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Review

Management strategies for coral reefs and people under global environmental change: 25 years of scientific research

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ABSTRACT

Coral reef ecosystems and the people who depend on them are increasingly exposed to the adverse effects of global environmental change (GEC), including increases in sea-surface temperature and ocean acidification. Managers and decision-makers need a better understanding of the options available for action in the face of these changes. We refine a typology of actions developed by Gattuso et al. (2015) that could serve in prioritizing strategies to deal with the impacts of GEC on reefs and people. Using the typology we refined, we investigate the scientific effort devoted to four types of management strategies: mitigate, protect, repair, adapt that we tie to the components of the chain of impact they affect: ecological vulnerability or social vulnerability. A systematic literature review is used to investigate quantitatively how scientific effort over the past 25 years is responding to the challenge posed by GEC on coral reefs and to identify gaps in research. A growing literature has focused on these impacts and on management strategies to sustain coral reef social-ecological systems. We identify 767 peer reviewed articles published between 1990 and 2016 that address coral reef management in the context of GEC. The rate of publication of such studies has increased over the years, following the general trend in climate research. The literature focuses on protect strategies the most, followed by mitigate and adapt strategies, and finally repair strategies. Developed countries, particularly Australia and the United States, are over-represented as authors and locations of case studies across all types of management strategies. Authors affiliated in developed countries play a major role in investigating case studies across the globe. The majority of articles focus on only one of the four categories of actions. A gap analysis reveals three directions for future research: (1) more research is needed in South-East Asia and other developing countries where the impacts of GEC on coral reefs will be the greatest, (2) more scholarly effort should be devoted to understanding how adapt and repair strategies can deal with the impacts of GEC, and (3) the simultaneous assessment of multiple strategies is needed to understand trade-offs and synergies between actions.

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1. Introduction

Ocean acidification (OA) and climate change, including rising sea surface temperatures (SST), change in cyclone patterns, sea-level rise, and de-oxygenation, will adversely affect coral reef ecosystems in the coming decades (Cinner et al., 2016; Hoegh-Guldberg et al., 2014; Pendleton et al., 2016b). These global environmental changes (GEC) and their interactions will impact the goods and services provided by coral reefs upon which human populations depend (Brander et al., 2012; Pendleton et al., 2016a). Coral reefs support local and national economies (Burke et al., 2011), for instance by providing habitats for many species of fish on which local fishers depend (Teh et al., 2013), but also providing revenues from tourism and coastal protection. People, communities, and nations are vulnerable to the effects of GEC on coral reefs (Hughes et al., 2012).

Identifying ecosystems and human populations that are vulnerable to environmental change does not shed much light on appropriate response strategies (Hinkel, 2011). Vulnerability or impact assessments do not systematically identify which actions could reduce vulnerability (Tulloch et al., 2015). A necessary approach to reduce impacts and vulnerability is to identify the range and mix of possible actions (Ranger and Garbett-Shiels, 2012; Wilby and Dessai, 2010). Several scientific papers have attempted to help decision-makers and managers deal with the adverse effects of GEC on coral reefs by identifying management options (e.g. Mcleod et al. (2013); Rau et al. (2012)). However, they often focus on a narrow set of actions that can be taken within a specific management approach such as Marine Protected Areas (e.g. Green et al., 2014; Keller et al., 2009), a specific threat (e.g. ocean acidification) or a specific ecological process such as coral adaptation to warming (van Oppen et al., 2015). Of course, not all strategies are available or recommended in every situation, but a focus on too few strategies can be misleading (e.g. protective measures (Hilborn, 2016)). Evaluating a broader range of available strategies, and indeed combinations of actions, helps managers to estimate the trade-offs of different management approaches (Bozec et al., 2016). Multiple strategies may be needed to deal with different parts of the problem.

A new science of solutions is emerging to help guide the choice of action, especially regarding climate change adaptation (Hinkel and Bisaro, 2015; IPCC, 2014). A synthesis of management strategies, based on an understandable conceptual framework can help managers and decision makers consider different policy actions within the complexity of coral reefs social-ecological systems (SES). Such a typology of management strategies has the advantage of making sense of a large number of actions while enabling conditions to evaluate and articulate their advantages and barriers (Biagini et al., 2014). It is therefore important to evaluate the broad range of possible management strategies available in a typology, in order to implement the most appropriate strategies and to avoid maladaptation (Magnan et al., 2016).

One common way of dividing solutions to climate change, used by the Intergovernmental Panel on Climate Change (IPCC), is between mitigation and adaptation (IPCC, 2014). Mitigation involves reducing the amount of greenhouse gases (GHG) while adaptation involves solutions to cope and to adapt to the adverse effects of climate change. This dichotomy reflects societal decisions but does not fully reflect the complexities of social-ecological systems. A number of management strategies, notably on coral reefs SES, show that mitigation and adaptation actions are not exclusive. The concept of adaptation to climate change usually only includes human adaptation, therefore fails to reflect the ecological components of coral SES. A typology that encapsulates the societal as well as the ecological components of the system is therefore needed.

Gattuso et al. (2015) proposed a typology to deal broadly with the impacts of carbon dioxide (CO_2) on the marine environment. Four major categories of actions are described in this typology to reduce the risk posed by CO_2 on ocean ecosystems and ecosystem services: mitigate, protect, repair, adapt. We do not know of literature reviews that attempt to use this typology for coral reefs SES and therefore we build on this typology and refine it specifically for coral reefs SES.

In addition to constructing a typology, a systematic literature review is important to investigate how science is currently addressing solutions to respond to the challenge posed by GEC on coral reefs. First, science has a critical role to play in shaping adaptation policy and reducing vulnerability of the marine environment (Ekstrom et al., 2015), and in guiding the allocation of resources (Di Marco et al., 2017). An understanding of the global scientific endeavor can help guide future research and better integrate science in policy-making. Second, we do not know of any evaluation that attempts to link the current scientific effort devoted to managing GEC and coral reefs and that evaluates the degree to which this scientific effort covers places that contain high biodiversity, provides ecosystem services, and will be the most affected by GEC. The spatial distribution of exposure and of dependence on ecosystem services is not homogeneous (Pendleton et al., 2016a). Because of this uneven spatial distribution, it is important to evaluate whether the scientific literature sheds light on the places that will be the most impacted.

The first goal of this paper is to review the scientific literature to structure, using a typology, the suite of management actions that could be available to deal holistically with the entire chain of GEC impacts from climate change and OA on coral reefs, their resilience, and the services they provide to people. This typology organizes information to enable managers and decision-makers to assess the effectiveness of actions in their local settings. The second goal of this paper is to understand how the scientific effort targeted at coral reefs, GEC, and management is distributed through space, time, and categories of action. Through this systematic literature review, we hope to identify gaps in the global coverage of research and also gaps in our understanding of the range of strategies to deal with the impacts of GEC.

2. A revised typology of management strategies

2.1. Constructing a typology for management strategies of coral reefs and people under GEC

The typology presented in Gattuso et al. (2015) classifies management strategies into four major categories: mitigate, protect, repair, and adapt. This typology was designed to broadly identify actions to tackle climate change and ocean acidification for ocean ecosystems and the services they provide. To apply this typology to tackle the impacts of GEC on coral reefs ecosystems and ecosystem services, we created sub-categories to take into account specific aspects of coral reef management (Fig. 1). When refining Gattuso et al.'s typology to deal with coral reefs ecosystems, the same four categories of management strategies can be used: reduction of local and global threats (mitigate), repairing and restoring damaged reefs and associated ecosystems (repair), protecting existing healthy ecosystems to improve resilience and maintain ecosystem functions (protect), and adapting human societies to the reduction of ecosystem services when damage from environmental change is not avoidable (adapt) (Burke et al., 2011; Gattuso et al., 2015; Mumby and Anthony, 2015).

Coral reef management focus on different aspects of the chain of impacts. Some are dedicated to conservation, while others target socio-economic vulnerability. We focus on public policy actions to tackle the threat that high CO_2 poses on coral reefs and human populations who depend on them. Private responses to these threats have been analyzed in Evans et al. (2016). We compile actions that can be implemented by local, national or international managers and decision-makers from the literature. We use the analytical framework developed by (Gattuso et al., 2015) as the basis to categorize possible options. Taken together, they give a broad picture of actions across all components of coral reefs SES. We provide a brief overview of the Gattuso et al. typology and an explanation of our modifications. Differences between the two typologies are presented in SM2. For a more exhaustive list and discussion of available actions, see SM3.

The main strategy to deal with climate change and ocean acidification is the reduction of greenhouse gases and coastal pollution. These "Mitigate" strategies can be broken down into three major sub-categories, limiting CO_2 emissions, reducing the greenhouse effect, and reducing coastal pollution. In agreement with Gattuso et al. (2015), we include coastal pollutants in the mitigate category, since these actions directly interact with ocean acidification and sometimes temperature (with turbidity). Measures to improve water quality can mitigate the effects of ocean acidification locally (Kelly et al., 2011). Reducing pollution, nutrient loading and sediments runoff also affects the state and resilience of coral reefs. Other environmental factors influence the resilience of ecosystems, and are addressed in the category "Protect".

Another set of actions builds on the notion of protection of coral reefs from local anthropogenic activities to improve the resilience of coral reefs to global environmental changes, broadly interpreted to include Marine Protected Areas (MPAs), marine spatial planning, and fisheries closure areas. Following the original framework, "Protect" strategies can be broken down into three major sub-categories, reducing local stressors to improve resilience, protection of ecosystems and associated ecosystems in MPAs, and protection of ecological refugia. We distinguish between fully protected MPAs or no-take marine reserves (Roberts et al., 2017) and other area-based management approaches placing the former in the "protection of ecosystems" sub-category and the latter in the "reduce other environmental stressors" sub-category.

Once coral reefs and associated ecosystems are degraded due to human impacts or natural phenomena (e.g. diseases and cyclones) and after they experience the effects of GEC, it could be possible to implement actions to restore biodiversity and lost ecosystem functions. These "Repair" strategies can be broken down into three

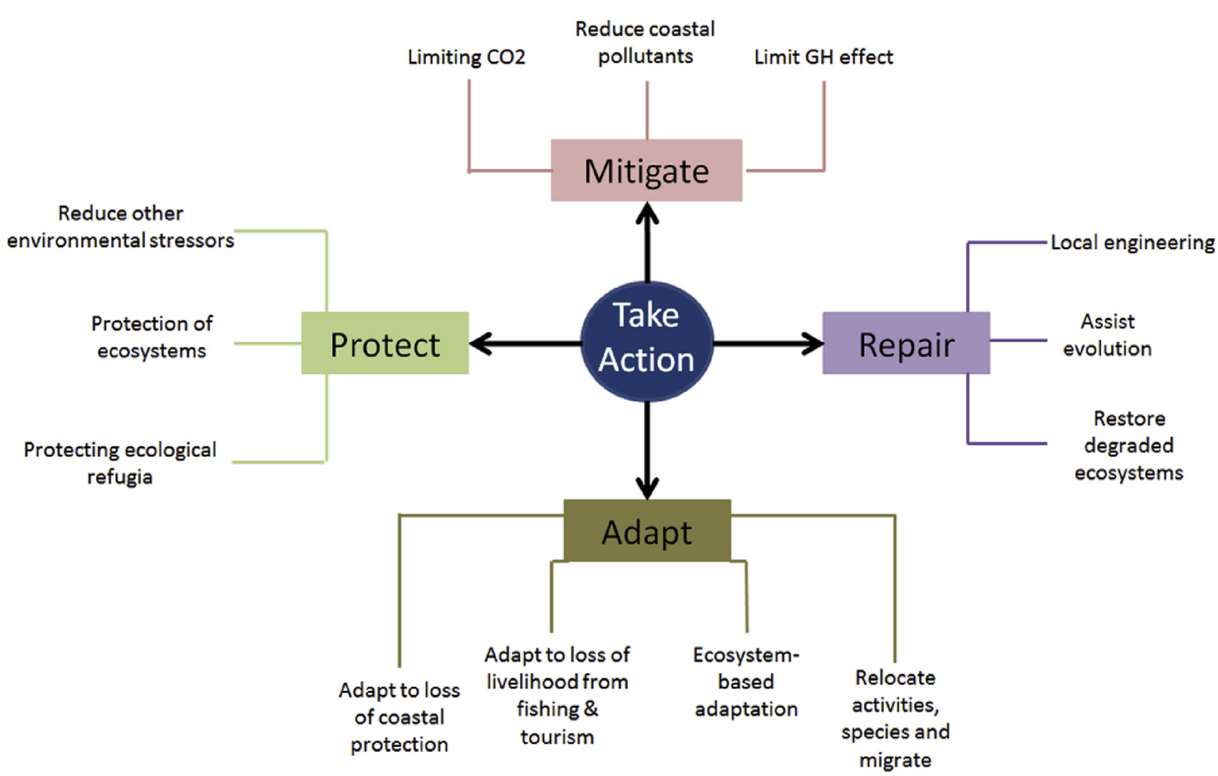

Fig. 1. Typology of management strategies to deal with GEC on coral reefs and people who depend on them; modified from Gattuso et al. (2015).

major sub-categories, restoring lost ecosystems, assisting evolution, and using local engineering to buffer against global environmental change. It could be possible to restore un-harmful environmental conditions for coral reefs at a very localized scale. These actions are categorized under the "local engineering" sub-category and include a more diverse set of actions than those enumerated in the Gattuso et al. (2015) typology that only considered adding alkaline material. Various other techniques are being developed to locally buffer against the unavoidable changes in ocean temperature and pH such as artificial shading to cool local areas (Rau et al., 2012). These methods are different from mitigate measures because they repair harm after it is done, while mitigation is here to prevent environmental changes.

Finally, "Adapt" strategies are those that assume future impacts of GEC will occur and help people cope with this new reality. The three types of strategies described above focus mainly on the ecological health and resilience of coral reefs, but not on the human activities and livelihoods that depend on coral reefs. Actions that address human adaptation to the loss of ecosystem services provided by coral reefs needs to be understood since climate change will and is already damaging coral reefs worldwide. While the typology developed by Gattuso et al. (2015) broadly addressed the adaptation of human activities and communities, we tailor these management strategies to the ecosystem services associated with coral reefs, the main ones being coastal protection, fisheries, and tourism. In addition, humans can harness nature to help societies adapt to the adverse effects that climate change will have on human systems, an approach that has been described by several authors as ecosystem-based adaptation (Jones et al., 2012). Adaptation strategies can be broken down into three major sub-categories: adapting to the loss of ecosystem services, using ecosystem-based adaptation, and relocation or migration of activities and populations.

In addition to these four types of strategies, there also are indirect strategies that focus on improving the underlying social, governance, and economic conditions necessary for the other four types of strategies to be effective. They can be divided in two categories: research and monitoring, and building capacity and are also detailed in SM3.

2.2. Linking management strategies to the impacts of GEC on coral reefs SES

The chain of impacts that link global environmental change to coral reefs and societies who depend on them is complex (Fig. 2). Local and global threats already have adverse impacts coral reefs. Local threats include coastal and marine pollution, overfishing, invasive species, crown-of thorn starfish, and physical damages. Global threats include sea temperature change, OA, and cyclones. For example, ocean acidification will impact calcification, but also other processes important for coral reefs development including reproduction, growth, and metabolism (Pendleton et al., 2016b). These changes may also produce opportunities for coral reefs and people, cyclones reduce sea surface temperature locally for instance. In turn, the degradation of reefs will affect ecological functions and species diversity that support the provision of services to human populations, including coastal protection, fisheries, and tourism. The purpose of management strategies is to reduce ecological exposure or sensitivity (Fig. 2) (Engle, 2011). Ecological exposure refers to the hazards (global and local environmental changes) as well as the health of coral reefs. Social vulnerability refers to the dependence of people on healthy coral reefs and their capacity to adapt.

All mitigate strategies target the reduction of ecological exposure, through the reduction of global and local environmental changes. Repair strategies also target ecological exposure, since they aim to improve coral reefs health under climate change. However, it is possible that restoration of degraded ecosystems could increase ecological exposure if it is done in regions where hazards will be more severe in the future (Fadli et al., 2012). In addition, the impacts of repair strategies on social vulnerability are not clear. Repair strategies could improve ecosystem services in the future by increasing coral reef cover and functions, but the distribution of these potential benefits across space and time has not been addressed in the literature. Protect strategies also target ecological exposure since their main purpose is to reduce and prevent anthropogenic pressures. The effect of protect management strategies on social vulnerability is unclear since these strategies, particularly no-take marine reserves, may have beneficial effects (e.g. through spillover of fish or by protecting reef structure important for shoreline protection), but could exclude some or all human activities and populations including those who depend on reefs for nutrition (Hilborn, 2016). Of course, even in the absence of protection, unsustainable levels of exploitation may also imperil the future of coral reefs. Adapt strategies are the only strategies explicitly targeted at reducing social vulnerability and the dependence of populations on coral reefs ecosystem services. Adaptation policies on land may threaten coral reefs socio-ecological systems (Evans et al., 2016). The use of ecosystem-based adaptation has the co-benefit of protecting ecosystems and restoring ecosystems, but these may not be viable solutions if climate change affects the capacity of these systems to provide ecosystem services (Pendleton et al., 2016a).

2.3. Conceptual ramifications of constructing a typology of management strategies for coral reefs SES

The typologies used in the literature are not always consistent. In several research articles, especially focusing on vulnerability (Cinner et al., 2013; MacNeil et al., 2010), "adaptation" is used to refer to strategies that increase the ecological resilience of the biological system while others use climate adaptation to refer to actions that enhance ecosystem services provisions under climate change (Arkema et al., 2013). Since this definition of adaptation refers to the reduction of vulnerability to the impacts of climate change, such measures may fall in three of our categories: protect, repair, and adapt depending on the definition of the systems under study. For example, mangrove restoration contributes to carbon sequestration (mitigate), resilience of coral reefs ecosystems (protect), and coastal population adaptation (adapt) (Duarte et al., 2013). Gattuso et al. (2015) use the term "adapt" to refer to adaptation of the society to the loss of ecosystems and ecosystem services, thus distinguishing between actions focusing on the ecology and actions focusing on human populations. Measures to improve the resilience of the ecosystem, as opposed to the resilience of the human society, are presented in the protect section. However, there are measures that use ecosystems to help human societies adapt to the adverse effects of climate change (i.e. ecosystem-based adaptation), and these are presented as adaptation strategies but rely on other strategies such as restoration.

Management actions tend to reflect approaches that differ along two important dimensions: 1) maintain/change – where actions fall along a gradient from those that seek to maintain the ecological and environmental status quo (or some previous state) to those that deal with future change, and 2) nature/society – where some actions attempt to directly influence natural conditions and others focus on influencing human aspects (Fig. 3). These two dimensions are important to understand which disciplines focus on which approaches. They may also reflect the preferences of managers and institutions that promote climate action and management. The protect and mitigate management strategies can be thought as

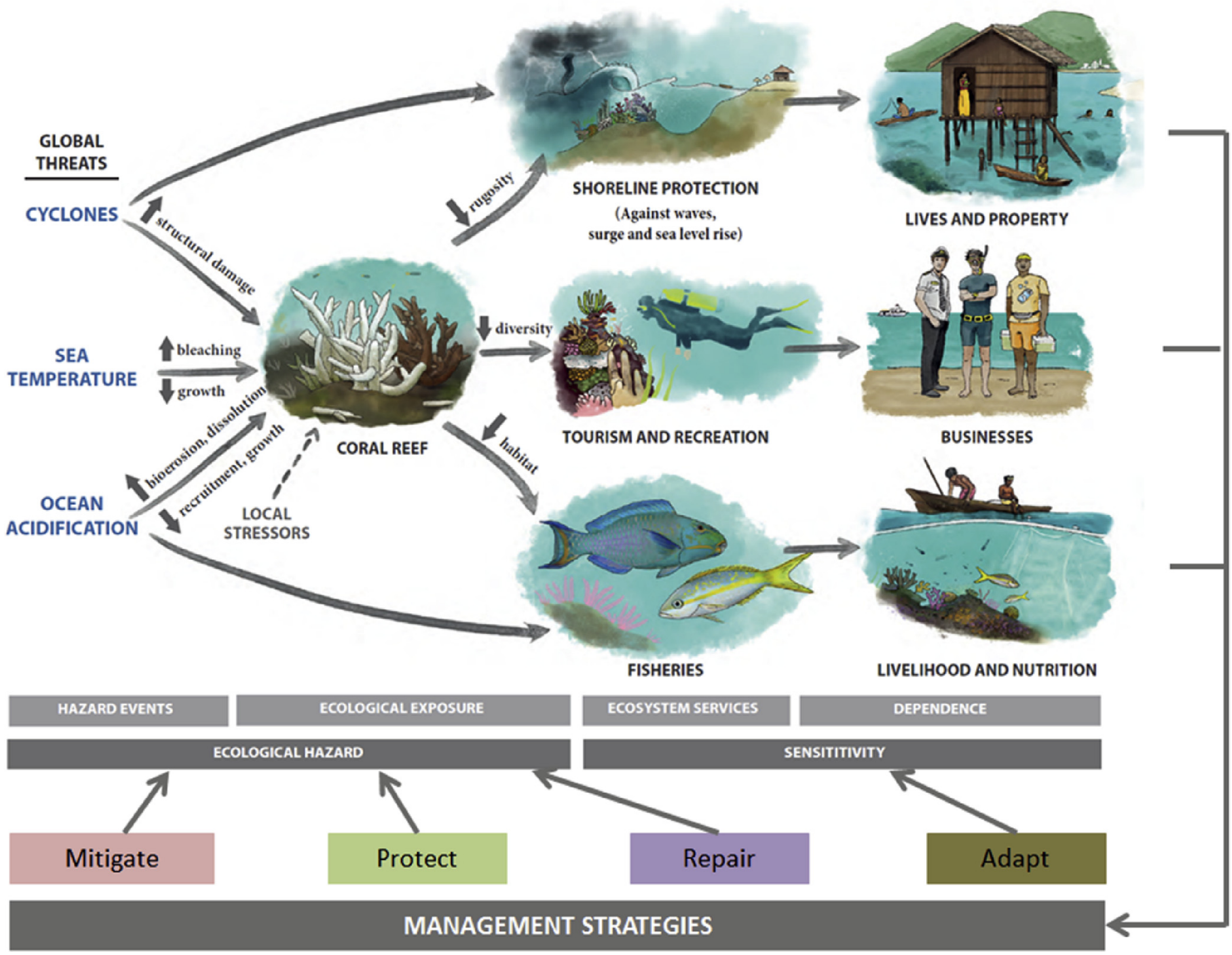

Fig. 2. Influence of the four categories of management strategies on the chain of impacts of climate change and ocean acidification on coral reefs and people dependent on the services provided by coral reefs; modified from Pendleton et al. (2016a).

conventional strategies since they involve a reduction in human activities (e.g. pollution, emission of CO_2, fishing) that has been promoted for many decades. Repair and adapt management strategies are the focus of recent innovation since they often require the change or the initiation of new activities (e.g. restoring coral reefs, changing economic activities) that has emerged more recently in the literature (Füssel and Klein, 2006). The mitigate and adapt categories of management strategies parallel the ones developed by the IPCC and used in the United Nations Framework Convention on Climate Change (UNFCCC) and apply mostly to societal responses and actions (Schipper, 2006). The protect and repair categories of management strategies mostly apply to natural systems. Together, these two dimensions serve to ground management strategies in a socio-ecological system framework.

3. Material and methods

We systematically searched the Web of Science and Scopus databases for articles, published from 1990 to 2016, that addressed coral reefs, climate change or ocean acidification, and that were action-oriented (see SM1 for equations to retrieve these articles). After deleting duplicates, 1177 references were found. A first screening on title of publication, title of journal, abstract, and key words removed articles that did not apply to coral reefs and associated ecosystems (e.g. general papers on CO_2, on cold water corals). Only peer reviewed articles were selected, acknowledging that important contributions may come from books, book chapters and the grey literature. 885 papers remained. After selecting for remaining references that had a component relevant for management or explicitly stated management implications based on title of publication and abstract, 767 publications remained.

Key words were used to assign categories of management strategies (mitigate, protect, repair, adapt, indirect) to the research articles. The Intellixir© software used for the treatment of the literature produced its own list of around 20,000 candidate concepts. A list of action-oriented concepts for each category was created based on this list. Several candidate concepts that describe actions were not explicit enough to fit a category of the typology (e.g. "Facilitate coral persistence") and were discarded. Strategies are not always single-objective and could apply to more than one category in the typology. For example, "ecosystem management" or "ecosystem recovery" are terms that include a very broad category of actions. Other concepts indicating properties of a system such as "adaptation" and "resilience" could be applied to different parts of the systems, therefore limiting our ability to categorize research articles.

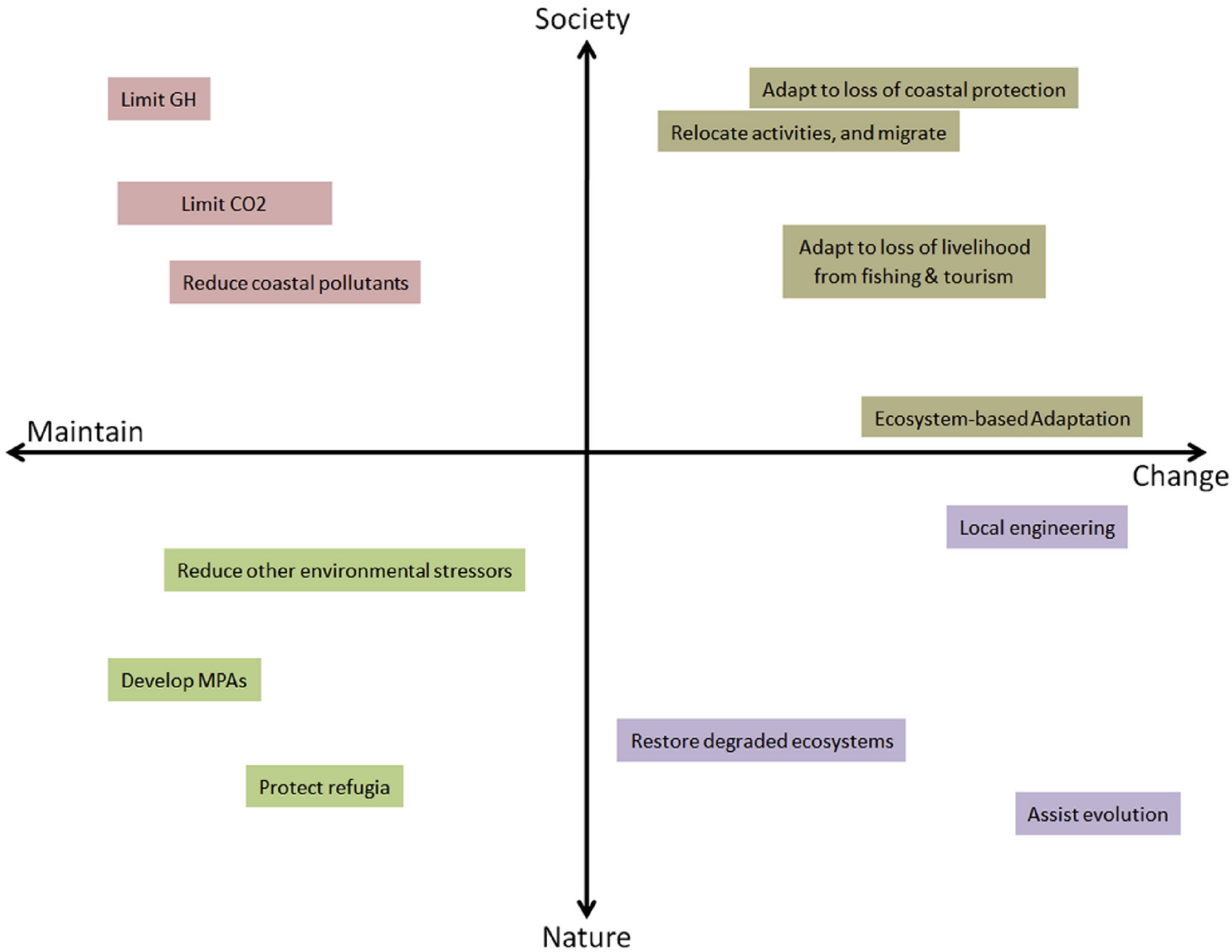

Fig. 3. The sub-categories belonging to the four categories of management strategies (mitigate in red, protect in green, repair in purple, and adapt in brown) fall along two axes: maintain/change and nature/society. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The final list of action-oriented concepts contains 228 concepts for the mitigate category, 138 for the repair category, 210 for adapt, 414 for protect, and 267 for the indirect category. These concepts were applied to the title, abstract, and key words of articles to categorize them. It was possible to assign one or more categories of management strategies to 690 out of 767 papers, or 90% of them. The remaining research articles either were too vague, broadly mentioned having implications for management without detailing how in their abstract, or in a few cases abstract was not accessible.

All contributing authors to the articles reviewed here were assigned to a country based on their affiliations. One caveat is that countries with overseas territories (France, UK, USA, and the Netherlands) sometimes have affiliations in both overseas territories and the mainland (note that these countries already produce the largest number of articles). Titles and abstracts of the 767 articles were screened to determine if they referred to case studies and the country or countries where these case studies were located. To understand whether social, demographic, economic, or ecological characteristics played a role in the location of studies, we collected data on attributes of countries including Gross Domestic Product (GDP) per capita (average between 2006 and 2013 in current US$, source: The World Bank, 2017), coral extent (source: UNEP-WCMC, WorldFish Centre, WRI, 2010), and ecosystem services (source: Pendleton et al., 2016a). A Principal Component Analysis (PCA) with hierarchical classification was conducted using the software “R” (with the packages Rcmdr and FactoMineR) to determine how the variability of countries was distributed across these variables and to understand how countries clustered around these variables.

4. Results

4.1. Distribution of the scientific efforts

There are 767 peer reviewed research articles included in this analysis. Seventy-seven research articles contain no explicit management action in their title, key words or abstract but state that their work is relevant for management. Actions that can be associated with at least one of the four management categories (mitigate, protect, repair, and adapt) are found in 599 research articles. Indirect actions are found in 362 research articles. For the articles that identify action in the four categories of direct management strategies, 61% discuss only a single category, while 39% discuss actions in two, three, or the four categories of management strategies (31%, 7%, and 1% respectively; Fig. 4). This suggests that a majority of research articles target a specific management strategy or a specific part in the chain of impacts, and therefore very few have a holistic scope. Nonetheless, this also shows that there are

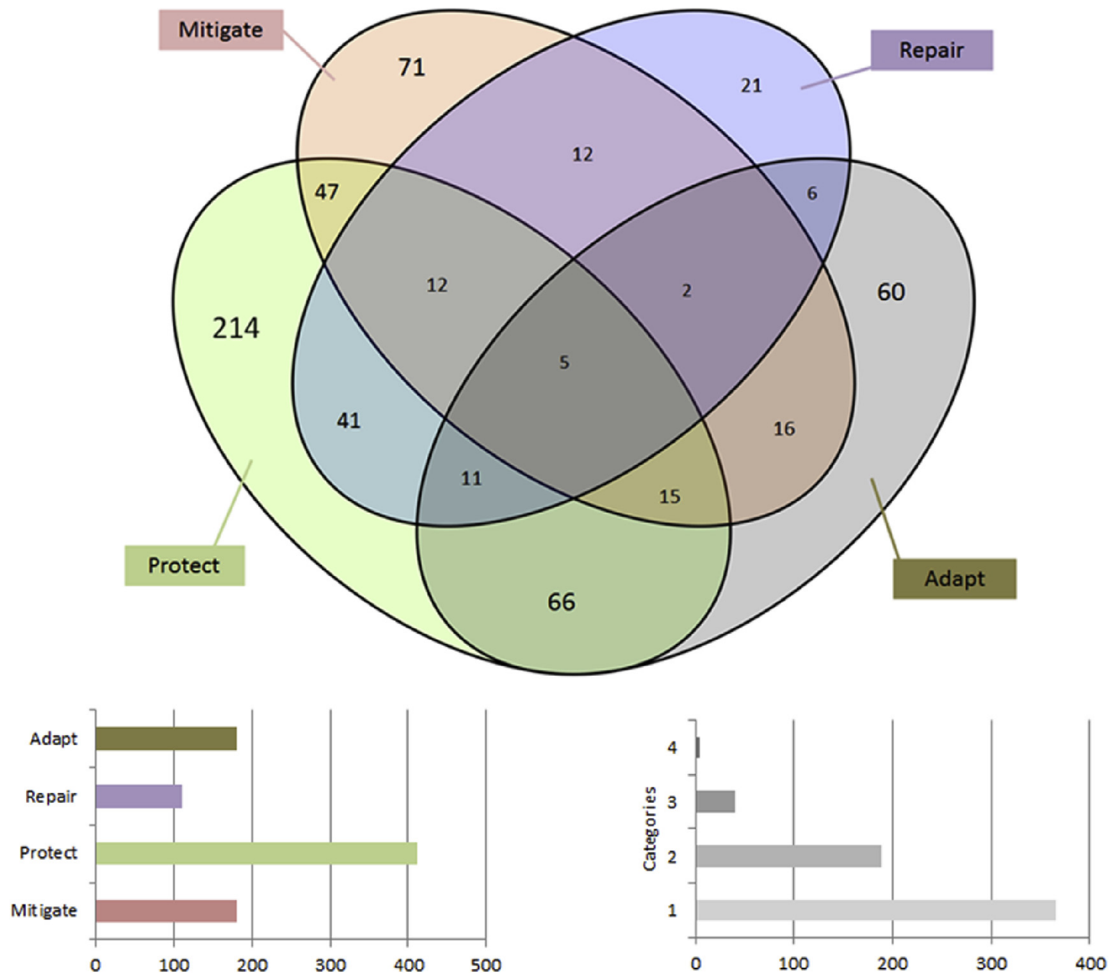

Fig. 4. Euler diagram of the number of actions identified in each category of management strategies, and the ones that overlap one or more categories. The same information is then broken up by category of management strategy and by number of categories address in research articles.

interactions between categories of management strategies that could be of two kinds: (i) actions that address two types of categories or (ii) research discussing a range of different solutions.

Several actions could be assigned to more than one category depending on their objectives. Typically, restoration of degraded ecosystems linked to coral reefs, including mangroves, wetlands, and seagrass, could fall in the repair, protect, or adapt category depending on their purpose and timing. Some of these measures actually serve more than one purpose. Mangrove restoration is beneficial in terms of carbon sequestration and therefore mitigates CO_2 emissions, at the same time it improves the resilience of coral reefs as an important habitat for young reef fish and through buffering pH locally, and serves as a natural substitute for lost coral ecosystems services (including as a cite for fisheries and a natural barrier for coastal protection of human population). Similarly, fisheries management can improve reef resilience and provide food security to people. MPAs could implement fisheries management, disease control, and marine and coastal pollution management (Keller et al., 2009), thus fitting in the protect and the mitigate categories.

Mitigate strategies are identified in 180 articles, protect in 411 articles, repair in 110 articles, and adapt in 181 articles (Fig. 4). The protect category, and especially MPAs is the most cited strategy in the research articles reviewed here. Many articles exclusively discuss this strategy with respect to climate change, particularly the design of MPAs, their effectiveness, or their implementation. This is coherent with the historic way of thinking and tools used for biodiversity conservation (Lubchenco et al., 2003; Roberts et al., 2002).

4.2. Changing scientific effort over time

There is a growing literature on the management of coral reefs and human populations to combat GEC (Fig. 5A). The engagement of the scientific community with this topic started later for coral reefs than for climate change in general, after the first global bleaching event of 1998. The number of peer-reviewed articles on the subject has steadily increased over the years especially after the second global bleaching event that occurred in 2005. The acceleration in publication rate started ten years ago and the number of articles tripled between 2009 and 2016, from 45 in 2009 to 156 articles in 2016. This rapid increase in publications over the years directly parallels the increase in scientific production in peer reviewed journals for the whole field of climate change (Fig. 5B). The increasing number of publications can be explained by the same factors that influence climate change and ocean acidification research in general, including global recognition of this topic, international collaborations (Riebesell and Gattuso, 2015) and the global review of ecosystems and ecosystem services (Millenium Ecosystem Assessment, 2005). Indeed, the focus on management

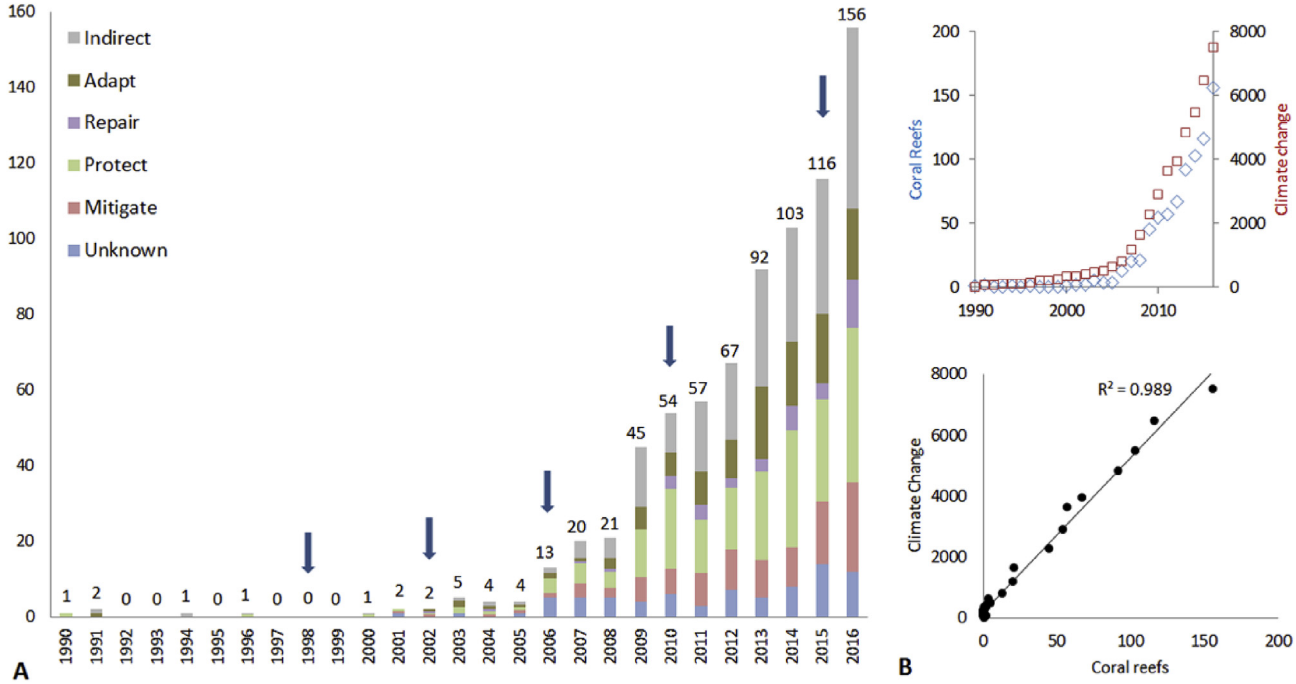

Fig. 5. Temporal analysis of action-oriented scientific effort on coral reefs and GEC, compared with climate change as a whole. (A) Number of research articles found per year, from 1990 to 2016, broken down by categories. Arrows represent global bleaching events in 1998, 2010, and 2015–16. Large scale bleaching also happened in Australia in 2002 and 2006, and in the Caribbean in 2006; (B) Comparison of coral reefs publications over the years with publications for the whole field of climate change research (see SM1 for methodology).

of coral reefs under threat started with the creation of the International Coral Reef Initiative (ICRI) and the Global Coral Reef Monitoring Network (GCRMN) in 1994.

Over the past ten years, the relative effort on the four direct action categories has remained fairly constant in the literature (Fig. 6A). About 20% of the actions identified are mitigate actions, about 50% are protect actions, about 10% are repair actions and 20% are adapt actions. The relative proportion of the repair category has increased just recently. The rates of change in publications over time, however, are different across the four categories of management strategies (Fig. 6B). Protect has the highest rate of increase in publications over the years, followed by mitigate, adapt, and repair. The relative stability of these proportions over time could reflect a dominant thinking in the research community towards the use of protect measures, with a minority of researchers considering solutions for social and economic consequences of a loss of coral reefs (and therefore human populations and ecosystem services).

4.3. Scientific effort varies around the world

The scientific literature is authored by researchers from 89 countries or territories. The vast majority of scientific articles reviewed here are co-authored by researchers who are affiliated with institutions in Australia (388) and/or in the United States

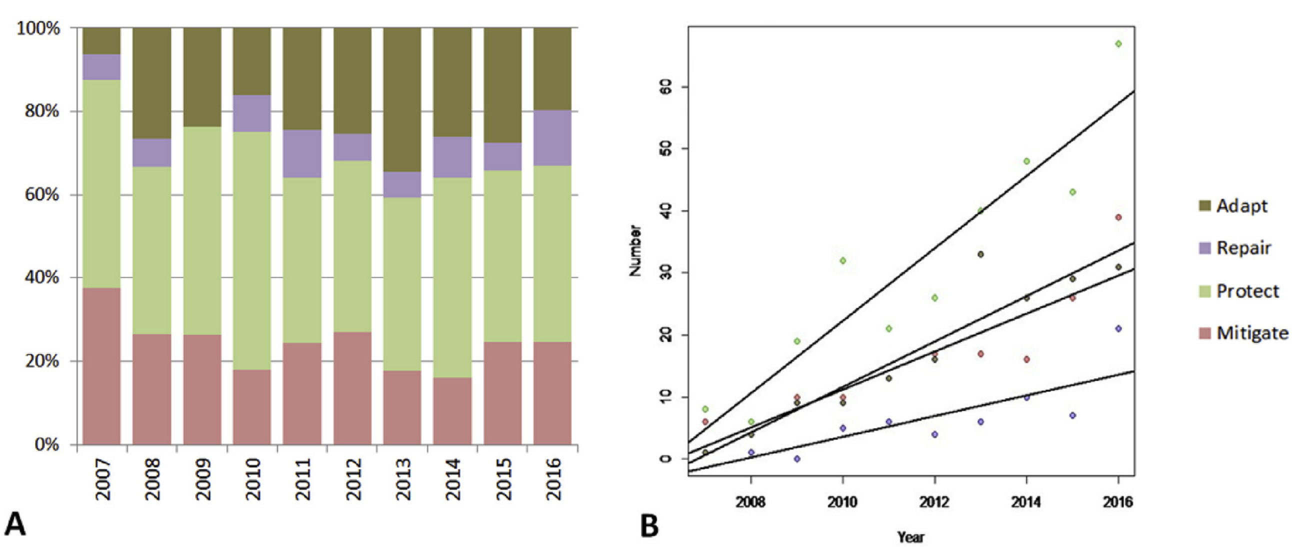

Fig. 6. Temporal evolution of the four management strategies over the last decade (2007–2016), (A) in proportional terms and (B) in absolute terms (with ANCOVA, $r^2 = 0.8849$).

(335). Authors' affiliated with institutions in other developed countries, including Canada and European countries also represent a large share of the publications. This pattern holds on aggregate and for all four types of management strategies (Fig. S1), suggesting that the origin of authors does not influence the type of management strategy studied. Forty-four countries or territories containing coral reefs do not have any authors publishing management-focused studies on coral reefs and GEC, including in the Caribbean and the Indo-Pacific region.

Half of the studies (50.5% or 387 out of 767) include case studies, which are located in 84 countries or territories. In addition to these 387 case studies that range from focusing on a single reef to a handful of countries like the Coral Triangle, 19 research articles focus on regional scale management (10 in the Caribbean, others in the Indo-Pacific or Pacific Islands) and are not counted as case studies. The highest number of case studies are located in Australia (132 case studies) and particularly in the Great Barrier Reef (Fig. S2). Other case studies are mainly located in the United States, the Coral Triangle, the Caribbean, and the Western Indian Ocean. The case studies examined focus primarily on protect strategies, and focus the least on repair strategies (the highest number of case studies focusing on repair strategies in a single country is 14 in the United States). This proportional distribution of case studies focusing on the four categories of management strategies is the same for each region of the world. The same pattern holds looking at affiliations or case studies (Figs. S1, S2).

Three main factors could explain the spatial distribution of authors and case studies across the globe: the locations of corals, the wealth of countries that are able to sustain research institutions and the services that reefs critically provide to populations. Authors tend to be located in institutions in high income countries and not necessarily in the countries with the highest coral extent. Developed countries play a major role in conducting research on coral reef management in developing countries in which the resources to conduct research are limited. Indeed, 42% of case studies are authored by researchers affiliated in a different country or territory than where the study is located. Twenty-nine percent of case studies are authored exclusively by researchers in the country where it is located, 27% include both authors affiliated in the country of the case study and foreigners, and 2% of the studies were conducted in overseas territories by authors affiliated in the mainland. For instance, 80% of the case studies co-authored by researchers affiliated in the United States are located outside of the United States. This pattern is influenced by at least two factors: (1)

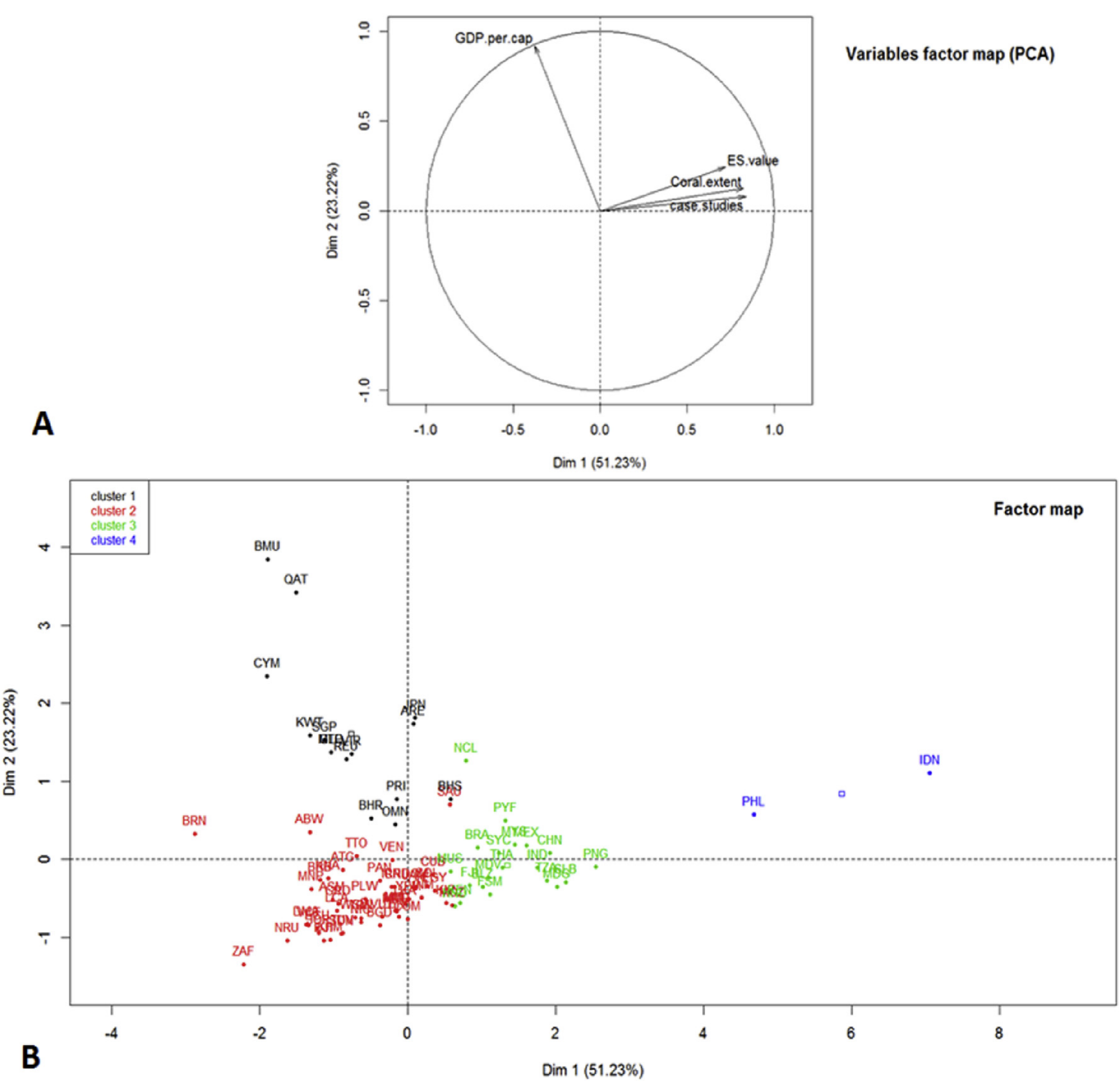

Fig. 7. PCA analysis with hierarchical clustering on countries containing case studies, excluding Australia and the United States. (A) Variable factor map with GDP per capita, ES values, coral extent, and number of case studies and (B) factor map along the two first dimensions.

coral reefs are located in the tropics, where most developing countries are also located, and (2) several developed countries, including the United States, the United Kingdom, and France possess overseas territories where coral reefs are located.

To gain a deeper insight into the factors influencing why and where case studies are conducted, a PCA was applied to the same factors that could influence their locations. Two outliers, Australia and the United States, both outliers characterized by very high amounts of case studies, were excluded from this analysis. Two dimensions of the PCA account for 74.45% of the variability in the data (Fig. 7). The variables factor map (Fig. 7A) shows that coral extent is a primary explainer of where case studies are located. The value of ecosystem services co-varies with coral extent and case studies but does not seem to be a primary determinant of where coral reef management studies are conducted. GDP per capita is orthogonal to these two variables, suggesting that all things being equal, GDP per capita does not play a role determining where case studies are located. The choice of case studies is therefore primarily driven by where vast areas of corals are found.

A hierarchical clustering shows that countries fall into four distinct groups of countries when trying to understand the role of GDP, coral cover, and case studies (Fig. 7B). The first cluster represents countries with very high GDP per capita like the Gulf countries, Bermuda, or Singapore. These countries could have the means to study coral reefs extensively but do not do so. The extent of coral reefs and ecosystem services is low in these countries. However, these countries may find it beneficial to invest in research on coral reef management since these are places that may be home to corals that are acclimated to future conditions (Fine et al., 2013). The second cluster contains small developing countries and island states such as Nauru, Aruba, Brunei Darussalam that are characterized by small coral extent, few case studies, and low GDP per capita. This cluster also includes middle-sized developing countries that have little or no case studies such as Cuba, Vietnam, or Panama. While these countries have less coral extent than other countries, local communities are likely to be highly dependent upon coral resources. As a result, investment in more research on coral reef management may have significant returns on investment. Lower middle income countries (as defined by the World Bank) found in this group are under-studied compared to their relative importance in terms of coral extent. The third cluster contains large countries such as Brazil, China and India, and countries with high coral extent with high levels of ecosystem services including Thailand and French Polynesia for example that contain more than average case studies. Finally, the fourth cluster regroups the Philippines and Indonesia that contain vast areas of coral reefs and high levels of ecosystem services, combined with numerous case studies. The number of case studies in these countries shows that regional and international research programs in the Coral Triangle should be encouraged. Twenty-six countries or territories containing coral

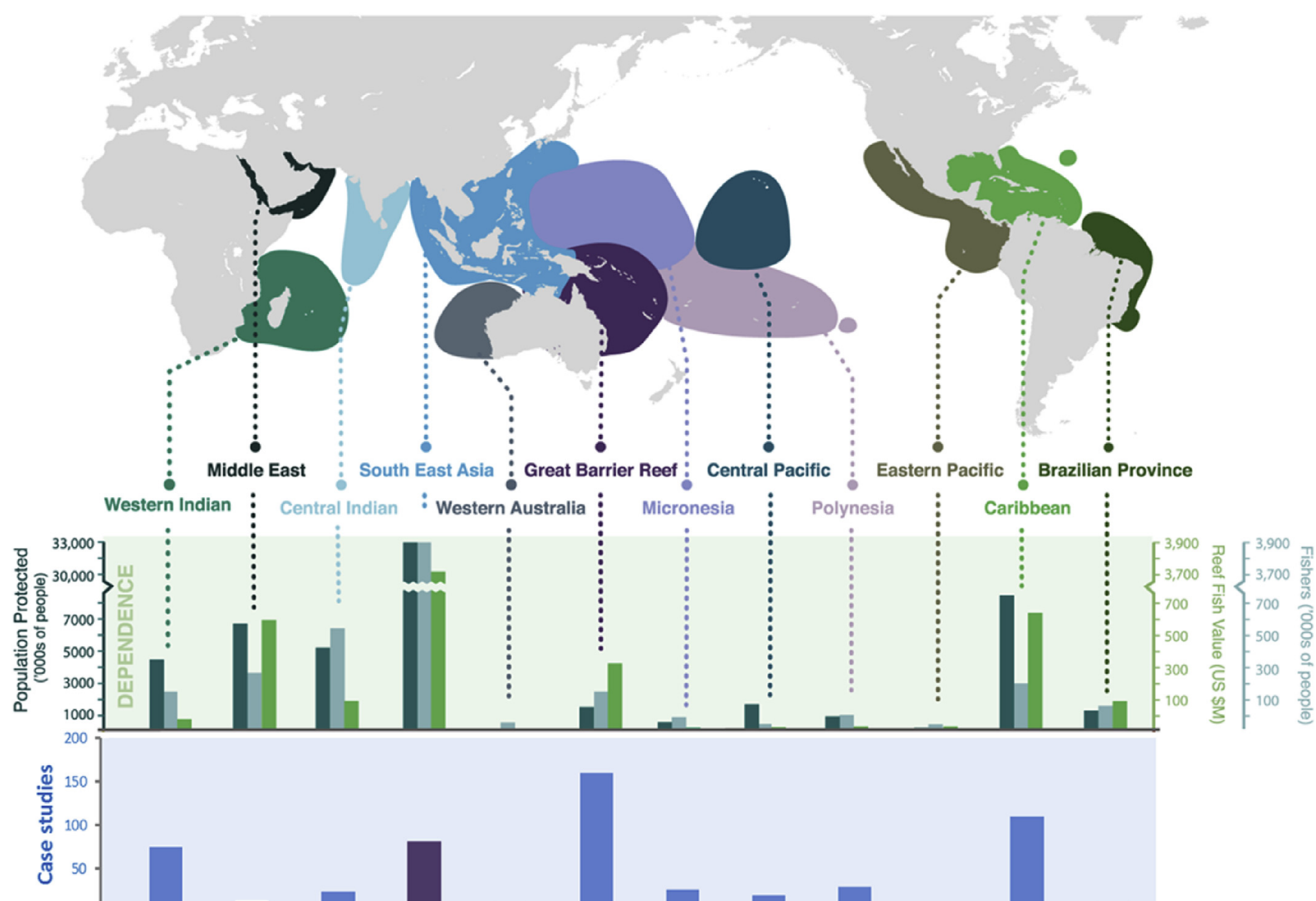

Fig. 8. Regional dependence, by ocean province (OP), on ecosystem services and number of case studies per ocean province, modified from (Pendleton et al., 2016a). For case studies, purple OPs contain proportionally less case studies than their share of ecosystem services. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reefs do not have case studies located in them. This is a serious gap, especially for Cuba and Eritrea which both contain large areas of coral reefs.

The distribution of future global environmental change is not homogeneous and science needs to study the effectiveness of management actions in those places where coral reefs and people may be most at risk from GEC. Current modelling suggests that SST warming will impact the Pacific and South-East Asia first, whereas OA will be more important towards the pole (Pendleton et al., 2016a). In addition, the distribution of the demand for ecosystem services is also heterogeneous, and South-East Asia is the most dependent on reefs for ecosystem services, followed by the Middle East, the Caribbean and the Indian Ocean (Fig. 8). Comparing the average proportions of ecosystem services across ocean provinces with the proportion of case studies, there is a deficit of case studies in the Middle East, the South-East Asia, and the Brazilian ocean provinces.

5. Discussion

5.1. The literature focuses disproportionately on maintaining the ecological status quo

The literature has focused disproportionately on efforts to hold the ecological line for coral reefs with more than 60% of studies focused on mitigate or protect, and less on helping people and coral ecosystems in a future in which the natural world will look quite different. Considerable scientific effort has gone into designing and effectiveness of MPAs, identification of sites and refugia, and managing fishing pressure and other environmental stressors. On the other hand, very little work has focused on repair measures that are more active management strategies aimed at rebuilding coral extent and ecosystem services after disturbances. Future research efforts need to focus on the effectiveness of repair strategies. Assisting the evolution of coral reefs to sustain them in a changing climate is in its early stage of development. In addition to the prohibitive cost of these techniques (Bayraktarov et al., 2016), ethical issues persists. Still, some argue that assisting evolution can be included in coral reefs restoration (van Oppen et al., 2017).

Despite the growing focus on adaptation in the climate change literature (Füssel and Klein, 2006), this new trend is not reflected in the coral reef literature with less than 25% of the studies focusing on adapt strategies. One reason for a lack of focus on human adaptation may be the ecological focus of the literature regarding coral reef management. There are two particularly striking gaps in the study of management strategies that relate to human populations dependent on reefs. First, migration of human population is mentioned as a sub-category of action but is not discussed in the 767 articles we reviewed. This is surprising given that this topic is well-covered in the general climate change adaptation literature (McLeman and Smit, 2006) and given that some coral reefs are located in low-lying islands particularly exposed to sea-level rise. Second, the issue of using indigenous knowledge for management under climate change was also barely touched on despite its important role for management (Veland et al., 2013). There are two possible explanations for the lack of coverage in the literature on these management strategies. It is possible that these are research frontiers that will be explored in the future. Alternatively, even though we reviewed 767 papers to identify management actions, we may have missed important contributions.

While numerous studies (e.g. Gattuso et al. (2015)) argue for a reduction of GHG emissions since the effectiveness of all other management strategies will depend on our success at stabilizing the climate around 1.5 °C or 2 °C of warming, the most optimistic emission pathway scenario will already lead to high impacts for coral reefs (Frieler et al., 2012). Reducing GHG emissions is now a matter of politics and not of science since the 1.5 °C target is written in the article 2 (a) of the Paris Agreement (UNFCCC, 2015), and given that dealing with local anthropogenic threats is already well studied (Ateweberhan et al., 2013; Kroon et al., 2014; Magris et al., 2015). It is therefore crucial to move away from maintaining the status quo (Hughes et al., 2017) and to scientifically explore a full suite of solutions, including repair strategies, adaptation to the loss of ecosystem services and to explore combinations of these solutions.

5.2. The literature is not addressing many places where coral reefs and people are threatened

Current scientific efforts do not target the full range of countries where coral reefs are located, including many places where corals and people are at risk of GEC. Most of the case studies examined are conducted in developed countries, and particularly Australia and the United States, which parallels their disproportional share of scientific contribution on biodiversity conservation in Oceania (Kingsford et al., 2009) and in general (Di Marco et al., 2017; Falkenberg and Tubb, 2017). It is important to note that there could be a bias in our analysis towards English speaking countries because only international peer reviewed journals in English are included in this review (Falkenberg and Tubb, 2017). There are few studies on coral reef management effectiveness for areas like South-East Asia, which has the highest dependence on coral reefs and also contains the highest coral diversity (Veron et al., 2015). South-East Asia, Brazil and the Middle East are all areas for which more scientific effort is needed to understand the human and ecological dimensions of coral reef management in the face of GEC.

The literature also reveals a tremendous patchiness in the distribution of human capacity to study the effectiveness and consequences of coral reef management actions to deal with GEC. Forty-two coral reef countries and territories were completely unrepresented in the affiliations of authors in these peer reviewed studies. The implications of such concentrations of authors at institutions in high income countries, studying coral reefs in other countries, are not clear. This aspect of research needs serious consideration given the disproportionate vulnerability of developing countries to the effects of GEC on coral reefs (Burke et al., 2011; Wolff et al., 2015) and given the fact that 26 developing countries and territories containing coral reefs also do not have case studies.

6. Conclusions

We refined a typology of management strategies in order to review the comprehensiveness of scientific investigation into the effectiveness and consequences of coral reef management in the face of GEC. The typology also reveals that management strategies differ along two key dimensions: 1) whether they seek to maintain an environmental status quo or accept environmental change and 2) whether they focus on ecological and environmental aspects or human aspects of coral reef social-ecological systems. Few studies examine a broad suite of ecological and human oriented approaches. The typology discussed in this article could also be applied to other SES, both marine and terrestrial. Typologies like the one refined and presented here can assist in conveying scientific knowledge to decision-makers (e.g. IPBES or IPCC) and building a dialogue between scientists, managers, and decision-makers around the issues of global environmental change in general (Moser, 2010) and of coral reefs in particular (Crosby et al., 2002). It is the role of managers and decision-makers to appropriate this knowledge and produce decisions and management plans that will shape the future of coral reefs and people who depend on them. We hope to have clarified the range of potential management strategies to respond to these threats so that this work can be used as a first step in the identification and appraisal of actions, for instance in adaptive management frameworks (Birgé et al., 2016).

If managers are to be able to weigh the tradeoffs of the full suite of management options, scientific efforts need to be broadened across management options and also across coral reef geographies. The existence of barriers and limits to the effectiveness of existing management strategies needs to be recognized (Barnett et al., 2015; Feagin et al., 2010). Yet, we find that the scientific literature has not focused enough on “adapt” and “repair” management strategies that deal with the inevitable impacts of GEC. It is clear that current research is biased towards developed countries (especially Australia and the United States) and towards “protect” management strategies. A re-organization of scientific research on the subject is needed. Under-studied geographic locations including developing countries in South-East Asia, in the Western Indian Ocean, in the Middle East, in the Pacific, and in the Caribbean should be the focus of future research. New research is also needed on adaptation of people who depend on coral reefs. Future research should attempt to study multiple strategies at the same time to understand trade-offs and synergies between management strategies. This reorganization is possible without undermining scientific efforts on traditional topics of protecting biodiversity thanks to the increase in the number of papers and scientists working on this field.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.051.

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