependencies (Thiault et al., 2017a). Indeed, the target-appropriate management actions cannot be standardized, and depend on local adaptive capacities, which reflect the community's ability to cope with the loss of fishing opportunities (for example mobility, education, material assets, livelihood diversity, attachment), and social sensitivity, all of which reflect a household's dependence on marine resources (Thiault et al., 2017b).

Many adaptation strategies are attempting to reduce vulnerability of the fishing sector, particularly on reducing the impacts of fisheries in or around coral reefs through changing fishing grounds and gears. The assets that communities depend on can be built through improving the productivity of the coral reef fisheries by using effective fisheries management measures. Most of these measures lie in controlling fishing effort and the catch amount. All of these adaptation options aim to maintain and conserve the diversity and abundance of marine resources and hence reduce and delay the impact of ocean acidification and climate change. Fishing effort can be reduced through licensing systems, seasonal closures of the fishing ground and the implementation of marine reserves. Marine reserves not only provide the functions of habitat and species protection but are also a low technology and cost-effective adaptation strategy that can lead to co-benefits at various spatial scales, i.e., from local to global (Roberts et al., 2017). Also, the larger the size of the available reef fish habitat, the less the impact of climate change on the composition of marine species (Maharaj et al., 2018). Hence, extensive Marine Protected Area (MPA) networks with well-enforced measures have been shown to generate the highest conservation benefits and effectiveness for serving as a mitigation and adaptation tool for climate change and ocean acidification (Roberts et al., 2017). Another management approach for improving marine resource status and productivity are the output control methods, including the Total Allowable Catch (TAC) control and individual transferable quotas (ITQs). Effective spatial management arrangements and input and output control measures should have the flexibility to adjust to accommodate the impacts of ocean acidification and climate change on the fisheries stocks including the increase in the variability of the abundance and catchability, and the occurrence of new straddling species (Jennings et al., 2016; Madin et al., 2012). All of these strategies require the cooperation of different institutes and stakeholders within the fisheries sectors and frequently also collaborations among different countries. With all these strategies, it is crucial to have participation from all fisheries stakeholders and communities to engage in ocean acidification and climate change adaptation strategies.

Similarly, environmental economics suggests several economic tools for biodiversity conservation and sustainable natural resource use. Within fisheries management, the concept of cap-and-trade is transferred to individual and transferable fisheries quotas (ITQs). Individual fishers are allocated fishing quotas, which they can use to harvest a specific amount over a given season or can sell to another fisher. Different configurations of ITQ programs may limit concentration of quota that a single firm can hold (to prevent monopolies) and/or restrict quota trading between small-scale and industrial vessels or different vessel classes. ITQ programs have demonstrably slowed the race-to-fish in U.S. fisheries, and similar programs could be implemented to sustainably manage coastal fisheries in different marine regions.

3.4. Self-regulated fishing and traditional tools

Empowering fishers to be pro-active in designing and implementing their own strategies to reduce stress on their fisheries and reefs is important. This means involving the very people who make their livelihood through fish catch, in the policy setting and management process.

Features that encourage fishers and their communities to self-regulate are the improvement of the community's access to alternative job opportunities and public services such as education and health. This is the case for the Vamizi Island Conservation Project in the northern Querimbas archipelago belonging to Mozambique. This area has a global conservation value since coral reefs are among the most diverse and pristine in the region and are resilient to bleaching (Garnier et al., 2012). The livelihood of the Kimwani people in this area has always depended on coastal resources. With increased immigration and the introduction of unsustainable fishing practices, there was a significant decrease in fish catch. The Vamizi Island Conservation Project came from the local community to allow fish stocks to recover and this contributes to explaining why it is one of the most successful examples of a community-managed protected area in East Africa. In order to favor income-diversification, the Querimbas archipelago, the Ministry of Environment, and the Global Environment Facility (GEF) are supporting the development of small businesses in Vamizi Island linked to tourism and cultural activities. Some of these businesses have already created jobs and generated revenues.

For the preservation of coral reefs, there is a need to share and relay local and scientific knowledge. Local knowledge can include cosmogonies, arts, social organization, rules, etc. These aspects of indigenous culture preservation and transmission must be integrated in environmental conservation efforts.

There exist several forms of community management techniques: LMMA (Local Managed Marine Areas), ICCAS (Indigenous and Conserved Communities' Areas), and others as *rahui* in Polynesia. Today hybrid governance describes forms which articulate local organizations and regional and national rules.

An example of where best environmental practices has worked comes from the Great Barrier Reef. The Great Barrier Reef Marine Park Authority, responsible for ensuring the sustainable use of the Great Barrier Reef, established a Reef Guardian program in 2011 to inspire various stakeholder groups such as commercial fishers to take on voluntary practices beyond what is required by law, and to share information. Its premise is based on recognizing good environmental practices that help to protect the Great Barrier Reef. It acknowledges individuals to be 'Reef guardians', and through enhancing social status of the industry within the broader community, inspires other fishers to also adopt best practices. The program represents an excellent opportunity for government to engage positively with the commercial fishing (and other) industries.[7]

3.5. Establishing Marine Protected Areas (MPAs)

Marine Protected Areas (MPAs) provide a regulatory framework for controlling human activities with the goal of reducing a range of impacts and protecting valued habitats and ecosystems. MPAs take a wide variety of forms, and are established across a diversity of coral reef settings for a range of reasons, spanning biodiversity conservation, fisheries management and reducing conflict among users (Ban et al., 2011). Increasingly, MPAs are also being seen as important frameworks for implementing measures to build the resilience of coral reefs to ocean acidification and climate change. The designation of an MPA normally provides for management arrangements that can manage local pressures, especially those that result from activities within the MPA, such as fishing and wastewater discharges from boats. They can also create the political imperative to address exogenous stresses, such as land-based sources of pollution, through collaboration with catchment management organizations or establishment of ridge-to-reef programs (Stoms et al., 2005). While the effectiveness of MPAs depends on many factors, including the existence and application of appropriate management plans, a comprehensive program of management activity and effective compliance (including enforcement) (Hockings et al., 2004), MPAs can provide an important framework for implementing measures that are necessary to build resilience of coral reefs to ocean acidification.

While MPAs alone cannot protect against global phenomena such as ocean acidification, they can enhance coral reef resilience to changing conditions through encouraging scientific research and monitoring and limiting human activities within the area. They can also allow comparisons of climate change impacts across zones. It will also be easier to follow the migration of the marine population, where necessary. The legislative framework underpinning the declaration of MPAs should provide tools for scientific research and promote and facilitate a scientific network between all marine areas and within the science community.

The expansion or establishment of MPAs should be accompanied by effective implementation and enforcement of all accompanying laws and regulations. Any penalties should be adapted to the local context and be sufficiently dissuasive to avert illegal behavior. This could mean incurring additional costs, such as hiring enforcement officers and vessels. Cross-country collaborations could lower costs, such as regional training workshops for enforcement officers and shared high seas monitoring efforts. Locally nominated "sheriffs" could further enhance local buy-in and effectiveness of these regulations, especially if said regulations are designed, implemented, and enforced by local communities.

Public–Private Partnerships may also motivate investment for Marine Protected Areas. To be successful, marine conservation requires sufficient financing and adequate management resources, both of which can exceed public budget priorities. In parallel, it has been demonstrated that, well marketed, vibrant marine biodiversity can generate important revenue from visitors and businesses, as well as provide economic benefits for local populations.

During the last 15 years, impact investors have been exploring investments in conservation with more than US$ 8 billion invested since 2004 in food & agriculture, forestry, habitat protection, clean water initiatives and other conservation projects (Pascal et al. 2018). In marine biodiversity, a limited, but positive, track record of impact investments has confirmed that environmental, social and financial returns can be gained.

Entrepreneurial Marine Protected Areas (EMPAs) have been identified as a potential asset class for investors (Bos and Pascal, 2015; Credit Suisse AG 2016). An EMPA is a management area that is primarily funded by a profit-bearing business model, typically associated with nature tourism (Bottema and Bush, 2012). EMPAs belong to marine impact investments as they are designed to produce environmental and social impacts, and they primarily employ business models instead of grants to achieve those outcomes. While many terrestrial protected areas have private sector involvement (Dearden et al., 2006), significantly fewer MPAs include the private sector.

Recent studies have all shown that until 2014, the type of entrepreneurial intervention in EMPAs ranged from collecting diver fees that directly fund park management, to designing and implementing co-management arrangements in state designated parks, and to varying degrees of private tenure over marine habitat (Bottema and Bush, 2012). While the specific drivers for private sector involvement differ per case, one constant challenge has been maintaining a requisite level of legitimacy and authority to practice conservation.

Another study has argued that the economic feasibility, ecological effectiveness, and the socio-cultural implications of EMPAs require further investigation (Bos and Pascal, 2015).

4. A framework for prioritization of mitigation efforts

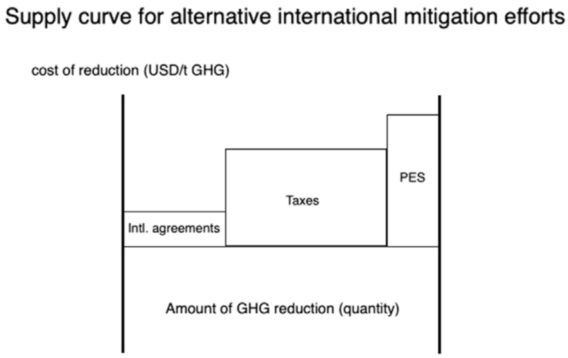
As all mitigation measures discussed above, come at a cost, either monetary or non-monetary, and financial resources are scarce, it is necessary to prioritize between them.

Comparing costs and benefits of different actions has been proposed as a guide to such prioritization (Boardman et al., 2014; FAO, 2018). Such analysis can be performed at all the three levels discussed above, i.e. international, national and local.

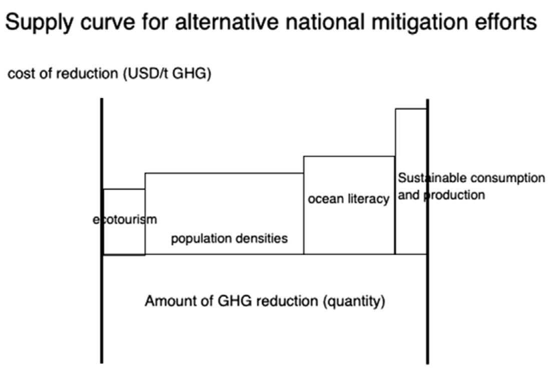
The following presentation of different options, their costs and effects, can be helpful for decision makers. Here we present the framework, but future work should focus on finding numerical estimates for the costs and effects.

Starting with alternative international mitigating efforts, policy makers should prioritize the tools that reduce OA stressors (here proxied with the amount of GHG reduction). The cost of GHG mitigation increases with the amount of GHG reduced and the supply curve shows that the cost of international agreements is the lowest and cost of PES (payment for ecosystem services) is the highest.

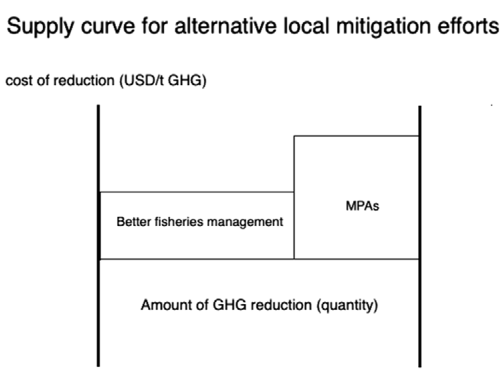
7 http://www.gbrmpa.gov.au/our-partners/reef-guardians.



Similarly, for national policies it is possible to rank different mitigating efforts by costs and at the same time get an idea of their effectiveness in reducing the underlying OA stressors.



Finally, the same framework can be used to rank more local policy options, as seen below.



All these figures are purely indicative. Filling out the numbers for costs and stressors — reduction is an avenue for future work in this area.

5. Conclusion

Of the agreements, policies, and socio-economic tools and instruments reviewed in this paper, no single mechanism is a panacea or a silver bullet. Key to the future of coral reefs will be building resiliency through the use of multiple mechanisms, i.e. innovative policy combinations, complemented by environmental technology innovations and sustained investment. To increase the resilience of coral reefs to warmer temperatures and lower pH, it is crucial to reduce the threats from all other human-induced disturbances, such as fossil fuel dependence. Scientific knowledge is crucial and multidisciplinary research is still needed to understand the threats and impacts on coral reefs in order to inform on appropriate governance responses to protect them. Besides, a new economic understanding and transformation of the economies are necessary in order to enable sustainable consumption and production as well as to combat climate change. Human activity and the prioritization of economic growth are to be blamed as the primary causes of not only climate change, but also issues related to coral reefs. Development policies need to be re-designed in order to ensure the protection of coral reefs into sustainable development strategies rather than merely focus on economic growth where relevant. Increasing subordination of the environment to the priorities of rapid and deepening industrialization in the coral reef dependent regions indicates that nature is being exploited at the expense of the well-being of future generations.

Now, more than ever, coral reef preservation is a challenge for all of humanity, not only the coastal communities in coral reef areas. It concerns all stakeholders and only proactive and collaborative policies can really solve the problems faced by coral reefs.

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Appendix

Highly relevant general and specific and regional binding norms

In order to ensure the protection and preservation of the marine environment and the conservation of its resources, a large spectrum legal tools have been developed.

At the global and regional level, a number of international instruments exists aiming at combating different sources of pollution. In addition, a number of declarations or instruments of a voluntary nature where States have committed themselves in taking actions or meeting policy goals and targets, are also significant.

General

- *The 1982 United Nations Convention on the law of the sea (CNUDM)* sets out the legal framework within which all activities in the oceans and seas must be carried out. In this regard, Part XII of the Convention, which deals specifically with the protection and preservation of the marine environment;
- *The Convention on Biological Diversity 1992* establishes a regime for the conservation and sustainable use of biological diversity and the equitable sharing of the benefits arising out of its utilization;
- *The United Nations Framework Convention on Climate Change 1992 with the Kyoto Protocol* (1997) *and the Paris Agreement (2015)* establish a global regime for addressing anthropogenic climate change due to the release into the environment of certain greenhouse gases.

Specific

- *The International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78)* is the major IMO instrument which contains most of the international rules and standards on the prevention, reduction and control of pollution by ships;

- *The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and the 1996 Protocol to the Convention*. The Protocol represents a major change of approach to dumping from the Convention. It enhances the application of the precautionary approach and of polluters-pays principle.

Regional

The Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources (LBS Protocol), adopted in 1980, and came into force on 17 June 1983. It was amended in 1996 *as the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources and Activities*, following the revision of the Barcelona Convention in 1995, known as the Convention for the protection of the Marine Environment and the Coastal Region of the Mediterranean.

To combat overfishing and particularly illegal, unregulated and unreported fishing, several instruments were adopted under the auspices of FAO. They deal either with the respect of international conservation measures by fishing vessels like the *1993 Agreement on compliance with conservation and management measures*, or the increase control by port States to ensure that fishing vessels entering in a port did not violate the measures taken at the regional or sub regional level. Two other major instruments can be mentioned: (i) the 1995 *Agreement on straddling fish stocks and highly migratory fish stocks*, and (ii) the 2009 *Agreement on port state measures to prevent, deter and eliminate IUU fishing,* in force in 2016. It will enhance regional and international cooperation and block the flow of IUU caught fish into national and international markets.

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