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People and the changing nature of coral reefs

Hoegh-Guldberg Ove [1, *], Pendleton Linwood [1, 2, 3, 4], Kaup Anne [4]

[1] Global Change Institute, University of Queensland, Brisbane, QLD 4072, Australia
[2] Global Science, World Wildlife Fund, Washington, DC, USA
[3] Ifremer, CNRS, UMR 6308, AMURE, IUEM, University of Western Brittany, Plouzané, France
[4] Duke University, Durham, NC, USA

* Corresponding author : Ove Hoegh-Guldberg, email address : oveh@uq.edu.au

Abstract :

Coral reefs are biodiverse and productive ecosystems but are threatened by local and global stresses. The resulting loss of coral reefs is threatening coastal food and livelihoods. Climate projections suggest that coral reefs will continue to undergo major changes even if the goals of the Paris Agreement (Dec 2015) are successfully implemented. Ecological changes include modified food webs, shifts in community structure, reduced habitat complexity, decreased fecundity and recruitment, changes to fisheries productivity/opportunity, and a shift in the carbonate budget of some ecosystems toward dissolution and erosion of calcium carbonate stocks. Broad estimates of the long-term (present value) of services provided by the ocean's ecological assets exist and are useful in highlighting the value of reefs yet must be contextualised by how people respond under ecosystem change. The dynamic nature of the relationship between people, economies, and the environment complicates estimation of human consequences and economic outcomes of changing environmental and ecological capital. Challenges have increased given lack of baseline data and our inability to predict (with any precision) how people respond to changing coral reef conditions, especially given the variability, flexibility, and creativity shown by human communities and economies under change. Here, we explore how the changes to the three-dimensional structure of coral reefs affect benefits for people, specifically coastal protection, fisheries habitat, and tourism. Based on a review of available data and literature, we make a series of key recommendations that are required to better understanding of how global change will affect people dependent on coral reefs. These include: (1) baseline studies and frameworks for understanding human responses to climate change within complex social and ecological setting such as coral reefs, (2) better tools for exploring environmental benefits, markets, and financial systems faced by change, and (3) the integration of these insights into more effective policy making.

Highlights

► Large numbers of people in tropical regions are highly dependent on the goods and services produced by coral reef ecosystems. ► Coral reef ecosystems are under severe threat from both local and global threats, which are degrading the ecosystem services that they provide to humanity. ► Past studies have assumed that the loss of ecosystem services will lead to a proportionate impact on people. ► We argue that this is unlikely to be the case in the short-term due to the high level of adaptability illustrated by communities associated with coral reefs. Eventually, however, stress will reach levels that exhaust the capacity of people and communities to adapt. ► Data sets and analysis are sparse, however, we call for a greater focus on understanding the flexibility and adaptability of people associated with coral reefs, especially in a time of rapid global change.

Keywords : Coral reefs, Global climate change, ‘the dumb farmer’, Adaptability, Human interactions

1.0 Introduction:

Warm-water coral reefs are an important component of the Earth's biosphere, dominating coastal habitats in tropical and subtropical areas (Knowlton et al., 2010). Many human coastal communities, comprised of at least 500 million people worldwide, have developed a high degree of dependency on ecosystem goods and services provided by coral reefs (Burke et al., 2011, 2002; Speers et al., 2016a, Wilkinson, 2008). These communities look to coral reefs for their daily food, income and other needs. Unfortunately, unsustainable environmental stress and escalating demands on coral reefs and nearby watersheds and ecosystems have resulted in the loss of about 50% of coral reefs since the early 1980s (Bruno and Selig, 2007; De'ath et al., 2012; Gardner et al., 2005). The principal drivers of these changes have been increasing levels of pollution, unsustainable coastal development, overfishing, and outbreaks of coral predators like the Crown of Thorns Starfish (*Acanthaster planci*) (Albright et al., 2016; Fabricius et al., 2010, 2008). And, if these pressures were not enough, human-driven climate change is having devastating impacts on coral reefs through anthropogenic ocean acidification and warming (Hoegh-Guldberg et al., 2007; IPCC, 2014).

A central theme of this review is the need to understand how these rapid environmental changes are affecting coral reef ecosystem services and, consequently, human communities. To do this, we have reviewed the literature on ocean warming and acidification and have reflected on the vulnerability of associated human communities reliant on benefits associated with coral reefs. Notably, we focus on the combined impacts of ocean warming and acidification, given the difficulty of separating these two drivers of environmental change on coral reefs. Our review attempts to provide some preliminary estimates of how reduced levels of coastal protection, fisheries productivity and tourism are likely to affect the millions of people who are dependent on these coral reef benefits.

While recent estimates of the minimum economic dependence upon coral reefs certainly provide powerful support to the inescapable conclusion that coral reefs make a very substantial economic contribution to coastal societies (Cesar et al., 2003, 2002; Cesar and Chong, 2004), these studies falter when it comes to outlining the rich set of relationships between biology, economics and human behaviour (Cinner et al., 2012; L. Pendleton et al., 2016a, 2016b). The ability to understand how human communities along coastlines will respond to the loss of coral reefs is complex and requires datasets that are incomplete or are not currently available (L. Pendleton et al., 2016b). In this regard, we call for a greater effort to understand both the flexibility, inertia, and options for coastal societies facing the massive ecological disruption that has begun and will continue as the next few decades unfold. Our study uncovers an urgent need to develop a better fundamental understanding of the relationship between humans and living ecosystem resources such as coral reefs.

This review attempts to address three key issues. First, how will the health of coral reefs change under rapid ocean warming and acidification? Second, how will these changes influence the benefits that humans derive from the ecosystem services provided by coral reefs? In this regard, there is a big difference between estimating the current human dependence and economic value of existing stocks, and that of trying to determine how dependence or value might change as a result of varying conditions on coral reef ecosystems. Third, what do we need to know in order to understand the likely impacts of these changes on the wellbeing of coastal human populations, as well as their options for adaptation or migration as a response to coral reef ecosystem damage? To what degree will the loss of healthy ecosystems such as coral reefs directly translate as a downturn in economic activity and value, and at what scale? Furthermore, how can an economic understanding of the impacts of coral loss help us better manage corals and other ecosystems, especially when much of this loss in ecosystem services may be inevitable?

2.0 Coral reefs and their ecosystem services

The relationships between coral reefs and humans are intricate and interwoven and have been in existence for thousands of years at least. Approximately 850 million people live within 100 kilometres of reefs and more than 275 million reside within 30 kilometres, many of whom are likely to be highly dependent on coral reefs, especially those who look to these marine ecosystems for food and livelihoods (Burke et al., 2011). These 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). They also support fisheries that, in turn, 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; Deliotte, 2013; O. Hoegh-Guldberg et al., 2014). Coral reef ecosystems and the benefits they generate, however, face a series of growing challenges arising from pressures that result from the direct use of coral resources, the human-caused degradation of associated ecosystems and nearby watersheds (e.g. nutrient pollution, sedimentation run-off and physical damage), and large scale global environmental pressures including climate change, ocean acidification, and de-oxygenation. Given the huge and likely growing dependence of people on coral reef ecosystems, and the accumulating local environmental pressures on these systems, considerable concern has arisen over the on-going sustainability of coral reef ecosystems and the human benefits, or "ecosystem goods and services," they produce (Millenium Ecosystem Assessment, 2005).

Coral reefs, despite their small size (<0.1% of the ocean surface) also provide habitat for at least 25% of all marine species, with estimates of over one million species living in and around coral reefs (Census of Marine Life, n.d.; Reaka-Kudla and Wilson, 1997). Coral reefs are ecosystems whose structures are a consequence of the abundance and calcifying activities of simple metazoan animals called corals and other organisms such as algae, other invertebrates and protists (Hoegh-Guldberg et al., 2017). Cold water corals occupy habitats that are cold, dark and maybe thousands of metres below the surface (Figure 1B). Warm-water corals, which are the focus of this review, occupy habitats that are close the surface (0-100 m) where they secrete calcium carbonate skeletons that accumulate over time, creating a complex 3-D reef matrix that provides habitat for hundreds of thousands of marine species. People living along tropical and subtropical coastlines rely particularly on many of these species for food security and as a means of gaining livelihoods (Burke et al., 2011).

The maximum depth of these shallow water corals is determined by the availability of enough light to power the photosynthesis of the single-celled dinoflagellates (*Symbiodinium*) that live within the gastrodermis (tissues lining the 'stomach' of corals) (Muscatine, 1990; Muscatine and Porter, 1977). The structure of warm water coral reefs is composed of the skeletal remains of scleractinian corals, which deposit substantial quantities of calcium carbonate over their life cycle, the consequence of the ready availability of energy via the dinoflagellate symbionts (Muscatine, 1990). Over time, these activities lead to the establishment of reef structures, islands and coastal barriers in tropical and sub-tropical waters.

In order to understand the sensitivity of coral reef ecosystems to global change, it is necessary to describe aspects of their biology and ecology. A fundamental component of this is the trapping of photosynthetic energy by the dinoflagellates (Figure 1A), most of which (>90%) is passed to the animal host (Muscatine, 1990). In return, the coral host provides access to inorganic nutrients such as phosphate and ammonium, thereby sharing in a powerful mutualistic symbiosis which functions to recycle and conserve nutrients in the otherwise low nutrient waters of the tropics. These interactions between coral host and symbiont are highly efficient, providing the large amounts of energy to precipitation limestone-like calcium carbonate (crystal form 'aragonite'), despite the low nutrient conditions of the water column that surrounds them (Muscatine and Porter, 1977). Over a single coral's lifetime, hundreds if not thousands of kilograms of calcium carbonate might be deposited, with this calcium carbonate being mostly retained by the benthos and building up over time to form the 3D-structure of the coral reef ecosystem (Kennedy et al., 2013).

[Figure 1 goes here – reef organisms involved in reefs]

Other organisms such as calcareous red and green algae, invertebrates and simple organisms such as foraminiferans, contribute to the reef-building process by infilling the structure with their skeletons and shells, and in the case of encrusting calcifying reef algae, bind the structure together much like a calcareous 'glue'(Glynn and Manzello, 2015a; Kennedy et al., 2013). These activities work together to build impressive biogeochemical structures that dominate many parts of the tropics and subtropics. De-calcification and dissolution of calcium carbonate is the flipside of these reef-building activities (Dove et al., 2013; Perry et al., 2014a). In these processes, large numbers of organisms bore into (e.g. cyanobacteria, sponges, annelid worms, and barnacles) or, grind and break up (e.g. sea urchins and parrotfish, Figure 1C-D) the calcium carbon structures of living and dead corals and related organisms. At the macroscopic scale, storms and wave action, even if part of natural cycles, can also play important roles in disrupting and degrading reef structures (Crabbe et al. 2008; Fabricius et al. 2008; Mumby et al. 2011). The processes that create calcium carbonate and those which remove it from coral reefs contribute to the "carbonate balance" (Glynn and Manzello, 2015b). The carbonate balance of corals may vary depending on their environmental surroundings (Figure 1E versus Figure 1F)(Kennedy et al., 2013). For example, at higher latitudes, coral communities may exist without the calcium carbonate structure typical of coral reefs at lower latitudes (Figure 1F) because light levels and carbonate concentrations naturally decrease at higher latitudes. Equally, reefs located at the tropics and thereby receiving high levels of light, may also lack calcium carbonate structures due to the influence of carbon dioxide rise conditions associated with upwelling systems such as those seen in the eastern Pacific (Manzello, 2010). Consistent with expectations developed below, these reefs have much lower biodiversity levels than what is expected for near-equatorial reef locations (Figure 1E).

Whether the carbonate balance is positive or negative determines whether carbonate coral reefs persist and house the significant biological diversity that underpins human opportunities in terms of food, income and livelihoods, or play a significant role in protecting coastal areas from waves. The benefits associated with carbonate coral reefs, however, go well beyond those of food, income and livelihoods. The carbonate frameworks of coral reefs also fortify coastlines by fostering the development of reef crests and barrier reef systems that protect more sensitive coastal ecosystems from wave action and storms, and have formed islands where many animal species have adapted to habitats (e.g. seabirds, turtles, and whales) and where large communities of humans may live.

[Figure 2 goes here – carbonate balance from Kennedy et al. 2013]

The typical structure of a healthy carbonate coral reef includes a surface community of living corals and other organisms, which sits on top of a dead and consolidated calcium carbon matrix. This consolidated reef matrix can provide additional habitat as well as an important barrier to wave impacts associated with storms and cyclones (Arkema et al., 2013; Barbier, 2015; Crabbe et al., 2008). Understanding the nature of these ecological functions and ecosystem services in greater detail, and how they might change, is central to understanding how global change will affect economic outcomes in a warming and acidifying ocean (Kennedy et al., 2013).

3.0 Human activities and record rates of coral reef degradation.

As well as being a vibrant ecosystem with its many goods and services, coral reefs appear to be very sensitive to human activities (Figure 3), many of which have expanded greatly over the past 50 years (Bruno and Selig, 2007; Côté et al., 2005; De'ath et al., 2012; Gardner et al., 2003). During this time, populations have grown and the *per capita* demand on resources has escalated, with the outcome that there are few if any coral reefs today that have not been significantly modified by human activities with the possible exception of some remote sites (e.g. Cuba). These modifications have, in many cases, resulted in a rapid and transformative decline in the distribution and abundance of coral reefs. A number of studies have tried to measure the nature and rate of this decline, and have found that roughly 50% of reef building corals have disappeared over the past 30 years (Bruno and Selig, 2007; Côté et al., 2005; De'ath et al., 2012; Gardner et al., 2003). This section explores the factors that have resulted in this dramatic decline in the health of the world's coral reefs.

The demand for food, places to live that are protected from storms and storm surge, and a need for activities that support livelihoods has meant that the number of people living along tropical coastlines has increased together with concomitant damages to coastal ecosystems (Burke et al., 2011; Martinez et al., 2007; van Wesenbeeck et al., 2015). Coastal forests have increasingly been cut down to provide resources and to make way for agriculture, as well as the expansion of coastal communities and urban centres. Ecosystems such as mangroves, seagrass and salt marsh have been increasingly degraded leading to changes in water quality (i.e. increased sediments, nutrients, agrichemicals, and other pollutants) and the loss of habitat for many species, including many that are important for food as well as industries such as fisheries and coastal tourism (Beeden et al., 2014; Cesar et al., 2003; Talbot and Wilkinson, 2001; Wilkinson and Salvat, 2012). Fisheries have been overexploited, with the resulting loss of key functional groups such as herbivores (e.g. parrotfish, sea urchins) affecting reefs to a point where coral dominated reefs have transformed to become dominated by macroalgae (seaweeds) (Harborne et al., 2008; Mumby et al., 2007, 2014) but see (Bruno et al., 2014; Lowe et al., 2011). As international trade has expanded, so too has ship traffic with an increased exchange of diseases and invasive species across the tropics and sub-tropics. These changes have also been exacerbated by the introduction of foreign species through aquaculture (Bax et al., 2003; Naylor et al., 2000) and the ornamental aquarium market (Betancur-R. et al., 2011; Grieve et al., 2016; Whitfield et al., 2002).

[Figure 3 goes here: Main actors and relationships in the effect of local and global factors]

Many of the ecological changes in coral reefs can be traced back to human activities that began centuries ago with recent rates of change escalating and leading to unprecedented losses of ecosystem services. Evidence compiled by Jackson et al. (Jackson et al. 2001; Jackson et al. 2014) indicates that coral reefs have been in decline for many centuries, and that current distribution and abundance of coral reefs is a poor shadow of the extent covered by coral ecosystems prior to the rapid expansion of human activities in places like the Caribbean. Nearby coral reefs appear to show a story of decline (Wachenfeld, 1997) as do fisheries landing – evidenced by photographs of what was caught by amateur and commercial fishers in Florida and the wider Caribbean fifty years ago (Jackson et al. 2014). In Australia, sedimentation running off the Australian landscape saw a tenfold increase soon after European farming methods (i.e. cattle, crops) were applied to the river catchments associated with the Great Barrier Reef (McCulloch et al., 2003). The full list of environmental pressures that arise from human activities has been documented by a number of detailed global projects (Burke et al. 2011; Halpern et al. 2008; Jackson et al. 2014; Spalding et al. 2007).

While awareness of the rapid decline of coral reefs has increased, and many projects have been initiated to try and reverse the impacts of local factors on the health of coral reefs throughout the world, the rate of decline has remained the same or has increased (De'ath et al., 2012; Hughes et al., 2017). Exploration of data sets going back to the early 1980s reveals that the percentage cover of reef-building corals may well have decreased by as much as 50% across the Indo-Pacific region (Bruno and Selig, 2007; De'ath et al., 2012) although not in all sites (e.g. Moritz et al. 2018). Similar losses of coral have been reported from the Great Barrier Reef (Bruno and Selig, 2007; De'ath et al., 2012) over the same period with losses intensifying (50% over 2016-2017; Hughes et al. 2017). The loss of coral cover has also been extensive in the Caribbean with decreases in coral cover across the wider Caribbean exceeding 80% over 3 decades although, like elsewhere, not all due to climate change (Côté et al., 2005; Gardner et al., 2003; J B C Jackson et al., 2014). Similarly, emerging reports now document large scale coral loss for the Indian Ocean (Baker et al., 2008) and other locations (e.g. Arabian Gulf, (Riegl, 2003). While there are many encouraging reports documenting that corals and other ecosystem components have been preserved, and in some cases, been rebuilt, the majority of human efforts have not been enough to avoid the general decline of coral communities and reefs (as evidenced by the decline). As if the task wasn't already challenging enough, dramatic changes from global climate change (i.e. ocean warming, acidification and sea level rise) have further accelrated the pace at which the abundance of corals on reefs has declined (Hoegh-Guldberg et al. 2007; Hughes et al. 2018; Hughes, Kerry, and Simpson 2018) and at which ecosystem services for humanity have decreased (Cinner et al., 2011). In the next section, the role of these global factors in changing the circumstances under which coastal communities can operate, is described. By exploring past, present and future drivers of change, it is hoped that the potential advanced warning will enable us to avoid the worst, and manage the unavoidable.

4.0 Climate change, ocean acidification and their impact on coral reefs

The ocean is one of the most important components of the climate system (O. Hoegh-Guldberg et al., 2014). Once thought to be relatively inert to changes in temperature due to the size and thermal mass of the ocean, it is now clear that the surface layers of the ocean are changing rapidly and that the implications are fundamentally important in terms of what they mean for human communities, especially to the 40% (Ferrario et al., 2014) of humans that live in close proximity (100 km) to coastal areas and are dependent on the ecosystem services already discussed. Approximately 93% of the extra heat trapped by the planet already has been absorbed by the upper layers of the ocean and has resulted in increased ocean temperatures (Alexander et al., 2013). As the ocean has warmed it has also expanded, leading to an increase in the average global sea level (~25 cm since Pre-Industrial Period). Climate change has also melted land-locked glaciers, which has contributed to the observed increase in sea level, with projections of as much as a metre of sea level by 2100 and much higher over subsequent centuries (IPCC 2013).

In addition to the increased absorption of heat by the ocean, approximately 30% of the carbon dioxide produced by human activities has dissolved into the upper layers of the ocean, causing ocean acidification (Caldeira and Wickett, 2003). Carbon dioxide reacts with water to produce a weak acid (carbonic acid) which subsequently releases protons (H^+) leading to a reduction in pH (i.e. increased acidity). The protons that are released as consequence of the extra carbon dioxide entering the ocean also react with carbonate ions to produce bicarbonate. This reduces the concentration of carbonate, which is an essential building block for many biological processes including reproduction, respiration, behaviour, calcification and the formation of skeletons and shells by many marine organisms (Doney et al., 2009; Kleypas, 1999)(Albright and Langdon, 2011; Ekstrom et al., 2015; Gattuso et al., 2015a; Kroeker et al., 2013). Geological exploration of geochemical proxies for pH reveal that the current rate of ocean acidification is unprecedented within the last 65 million years, if not 300 million years (Hönisch et al., 2012). Marine organisms are highly connected to the watery environment surrounding them, with pH and ions like carbonate/bicarbonate playing a central role across exposed tissues. Not surprisingly, there is an extensive and growing list of organisms and processes that have been shown to be affected by changes in temperature and acidity, in isolation or in combination (Gattuso et al., 2015b; Kroeker et al., 2013).

Climate change in the ocean has been observed to affect a wide range of variables important to corals including surface salinity, water column stratification, nutrient availability, ocean currents, oxygen concentrations, and wind and storm strength among other changes (O. Hoegh-Guldberg et al., 2014)(IPCC, 2013). These changes are likely to influence marine organisms and ecological processes. The evidence, however, is complicated by long-term patterns of variability as well as significant data gaps and baseline measurements (Kroeker et al. 2013). Despite this, there is overwhelming evidence that species and ecosystems have already responded to changing ocean conditions. A large number of marine species are moving to higher latitudes or to other warm regions, with fish and zooplankton showing the fastest rates of relocation. Warming ocean temperatures, at the same time, have altered the timing of life history events such as plankton blooms, reproductive behaviour, and migratory patterns (Burrows et al., 2011; Poloczanska et al., 2013). Many organisms, such as corals and macroalgae are fixed to the substrate and, not surprisingly, showing slower (if any) rates of relocation to high latitudes. Some of the greatest responses by marine organisms to ocean warming and acidification have been seen in these benthic ecosystems, with a clear line of sight, in some instances, of impacts on ecosystems services and hence coastal people (Hoegh-Guldberg et al., 2007)(Figure 3). These instances are a major focus of this report from now on.

Coral reefs have a profound response to stressful conditions which involves normally brown corals turning a bright white colour (Hoegh-Guldberg, 1999). This is referred to as coral 'bleaching' and involves the breakdown of the symbiosis between brown *Symbiodinium* and the coral host (Figure 4D). A range of conditions from too much or too little light, low salinities, chemical toxins like cyanide, and small changes in temperature can cause this disruption to occur (Hoegh-Guldberg, 1999). While corals may recover their symbionts when exposed to mild amounts of stress, prolonged exposure can result in starvation, disease and death. Prior to 1980, bleaching was only known from a few studies where small patches of coral reefs had been observed to bleach in response to freshwater after rainstorms at low tide and other local disturbances (Freeman et al., 2001; Goreau, 1964). In the early 1980s, however, coral bleaching began to affect coral reefs across entire regions such as the Caribbean (Glynn, 1983a). Experimental work plus field observations soon identified the driver of these large-scale mass coral bleaching events as due to small increases in sea temperature (1-2°C) above the long-term summer maximum expected for a particular region (Glynn and D'Croz, 1990; Hoegh-Guldberg and Smith, 1989; Strong et al., 1997a). Since the early 1980s, the frequency and intensity of mass coral bleaching has increased, with 3 (and possibly 4) global mass coral bleaching events occurring in 1982/83, 1998, 2010, and most recently in 2016/2017 (Berkelmans et al., 2004; Glynn, 1983b; Hoegh-Guldberg, 1999; Hughes et al., 2017). Elevated temperatures are driving the mass bleaching and mortality of coral, with satellites that measure positive sea temperature anomalies predicting when and where coral bleaching events occur with a high degree of accuracy (Strong et al., 1997b)(Heron et al., 2016).

The last 2-3 years have underscored the major threat that rising sea temperatures pose to corals and the reefs that they build (Hoegh-Guldberg, 2016, 2015; Hughes et al., 2017). In 2015, unusually warm temperatures appeared in the ocean, including tropical areas resulting in bleaching that affected a range of northern hemisphere coral reefs such as those of Samoa and Hawaii (Figure 4C). These globally driven temperatures reached the threshold for mass coral bleaching and mortality in the southern hemisphere in the early part of 2016 (Figure 4C), leading to massive impacts on coral reefs in the Indo-Pacific (including the Western Indian Ocean, Maldives, Great Barrier Reef, Western and Central Pacific). One of the best documented impacts was that on the Great Barrier Reef in Australia (Hughes et al., 2017). In this case, temperatures began to increase in the latter half of 2015, prompting the first reports of bleaching in February/March 2016 (Figure 4D). By the end of April, around a third of rebuilding corals had been killed across the Great Barrier Reef, albeit with impacts concentrated in the Northern and Far Northern sectors. Significantly, these impacts began again in 2017 in the first example of mass coral bleaching affecting Great Barrier Reef for two years in a row (Hughes et al 2017). The mortality of the 2017 event saw the additional loss of around 20% of corals (Hughes et al. 2018). The increasing stress plus the projections of multiple bleaching events occurring in successive years matches the predictions made soon after the 1998 bleaching event (Hoegh-Guldberg, 1999).

[Figure 4 – 2016-2017 bleaching event goes here]

Concern about the effect of ocean acidification on coral reefs was first raised in the late 1990s by a number of researchers (Kleypas et al. 1999). Models and measurements revealed that, since the Industrial Revolution, the upper layers of the ocean (700 m) had undergone significant changes in pH and in related concentration of molecules such as carbonate (Caldeira and Wickett, 2003; Raven et al., 2005). Since the beginning of industrialisation, average ocean pH had decreased by 0.1 units, representing an increase in hydrogen ions (protons) of around 25%. These changes have been matched by similar decreases in the concentration of carbonate ions (Figure 4B). Subsequent work followed which showed that a wide range of organisms and biological processes were influenced by changes to carbon dioxide, pH and water chemistry generally (Doney et al., 2009; Dove et al., 2013; Freeman Ja; Miller, Aj;, 2013; Kroeker et al., 2013; Riebesell and Gattuso, 2015). Table 1, updated from Kroeker et al. (2013) and Gattuso, Magnan, Billé, et al. (2015), illustrates the large range of responses that have been reported so far and demonstrates the not too surprising close linkage of the metabolism in many marine organisms to the chemical milieu that surrounds them (i.e. seawater). Ecological impacts are also likely to be far reaching and fundamental given that so many organisms and ecological processes are affected by ocean acidification (L. Pendleton et al., 2016b). There may also be important interactions with other factors such as intensifying storms, whereby coral skeletons made more fragile under ocean acidification may be more susceptible to breakage during storms, which may also be growing more intense (Hoegh-Guldberg et al., 2014).

Future ocean conditions will involve both warming and acidification, but not one or the other. Whereas some studies have tried to separate the impacts of warming from those of acidification, separating the impacts of the two drivers is questionable biologically, largely impossible in practice, and may only be relevant in the case of radiation management where it might be useful to understand how ocean acidification on its own might affect coral reefs.

[Insert Table 1: Response of organisms and processes to ocean acidification]

Given the direct and indirect effects of warming, declining pH and decreasing carbonate on physiological (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function) as well as ecological processes (e.g., primary productivity, reef building and erosion), the risk profile for people dependent on coral reefs for food, protection and livelihoods is increasing. As part of the 2015 Paris Climate Agreement, countries have been encouraged to make Intended Nationally Determined Contributions (INDC) which are voluntary commitments to reduce emissions based on what is feasible nationally. So far, however, modelling shows that pledged INDCs fall short of the 2°C or well below target, with current contributions leading to average global surface temperatures of around 3.0-[illegible]°C by the end of the century (Rogelj et al., 2016). Under these conditions, coral reefs and indeed many other ocean-based ecosystems will have disappeared by mid-to-late century with serious consequences for people and communities.

5.0 The Value of Current Ecosystem Service Provision

One of the signature characteristics of carbonate coral reefs is the rich surface community of calcifying organisms and the three-dimensional framework that provides habitat for many species as well as ecological processes and services for people (Kennedy et al., 2013)(Figure 3). Here, we summarize the recent literature on (1) the linkages between habitat structure and complexity (coral cover) and fisheries production, and (2) the linkages between net accretion rate and protection from waves. In doing this, we recognise that these are among the first steps to addressing critical questions in terms of how global environmental changes will affect the ecosystem services of coral reefs and that there are a number of assumptions within our analysis. Even if some or complete coral reef loss may be inevitable, the timing and distribution of this loss is still very much in play.

We start with a discussion of the current economic output and value associated with corals today. Then we examine how a loss in coral reef ecosystem health would affect the activities and wellbeing of people and communities. In doing this, we try to point out oversimplifications that are often made in traditional analysis of expected coral reef loss. Through narrative, we also attempt to show how we can begin to develop a more nuanced understanding of potential human change to coral reef loss. In doing so, we hope to catalyse a more realistic understanding of how global change influences ecosystem services and the wellbeing of coastal people.

[Figure 5 - illustrating carbonate 'matrix' and surface covering of corals - goes here]

5.1 Coral Reef Fisheries

Coral reef fisheries support as many as 6 million direct fishing jobs and more than $6 billion in revenues globally (Teh, Teh, and Sumaila 2013). "Catches by subsistence and artisanal fisheries make up more than half of the essential protein and mineral intake for over 400 million people in the poorest countries in Africa and south Asia." (Dulvy and Allison 2009; see also Hughes et al. 2012). Based on estimates of catch in 2005, Teh et al. (Teh et al., 2013) provide country-level estimates for the gross revenues associated with reef fisheries and the jobs associated with these fisheries. To summarize these estimates, we follow L. Pendleton et al. (2016a) and provide aggregated measures of dependence on reef fisheries, by ocean province (as defined by Donner and Potere 2007; Maina et al. 2011). These calculations provide a first approximation of the human dimensions of coral reef fisheries that depend on coral reefs, with Table 2 providing and exploration of how many fishing revenues and jobs might be supported under different levels of productivity for coral reef fisheries (holding all but coral cover unchanged).

[Insert Table 2: Fishing jobs and revenue as a function of lost reef productivity]

An important outstanding question is, 'how will these human benefits associated with reef fisheries change in the face of coral reef decline and death?" To shed light on that, we look at the potential economic output of fisheries under different assumptions about coral cover. The percentage cover (or abundance) of a reef by reef-building corals is regularly used as a measure of relative condition ('health') and the trajectory of reef systems (e.g. (Bruno and Selig, 2007)). Coral cover is a measure of the living community of calcifiers driving positive accretion (i.e. net accumulation of calcium carbonate over time) and maintaining reefs. The focus on the amount of living corals in an area makes considerable sense given the central role that reef-building corals play within the ecosystem that bares their name.

Studies of how coral cover has changed generally conclude that cover of reef-building corals has declined by around 50% since the early 1980s across the tropics and subtropics in a large number of cases (Bruno and Selig, 2007; De'ath et al., 2012; Gardner et al., 2003; Hughes, 1994). A range of non-climate as well as climate-related stressors has been attributed to the observed decline (see discussion above). The key question, however, is how these changes in the aerial coverage of reef-building corals have influenced the other organisms that live in and around coral reefs. Coral reefs support an enormous number of species, with estimates of the number of species associated with coral reefs ranging from 1-9 million (Census of Marine Life, n.d.; Reaka-Kudla and Wilson, 1997). One of the key factors underpinning the extraordinary biodiversity of coral reefs is the intricate, three-dimensional habitats that reef-building corals provide, and which enable species with very close ecological niches to coexist. Reef-building corals are essential to many species as resources (food) or as critical habitat. In the former case, many species have diets that are restricted to reef building corals and/or the organisms that live in them, and in the latter case, many species require specific corals in which to hide and/or spend significant parts of their life cycle in. How these coral-associated organisms change as coral cover declines is important, not only from a biodiversity point of view, but as a critical source of food and livelihoods for large numbers of human communities.

A range of studies have demonstrated the close association of coral fishes with living coral cover. The association of fish with coral communities is driven by key aspects such as recruitment preferences, prey availability and predator avoidance (Coker et al., 2012; Greenfield, 2003)(Darling et al., 2017; Richardson et al., 2017). The extent to which fish are specific in their association with living coral reefs is demonstrated by what happens when tropical reef systems transition from coral-dominated to being dominated by other organisms such as non-rebuilding corals and macroalgae (Wilson et al., 2010)(Graham et al. 2009).

In these cases, fish communities shift significantly from reefs that have changed from being dominated by fish species that like to live in and around coral, toward communities that are dominated by herbivores and species that otherwise do well in non-coral settings (Pratchett et al 2008). These shifts herald potential changes to important reef fisheries. Initial studies of how fish communities respond to reefs that had lost coral cover identified a 'lag time' of as much as a decade (Graham et al., 2007). Some studies (e.g. Pratchett et al. 2008) initially reported that the productivity of fisheries may not change and speculated that, in many areas, targeted fisheries species (e.g. Acanthurids) are not dependent on coral habitats and therefore may show few effects of the loss of corals reefs. More recently, however, the loss of coral reefs has been associated with a strong downturn in fisheries productivity (Graham, 2014; Pratchett et al., 2014; Speers et al., 2016a) possibly by at least a 3-fold reduction (Rogers et al., 2014). The loss of coral, degradation of carbonate structures and the 'flattening" of Caribbean reef systems (Alvarez-Filip et al., 2009) further emphasise the link between coral community abundance, associated organisms such as fish, and fisheries. In this case, structural features of many Caribbean reefs have been largely absent after 40-50 years in which calcifying organisms were lost. The evidence suggests that the loss of coral dominated communities is likely to be associated with, conservatively, a 30-50% decline in productivity and associated fisheries (Graham 2015). Taking this further, albeit in a dangerously simple way, the 50% decline in coral reefs over the past 30 years might lead to a 30% decline in fisheries productivity although the timing of reef decline and the loss of associated fisheries remains poorly understood.[1]

This leads to the conclusion that the relationship between habitat provided for fish by corals (coral cover) and the productivity of coral reef-based fisheries is conservatively two-for-one. That is, a 2% loss of coral cover, all other things being equal, may lead to a 1% loss in terms of the production of small-scale fisheries. This assumption is probably conservative given that other drivers such as productivity, temperature and species relocation are likely to result in a 40% decline in fisheries across the tropics generally (Cheung et al. 2010; Fernandes et al. 2013). These timelines for the loss of productivity from reef fisheries associated with coral reefs provide a perspective on the consequences of change, although the precise timing of these events is somewhat harder to predict (see discussions below). In this case, the complexity and layers of change suggest a culmination

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[1] Some mesocosm studies have observed that coral skeletons disappear rapidly (sometimes within 6-12 months under the warmer and more acidic conditions projected) as the activity of organisms that decalcify reefs increase several fold (Dove et al., 2013).

of distresses affecting the quantity and quality of ecosystem services that is likely to be more abrupt, indicating that these estimates are by nature highly conservative (Pendleton et al 2016).

5.2 Coastal Protection

Between 60 million (Pendleton et al., 2016a) and 200 million (Ferrario et al., 2014) people depend on coral reefs for physical protection from storm surge and waves. Coral reefs protect property and infrastructure, provide a natural alternative to hard armouring of shorelines, and can help to save lives (World_Bank 2016). Pendleton et al. (2016a) provide ocean province-level estimates of human populations living at or below 10 meters above sea level and within 3 km of a coral reef. These are people who currently are most dependent on coral reefs for shoreline protection.

Again, the challenge is to understand how environmental stress may lead to a loss of the shoreline protection provided by coral reef ecosystems and how this in turn will affect low elevation coastal communities (Table 3). Reef-building corals generate calcium carbonate skeletons that may consolidate under the right conditions (warm, sunlit and shallow locations that have an aragonite saturation > 3.3, Kleypas 1999)) with other organisms such as invertebrates and red calcareous algae, adding to and sometimes ‘gluing’ the reef framework together. These processes contribute positively to the carbonate balance of coral reefs, and to the formation of the extensive reef matrix that lies under the living surface consisting of reef-building corals and other organisms (Figure 5). In addition to providing habitat, the three-dimensional structure of this living layer also provides some frictional resistance to water movement ensuring a degree of coastal protection by absorbing a portion of the wave energy impacting a shoreline. The underlying structure of the consolidated reef matrix, however, plays the major role in protecting coastal regions from wave energy and storm systems. While the structure of the surface communities can disappear relatively quickly (Alvarez-Filip et al., 2009; Dove et al., 2013; Kennedy et al., 2013), the rate at which the consolidated reef matrix disappears is less understood and probably varies with respect to the position and exposure to wave stress. Ultimately, how the carbonate balance is affected by different contributing factors will determine the rate at which recently dead coral reef ecosystems as well as the reef matrix will survive and provide coastal protection services.

In addition to the organisms and processes that lead to carbonate deposition described above, there are also processes that result in the removal of calcium carbonate. Coral skeletons can be invaded by ‘internal’ bio-eroders such as excavating sponges (Fang et al., 2017; Reyes-Nivia et al., 2014a), cyanobacteria (Reyes-Nivia et al., 2014b) as well as the range of boring invertebrates (i.e. molluscs, barnacles, and worms; Figure 1C). These organisms can significantly reduce the structural integrity of coral skeletons, as either living or dead colonies, breaking them down with the assistance of wave action and storms. Bioerosion of calcium carbonate on coral reefs can also occur in response to external factors. These include the grazing impacts of organisms such as parrotfish and sea urchins (Glynn and Manzello, 2015b) which either directly eat corals, or scrape/break coral colonies as part of their grazing on macroalgae and other coral reef organisms. Storms and waves also act to remove calcium carbonate by fracturing and removing coral structures, which in cases can have major effects on coral communities that may take 15-30 years to recover. Damage and recovery from large storms are very much part of the natural cycle of coral reefs. There is increasing evidence, however, that storms are becoming more intense, with a shortening of the interval between disturbance and recovery.

[Insert Table 3 here – low elevation countries]

The increased rates of erosion of coral reefs are being matched by reduced rates of coral growth and recovery, resulting in net rates of accretion on many coral reefs that decrease below zero ((Kennedy et al., 2013; Perry et al., 2014b) Figure 2 and Figure 5). Ocean acidification acts as a 'control' variable, with dampening effects on calcification and stimulating effects on reef erosion leading to negative rates of net accretion at aragonite saturation values of 3.3 or less, for many parts of the tropics and subtropics (Kleypas et al., 1999). The relationship between aragonite saturation and reef accretion has been investigated by a number of studies. These studies have found that changes in the level of reef accretion (as well as calcification and de-calcification independently) vary either linearly or non-linearly (Kennedy et al., 2013)) with the aragonite saturation state. These relationships enable the development of a potential index for describing how ocean acidification might influence the overall contribution of coral reefs to the coastal protection of inshore ecosystems and human infrastructure.

In its broadest sense, the net accretion rate of a coral reef determines whether or not coastal protection is increasing or decreasing. For example, if calcium carbonate is being deposited, then processes that result in calcified structures dominate those removing calcified structures. According to a review of regional accretion rates by Kennedy et al. (2013), regions such as the Great Barrier Reef (-6.8 to 1.31 kg.m^{-2}.yr^{-1}, Figure 2) have much lower net accretion rates when compared to areas such as the Coral Triangle (-0.79 to 11.7 kg.m^{-2}.yr^{-1}). These differences probably translate as increased loss of corals when it comes to climate change, with regions like the Great Barrier Reef being more likely to erode as oceans acidify than regions like the Coral Triangle. It is unclear, however, as to whether the rates of accretion are being driven by the surface communities and/or by the matrix of these reef systems, given that carbonate consolidation of the matrix may involve a series of calcifiers other than corals (Kennedy et al., 2013). The relationship between carbonate accretion, loss of three-dimensionality, and shoreline protection is also critical.

A meta-analysis looking at the role that reefs play in dissipating wave energy reveals that coral reefs reduce wave energy by an average of 97%, with the reef crest components (as opposed to intertidal areas behind reef crests) dissipating 86% of this energy alone (Ferrario et al., 2014). The two determinants of the effectiveness of reefs in dissipating wave energy were the depth of the reef crest (i.e. shallower reefs reduce wave energy more) and the surface roughness (i.e. greater roughness, greater dissipation of wave energy) (Ferrario et al., 2014). While the depth of the reef crest tends to be constant, surface roughness (Figure 5) can vary greatly as in the example of the flattening of Caribbean coral reef structures (Alvarez-Filip et al., 2009). Sea level rise at longer timescales, especially if corals cannot keep pace, is expected to also increase the impact of wave energy on areas otherwise protected by reef crest (Saunders et al., 2014, 2013).

While the role of coral reef structures in coastal protection is becoming increasing clear, our understanding of the timelines of change is less developed. In this regard, it is difficult to estimate the timing of the loss of coastal protection given the lack of information on the rate of loss of the matrix. For this reason, we explore the potential economic consequences of coral loss by focusing on the implications of losing 20%, 50% and 80% of the protection offered by the calcified matrix component of coral reefs. Our ability to predict whether a 20% loss of coastal protection will occur in 20 versus 200 years is relatively uncertain. It is also unclear how the reef matrix will change under low versus high atmospheric carbon dioxide although empirical evidence suggests that it can be rapid and potentially synergistic with warming and storm intensification (Dove et al 2013).

5.3 The Value of Reef Loss

As a simplifying assumption, many studies of the economic impact of ocean acidification on coral reefs assume some fixed relationship between coral cover and the supply of ecosystem services (Armstrong et al., 2012; Speers et al., 2016a)(see above). Several authors consider non-linear relationships between coral abundance and the per area value of coral. Chen et al. (2015) assume a quadratic relationship which would imply that more coral cover, beyond some point, would reduce the value of coral. Brander et al. (2012) assume a more complicated relationship in which the per area value of coral has a logarithmic relationship with coral cover where the unit value of coral reef area increases exponentially with reef loss (this assumes loss of quantity of coral reef without a loss in quality). In nearly all cases, authors assume that lost value does not accrue somewhere else (although see Speers et al. (2016) who estimate consumer wellbeing including fixed assumptions about the availability of other substitute forms of protein).

To understand the economic value of coral reef loss, we need to have quantitative estimates of human activity that would have occurred with and without reef loss (the counterfactual). The task is made even more difficult if our goal is to focus on the human outcomes of just a selected set of environmental stressors like climate change. History shows us that growing human use of coral reefs and related ecosystems have had their own deleterious effects and will likely continue to do so. So, global environmental changes may simply hasten coral reef loss and cannot be considered in isolation of these other factors. Of course, these local factors can be reversed by better policies that have their own costs which must also be considered.

A key to understanding and estimating the human outcomes of coral loss is to consider what might be human uses in the presence and absence of changes in coral reef health and abundance. Even without a change in coral abundance, it is difficult to know the future “without (coral) change” human use scenarios. To do so would require that we project future population growth and spatial patterns of coastal human populations, demographic trends, and even future economic conditions. For example, coral reef fishing depends largely on demand (which in turn depends on population size, access to markets, preferences for fish, consumer income, alternative sources of food (Brewer et al., 2011; Maire et al., 2016), the cost of fuel, and the availability of labor). Speers et al. (2016) (Speers et al., 2016a) used estimates of future demand for fish, but do not consider other cost factors or changes in the availability of substitutes (e.g. mangrove fish or aquaculture or even different non-marine food options). Similar projections would be needed to understand the future demand for reef tourism or how many people might benefit from the shoreline protection value of reefs. The global estimates of the economic value of coral reef loss due to ocean acidification determined by Brander et al. (2012) are driven largely by projections of population growth and an assumed increase demand for coral reef tourism. These studies never, to our knowledge, estimate the environmental costs associated with growing populations and incomes that could also lead to a loss of coral reef resources, even in the absence of climate change. Because of the uncertainty and complexity of creating future projections of human uses and benefits of future uses, many studies use current conditions as the baseline against which the impacts of coral change can be assessed (Chen et al., 2015; L. Pendleton et al., 2016a; Speers et al., 2016b)

Even holding future population and economic growth fixed, the analyst is still faced with the task of projecting a world with less coral reef area and overall reef 'health.' In economics, the hypothetical "with change" scenario or "the counterfactual" requires that we predict what people will do when faced with environmental change. Yet, few studies attempt to model how people will react to a loss of coral reefs (Hilmi et al., 2013a) and thus studies that fail to do so likely overestimate the impacts of a loss of coral reefs.

For instance, in the face of coral reef degradation, people may:

- simply continue business as usual, but with diminished economic value (measured as nutrition, profit, enjoyment, etc.)
- they may start to use local substitutes for the ecosystem services they lose
- they may nurture and restore other ecosystems that provide similar ecosystem services
- or they might simply adapt or migrate

Following the call of (Hilmi et al., 2013b) to better understand how people will respond to a loss of coral reef ecosystem services, we use a descriptive narrative to try to move beyond simple assumptions that assume people do not take steps to deal with a loss of resources and that the value of activity that currently depends on coral reefs is simply lost due to coral change. This is what the IPCC (Chapter 18, IPCC 2014), summarizing many others, calls the 'dumb farmer' assumption. To move us beyond the equally 'dumb coastal resident' approach in understanding the economic impacts of coral reef loss, we look specifically at the ways in which coral reef degradation and loss may affect people, how they might respond, and explore the types of additional information that we need in order to better understand how progressive loss of corals and coral reefs will affect human activities and economic value. To begin to do this, we ignore future demographic and economic trends and just ask whether, if all else is held equal, current economic measures are a good proxy for the value of reef loss and if not, how much do current values overestimate the potential economic cost of reef loss. By exploring how people may respond to coral reef loss, we hope to push the discussion beyond simply creating overestimates of the cost of the inevitable to one in which we can more carefully target options that may be available to reduce the impacts of coral reef loss.

6.0 Thought experiment: how do human responses affect the economics of coral loss?

Environmental stress on coral reefs can result in a reduction in the quality, quantity, and the reliability of the ecological functions and ecosystem goods and services upon which people depend. Each of these factors has a different implication for economic value. Loss of quality or quantity could affect total revenues, net revenues, or local consumption. A loss of quality can affect price, cost or enjoyment. A loss of quantity also could affect price and cost, but in different ways. An increasingly scarce resource may command a higher price (Brander et al., 2012) which could help some producers and hurt consumers. Loss of a resource may also increase competition and costs – both economic and social. The ultimate magnitude of impact essentially depends on the availability of substitutes including replacements for the ecosystem service lost, the ability to find new livelihoods or sources of nutrition, alternatives for consumer enjoyment, and even geographic options. Those with more options generally are better able to cope with or adapt to change (a key concept behind adaptive capacity). Those that cannot cope or adapt are more vulnerable.

Estimates of the impact of coral reef loss rarely consider the potential impacts of positive changes in other ecosystem services that may offset the loss of coral reef ecosystem services. In many regions, mangrove restoration and/or the natural expansion of mangroves could offer new fisheries resources (Carrasquilla-Henao and Juanes, 2017), shoreline protection (Barbier, 2015), and increased tourism opportunities (Prastiyo et al., 2015). Because mangrove ecosystems may respond differently than coral reefs to climate change, some places could benefit from expanded mangrove ecosystem services that might counter reduced economic opportunities due to coral reef degradation (Saunders et al., 2014).

Finally, it often is assumed that coarse estimates of lost ecosystem services are conservative and underestimates of the potential impact of coral loss. The idea is that these estimates are conservative because they fail to consider the full array of values that may be lost. While failure to account for all values underestimates the economic impact of coral reef loss, failure to account for costs and the human responses that are likely overestimates these impacts. We use narrative to explore these biases for fisheries, coastal protection, and tourism. Without more data and a better scientific understanding of how people respond to a loss of corals and related ecosystems, it is impossible to know whether our estimates are conservative or not.

6.1 Commercial Fisheries

Coral reefs support substantial local and export fisheries. These fisheries, in turn, provide jobs, nutrition, and livelihoods (Teh et al., 2013). Studies of the value of reef fishing, indeed most fisheries, often focus on the gross revenues associated with fishing or the gross value of production. While these estimates demonstrate the economic activity that is generated by fishing, they do not account for the fact that fishing is sometimes a costly endeavour that requires labour, capital, fuel, and may come with inherent risks to lives and livelihoods. Furthermore, many fisheries are profitable only because of government subsidies which means they could represent a negative economic value to society (Sumaila et al., 2016). Because these varied costs are difficult to quantify, it is rare to find a study that measures the net economic value to fishers of coral reef fishing. Similarly, there is little empirical data collected on the net value to consumers, especially local consumers, from eating reef fish. Thus, we rarely have the luxury of off-the-shelf estimates of the net economic value of coral reef fisheries.

It is often assumed that a loss of coral reef cover will result in a loss of fish stock which will in turn result in a direct loss of economic value roughly equal to the difference in fish stock and thus revenues. This kind of assumption dramatically oversimplifies and overestimates the economic consequences of a loss of coral cover. Here we provide a narrative regarding the potential economic responses within the commercial fishing realm that could result from a change in coral health.

Earlier, we established that different levels of coral cover supported different amounts of fish biomass, without making any assumptions about distribution, size or species composition. If fishers catch less fish or are driven out of the market, the loss to the economy is not equal to the change in the gross value of fish landed compared to what was caught previously. If fishermen no longer fish, they no longer need to buy fuel and equipment. Boats can be sold and traded. Time is freed to pursue other economic activities. Similarly, if people no longer spend money on fish, they can save that money or spend it on something else. While many studies focus on the potential change in gross values, estimating the actual change in net revenues (and net benefit to consumer) is difficult.[2]

Fewer reef fish may not translate into a proportionate decline in catch, it may simply mean fishers spend more time and money searching for fish. Perhaps fishers will increasingly focus on other nearby ecosystems such as mangrove areas and seagrass meadows. It could also mean fishers venture farther from shore or to coral areas that are less degraded in search of fish. This, in turn, could increase time, cost, risk, and conflicts with other fishers. In any case, the result would be that the relative cost of fishing could rise. This could reduce profits (and thus net benefits) of fishers. Whether or not these increased costs could be passed on in terms of higher prices for fish would depend on whether there were other substitutes for consumers. If imported fish were available, the fishers would have little ability to raise prices and would be stuck with diminished profits. If imported fish were of lower quality or completely unavailable, consumers would bear the brunt of the loss of the fisheries ecosystem services – by paying a higher price, consuming less, or having to consume more of an inferior alternative.

There are other aspects of fishing that feed into the overall dynamics of economic responses. Coral reef loss might lead to smaller fish or a different mix of species that can be caught currently on reefs (Pratchett et al., 2008), and economic value declines, even if the total landings of fish remain the same. If smaller fish or different fish fetch a lower price on the market, then the net economic value of fishing could decline - from the fishers' perspective, the loss may be felt by reduced net revenues. For the consumer, it may simply be that the new catch is inferior to the previous catch and they still enjoy a certain amount of nutritional value, taste, and even cultural value, but less than before. Overall, it could be that economic value declines, even if the total landings of fish remain the same.

Fishers and consumers depend on the reliability of catch. To the degree that future coral reef loss might be reflected in a series of increasingly severe bleaching events or sporadic coral die off, the reliability of fish landings may be affected well before a total crash in reef fisheries. Even sporadic coral reef death can push people to make permanent changes in their use of fish and could lead fishers to sell their boats in order to avoid idle periods when their useful capital incurs costs but does not generate revenues. Fishers may take advantage of an economy that supports other types of employment including closely related work (e.g. leading nature trips, wildlife guiding, park enforcement) or they may have educational or training opportunities to find other unrelated

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[2] We know of only one example of estimated changes in consumer net benefits from a loss of reef fisheries due to ocean acidification (Speers et al., 2016a). We rarely have any data about the costs of fishing that are needed to estimate changes in net producer surplus, let alone empirical data that would allow us to quantify how the decisions and activities of fishers might change at a local level.

employment. Consumers may have access to other sources of protein or fish that are not dependent on corals (e.g. mangrove fisheries and offshore fisheries). Fishers and consumers living and working in areas with few options will be more likely to experience losses that may be roughly equal to the net value of what is currently at stake. Those with more options, however, will simply transition to other economic activities or patterns of consumption. The economic consequences of coral loss will be substantially less than the net value of fish and fisheries currently supported by corals.

6.2 Recreational Fisheries

It is often assumed that a loss of coral reefs will result in a straightforward loss in the value of recreational fishing. Factors similar to those discussed for commercial fishing, however, might affect the economic losses to recreational fishing that could result from a loss of coral reefs.

The recreational fishing experience depends on many things including the size of fish caught, the amount of fish, and other amenities that may be associated with a fishing trip. It is not at all clear that there is a one-to-one relationship between fish abundance and the economic welfare of recreational fishers. A study of recreational fishing on the Great Barrier Reef minimal or no loss from coral bleaching for recreational fishing based on previous "fisher satisfaction studies" that found a 25% decline in catch sizes had little effect on the fisher consumer surplus. That is, "the experience of the catch" was preferred over "catch matters" (Oxford Economics, 2009; Prayaga et al., 2010).

A failure to account for the costs of fishing, changes in fisher behaviour, and the substitutes for both fishers and consumers leads to estimates of impacts that may be many times larger than what we would estimate if we had a better understanding of human responses to a loss or change in reef fish. One must consider that spending, which once went to buy fish, will be directed elsewhere in the economy. On the other hand, a failure to account for the knock-on effects of fishing, including social and cultural aspects associated with fishing, would create a bias in the other direction where, another business or vendor may benefit even as affected fishers will be harmed.

5.3 Coastal Protection

The ecological relationship between reef health and the human responses to changing levels of coastal protection is not straightforward. The coastal protection offered by reefs depends on the depth of the reef crest and the roughness of the reef surface (Ferrario et al., 2014; Figure 5). So, while a gradual loss of coral cover may increase wave energy arriving on shore, even a narrow reef provides significant protection against storms and large waves. As a result, we need to consider separately how a loss of cover effects long-term shoreline change compared to how reef loss affects storm damage.

A loss of coral reef can increase routine wave energy along shores and result in chronic shoreline erosion that may result in long term costs associated with armouring shorelines, gradual loss of property value and an increased need for people to resettle. The loss of coral structure does not happen quickly (i.e. it is not something that generally happens within days or weeks) and the human and economic loss as a result of coral loss depends crucially on the timing and rate of coral loss. Many estimates of coral reef shoreline protection value provide data on the capital value of shoreline property currently protected by reefs. These are useful examples of what is at risk and even the current value of coral reefs, but unless coral reefs disappear overnight, the current capital value is an upper-bound, at best, of the economic impact that might result from a loss of coral cover. Over time, people will adjust to a loss of shoreline protection, and property will not be lost overnight and so the current value of property cannot be used as the sole measure of potential loss. Even today, if shoreline erosion is evident (as it is almost everywhere) and coral degradation is apparent, property values are likely to already account for some risk of increased erosion – that is the cost of coral loss, in many places, may already be capitalized in the value of coastal property.[3]

Coastal protection is largely a public good and is managed at both public and private levels. Actions to protect the shoreline will likely be taken as coral related protection is lost. These actions could include the restoration of other ecosystems (e.g. mangroves), the creation of artificial reefs, the hard armouring of shorelines, and even making coastal property more flood resistant[4]. Quantifying the counterfactual, in this case, would require that we know what mix of defensive expenditures will be made, how much these will cost, and what will be the economic productivity and wellbeing of the people and businesses that remain. We also need to know people's ability to migrate to higher ground, other coastal areas, or a different country, island, province and so on.

In some cases, no defensive expenditures will be made, shoreline property will be abandoned, and people will move. There are significant costs to moving to other coastal areas. These costs include the out of pocket costs of moving, the social costs of dislocation and conflict that may result, and the environmental costs associated with increasing human pressures in the newly occupied areas (whether those new areas be coastal or inland). In this case, however, we need to know not just the cost of migration and loss, but how the net benefits of the "retreat" option (which could include new ecosystem services from shoreline retreat) would compare to the without change scenario (the net benefits to producers and consumers that would exist without change).

It is common to assume that a loss of coral reefs could result in short-term loss of life and property from storms. The level of protection provided by coral reefs depends on the condition of the local reef and the intensity of the storm and resulting waves and storm surge that is dissipated. The value of this protection depends on the size of local coastal populations and the value of coastal property. It also depends on the frequency and intensity of storms and storm surge.

How many lives are at risk with and without changes in the abundance of corals also depends on the preparedness of coastal dwellers and actions they will take. To further complicate matters, it is likely the case that levels of preparedness may increase with experience of catastrophic storm damage. The large loss of life that was associated with 2013's super-cyclone Haiyan (aka Super Typhoon Yolanda), for example, resulted in a loss of life of at least 7,000 people, with 1.1 million homes damaged or destroyed, and 4 million people temporarily displaced (Sherwood et al., 2015). Just three years later, however, Haima, a storm of similar intensity struck the Philippines resulting

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[3] See for instance this NYTimes article that shows the steady decline of coastal housing values in low lying areas of the U.S. due to coastal flooding. https://www.nytimes.com/2017/04/18/magazine/when-rising-seas-transform-risk-into-certainty.html

[4] We don't even consider the role of insurance and the net benefits and costs to property owners and insurance companies.

in similar property damage (approximately $2.8 billion USD for Haiyan and $1.96 for Haima), but with only 19 deaths – thanks, at least in part, to better preparedness. Over time, one would expect loss of life and property caused by storms to decline, even in the absence of coral reefs, simply due to migration and improved preparedness. Even today, only a small fraction of coastal residents die from storms, although Typhoon Haiyan was reported to have displaced as many as half of all people that we estimate live in the coastal areas of the Philippines now protected by corals. Currently, it is quite difficult to know whether, when future storms hit, these costs and lives lost will rise or fall compared to the baseline (historical damage), let alone the counterfactual (predicted environmental change).

On one hand, we are likely to overestimate the magnitude of loss to erosion if we simply focus on a linear relationship (or total loss) in the number of people exposed to risk or a loss in gross property values. On the other hand, a failure to account for the economic and social costs of struggling against change and migration would have the opposite effect and would underestimate the costs of change. Finally, many estimates of the economic cost due to the lost value of coral-related shoreline protection are based on estimates of the cost of replacing corals with hard armouring or other forms of built shoreline protection. Such estimates of replacement cost are generally gross overestimates of the value of shoreline protection provided by corals. In fact, many coastal areas already are eroding or are vulnerable to storms, but remain unprotected. Shoreline retreat is increasingly preferred to coastal armouring. Hard armouring will likely be employed along just a fraction of the coastline currently protected by coral reefs.

5.4 Tourism

Some 30% of the world's coral reefs are thought to support tourism that generates as much as $36 billion (USD) annually (Spalding et al., 2017). These expenditures represent economic activity that supports jobs, taxes, and revenue for businesses. Tourism, however, can be a costly business (Yahya et al., 2005) especially for small islands and developing countries where many of the intermediate inputs needed to operate a tourism business (from toilets, to beds, to staff, and food) must be imported. Even when inputs and staff can be found locally, the cost of these inputs is more than just a cost of doing business; these costs represent the "real cost" of tourism to the local economy. The real cost includes the cost of using resources (intermediary inputs) for tourism as opposed to other local uses, and also social and environmental costs resulting from tourism. Tourism can have significant collateral costs including costs associated with social disruption, inflation, and even a loss of local fish for local consumers[5]. These costs are rarely accounted for in valuations of coral reef-related tourism.

[Table 4 - Reef-related Visitor Expenditure within the ten jurisdictions with the highest total values goes here. Adapted from Spalding et al. 2017]

Reef tourism also provides direct economic benefits to reef tourists who often would be willing to pay more than what they are required to pay for a reef vacation. This value was estimated early on by Pendleton (1994) and more recently by a number of studies (for instance see (Deloitte Access

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[5] See http://geographyfieldwork.com/TourismProsCons.htm for an interesting breakdown of the costs and benefits of tourism.

Economics, 2017)) that estimate the per person per vacation net economic benefit of coral reef tourism is on the order of $600 or more USD. Dozens of other studies conducted over the last 23 years found similar results. When tourists are from abroad, the value they enjoy does not benefit local communities beyond what those tourists spend, but does contribute to local reef protection. Often missing from estimates of the value of reef tourism is the value of local recreation – a type of reef use for which expenditures may be low or very low, but for which the net economic value, including social and cultural value, might be significant (Hargreaves-Allen, 2010).

When coral reefs die in one location (but not all), tourists have options. Tourists and local visitors may simply continue to visit the same destination, but they may participate in other activities. For instance, Bonaire offers both world class scuba diving and equally good wind surfing. Other reef destinations may offer horseback riding, hiking, infinity pools, gambling, fine dining and other options. The local economies of destinations with many activities or where coral reef-based activities are not the primary reason for visiting may not feel the same economic impact from coral reef loss as those destinations where the reef is the primary or only attraction. Of course, some coral reef tourism destinations are isolated, low-lying and offer few activities beyond sun-bathing, diving and snorkelling. These places are likely to suffer as tourists choose other destinations in the face of local coral reef decline.

When the loss coral reefs is restricted to particular reefs, tourists may simply choose a more intact coral reef for their vacation. If that destination is nearby, it may represent a shift in tourism revenues within a country or region – the impact on local businesses may be high, but other businesses at the new destination may benefit from increased business and the overall impact within the regional economy may be less than would be anticipated if one simply assumed that all reef-related tourism revenues were lost. If the next best destination is farther away, in a different country or a different part of the world, the distribution of benefits and costs will vary accordingly. In both cases, the lost value to tourists themselves will only be equal to the net value they would have enjoyed at the original destination compared to the net value they enjoy at the next best destination. As long as there are other good options, the impact on tourists will be small.

Tourism operators differ substantially in their ability to adjust to a loss of coral reefs. Dive shop owners, live-a-board dive operations, and even divers may work to find, or even create, dive locations that don't rely on coral reef ecosystems (e.g. wreck diving, underwater sculpture parks). Others may not be able to offer other options locally, but could simply relocate. The cost and feasibility of relocation must be also considered. Local restaurants and taxi drivers, and similar businesses, may be able to cater to tourists that switch to non-reef activities, but may not find it easy to move to other destinations.

International tourists that seek sun and sea have a lot of options (Mak, 2004). Coral reef tourists certainly have fewer options, but with only 30% of current reef areas being visited routinely by tourists, the options are still significant (Spalding et al., 2017); coral reef loss in the near term may have a small effect on tourists. As coral reef losses mount (or coral degradation becomes more widespread), though, options for divers and snorkelers will diminish as will their options (meaning larger losses in the net value to tourists). There also are coral reef destinations that are iconic (e.g. the Great Barrier Reef, Hanauma Bay State Park (Mak and Moncur 1997)) or unique (although many unique reef destinations owe their uniqueness to non-reef related attractions, like Palau's

Jelly Fish Lake, Grand Cayman's Stingray City, Chuuk Lagoon's sunken ships) for which there are fewer close options or existing substitute destinations. Artificial reefs and sunken ships, however, add another increasingly popular option for divers. If coral reefs in a region are resilient to climate change and ocean acidification (Cinner et al., 2016), then these reefs may be the recipient of new tourist arrivals who are substituting away from other regions that have lost coral reef cover. The value of tourism for these surviving reefs could increase even as reef tourism value declines elsewhere, and cost-competitiveness is an important consideration when understanding the role of substitutes in determining the economic impact of reef loss.

From the perspective of the local economy, the extent of bias in our estimates depends importantly on whether we consider business owners, workers, or those employed in secondary business activities. Estimates of large-scale losses in tourism are almost certainly over-estimated for all but those local workers who have few other options.

5.5 Timing of Reef Loss

Whether coral reef and ecosystem loss happens soon or in the future makes a difference. Losses that occur now or in the near future will provide little time for adaptation by human or natural systems. Future losses could be diminished if people act soon to avoid consequences of advanced ecosystem losses. Because of economic discounting, impacts in the distant future also have less present value (cost) than those in the present or near future. All of these factors would suggest that current estimates of reef value over-estimate the value of losses that occur in the future. On the other hand, as more and more coral reefs are lost, the substitution possibilities for coral reef users will decline. The effects of the cumulative loss of coral reefs will be felt locally, regionally, and globally as coral reef loss becomes more widespread. Fewer substitutes, in turn, mean it will be increasingly difficult for those that depend on coral reefs to simply move to other coral reef areas. This means the relative economic cost of coral reef loss will likely increase as a function of coral loss.

The rate of reef loss also is important. As discussed before, the economic consequences of the loss of coral reefs depend on how well people can adapt to or cope with reef loss and the associated loss of ecosystem services. Sudden and unexpected reef loss will give reef users little time to plan and attempt to compensate or adjust to such losses. More gradual reef loss, on the other hand, will give reef users and planners more time to mitigate the economic and human consequences of reef loss. Thus, to properly evaluate how people will respond to coral losses caused by ocean acidification and bleaching, we need to be keenly aware of: a) the timing of the biophysical rate of coral reef loss, b) the timing of losses in ecosystem services, and c) how much warning regarding these losses can be given to (and acted upon by) coastal managers and coral reef users.

Timing also has a counter-intuitive effect on the value of coral reef tourism. It is quite possible that as coral cover declines globally, those remaining coral reef areas may benefit as the value of coral reef tourism increases locally (Brander et al., 2012). While Brander et al (2012) assume this means a greater economic impact when these increasingly rare reefs are lost, it also means that coral reef refugia could actually benefit in the near term from loss of coral reef elsewhere. Discounting comes into play since near-term gains have higher present value than future losses (all else being equal).

The critical role of timing sheds light on the economic value of better coral reef science and management. Better science and data collection can provide more and more accurate advanced warning about coral reef and ecosystem service loss. Better management, that can delay the biophysical effects of ocean acidification and bleaching, can provide more time for adaptation. On the other hand, if conservation professionals over-promise the ability of management (e.g. MPAs) to make coral reef ecosystems "climate resilient," coastal managers and reef users may delay taking steps to adapt which ultimately could make the costs of coral reef loss more severe when it happens.

6.0 Conclusion: future research priorities

The valuation of ecosystem services was originally intended to highlight the economic and human benefits provided by nature (Costanza et al., 1997). Over time, these valuation techniques were turned to focus on the evaluation of changes in environmental quality and access. Negative changes were valued to help set fines and fees for polluters and those who have caused the particular damage in question. Positive changes can be valued to help identify the benefits of investment in conservation and management (Börger et al., 2014). Increasingly, the valuation of ecosystem services has been used to estimate the impacts of climate change (Hungate and Hampton, 2012), but with the notion that measures could be taken to avoid these impacts and valuation would help to make clear the economic benefits from ameliorative actions (Nelson et al., 2013).

Valuing the impacts of ocean acidification, even if only coarsely, was important originally to show the potential economic consequences of carbon emissions to the atmosphere and the specific impacts from an acidifying ocean (Alexander et al., 2013), including those impacts on coral reefs (Brander et al., 2012; Chen et al., 2015; Speers et al., 2016b). But with that done, what then is the purpose of trying to value the economic losses of inevitable ocean acidification and climate change, especially apart from other drivers of environmental change?

It remains important to estimate the potential costs of OA and climate change, and with increased precision, in order to help identify to whom and where economic aid needs to flow to help people deal with climate change, especially when much of that damage is not of their own doing (this is the purpose of the UNFCCC Green Climate Fund). In this sense, valuation becomes a tool for development and aid, not necessarily for conservation. If we choose to follow this course, we have to pay more attention to the uneven timing of coral reef loss around the world and how this will affect local and regional impacts. We also need to more fully incorporate how economic and social capacity and response options available across regions can vary in influence to OA and/or warming conditions. With proper planning and intervention, many of the worst-case scenarios of economic losses from coral losses can be avoided.

From a conservation perspective, simply valuing the inevitable loss of corals is akin to counting deck chairs on the Titanic. What are we to make of these values? What signal does it send, when coral reefs can die over the course of a few hot months, to insurance and re-insurance companies to whom we have sold coral reefs as viable alternatives to artificial shoreline defences? How do we interpret these estimated losses in a world in which good management and MPAs have been promoted as a means of avoiding losses from climate change? Do these large estimates of economic loss from coral reef decline dilute the more modest benefits we may gain from managing these ecosystems through their transition?

Even if ocean warming and acidification are indeed inevitable to some extent, and even if coral reefs eventually disappear from the planet, it is important that we turn our attention to the valuation of the difference between potential future trajectories of reef health and loss given future states of atmospheric carbon emissions, deoxygenation, sedimentation, storm frequency, intensity and track, and local environmental stresses. The value of the differences will shed light on the economic and human benefits of continuing the fight to rein in atmospheric CO_2.

To better understand the value of investing in coral reef health and resilience, we redirect our efforts to understanding the benefit of conservation actions that can diminish the economic and human impacts of coral reef loss. While MPAs and management are not sufficient to save coral reefs from extremes in temperature and detrimental changes in ocean carbon chemistry, growing (but possibly insufficient empirical) evidence suggests that these actions may contribute to improved resilience to climate change (Hock et al., 2016; Roberts et al., 2017). More precise estimates of the value of these changes in resilience (along with more empirical evidence that these actions work) will help demonstrate the human benefit of using conservation and management to delay reef loss and change. Finally, the health and extent of other ecosystems (e.g. mangroves and sea grasses) may serve both to increase resilience (and thus delay onset of the loss of coral reef services) and also to act as natural substitutes for many types of coral reef ecosystems services that may be lost (including food production, shoreline protection, and even tourism). We need to better understand the economic value of conserving and managing other ecosystems, in the face of coral reef loss.

Finally, we cannot continue to assume that, in the absence of climate change and ocean acidification, the spatial patterns and current trends in resource use, population, and population distribution will continue based on past experience. Even in the absence of climate change, non-climate pressures will cause ecosystem to change and thus the distribution of people and their dependence on ecosystems. We need to be much more sophisticated in understanding how people are likely to respond to these changes at a landscape/seascape level. The only way to do that is to start collecting and analysing basic data on the human dimensions of coastal areas, especially those that now benefit from nearby coral reefs. Without long-term data across many places, we will find it hard to develop accurate projections of shifting resource use, population distribution, and ecosystem service values for coral reefs or any other coastal ecosystems.

The detection and attribution of impacts from ocean warming and acidification is strong by comparison to other linkages between climate change and impacts on ecosystems and human systems. Separating the impact of ocean acidification from ocean warming and other changes due to climate change and human activities, however, is not possible. Also, despite the strong connection between climate change and impacts on coral reefs, putting a value on the evident degradation that is occurring is complex and requires an important focus for future research in this area. This is not to say that deriving the present-day value of ecosystems to human communities is not a useful first step. However, it is clear that the predictability of how human populations are likely to respond, and thereby what the costs are in terms of the response by humans, is uncertain and requires new types of information as to the behaviour of humans within these social-ecological systems, the timing of coral reef ecosystem loss and the difference in value derived from varying coral health futures. This may change as conditions become increasingly hostile and as the options and responses by people narrows. In this case, the human elements of these systems are projected to become far more predictable as stresses increase over time. Improving our understanding of how societies and economies interact with natural resources such as those inherent within coral reefs and related ecosystems is at the heart of the challenge of establishing the true costs of ocean acidification and climate change generally. Establishing the baseline for these interactions today, will be very important in terms of measuring and understanding the changes and impacts that are likely within our rapidly changing world. With a few exceptions these types of studies are far and few between, and must be increased.

This does not, however, diminish the clear and present danger that anthropogenic climate change represents to human systems. At rates which dwarf anything in the past many millions of years, the biological consequences of climate change are extremely serious. Even with the adjustments that we suggest above, the economic impacts of climate change on reefs will be large, especially at the local level. Perhaps the most important message offered here is that further increases in carbon dioxide and other greenhouse gases in the atmosphere will continue to frustrate our ability to plan due to the many interacting and, at this point, unknown factors, synergies and antagonisms involved.

7.0 References

1. Albright, R., Anthony, K.R.N., Baird, M., Beeden, R., Byrne, M., Collier, C., Dove, S., Fabricius, K., Hoegh-Guldberg, O., Kelly, R.P., Lough, J., Mongin, M., Munday, P.L., Pears, R.J., Russell, B.D., Tilbrook, B., Abal, E., 2016. Ocean acidification: Linking science to management solutions using the Great Barrier Reef as a case study. J. Environ. Manage. 182, 641–650. doi:10.1016/j.jenvman.2016.07.038
2. Albright, R., Langdon, C., 2011. Ocean acidification impacts multiple early life history processes of the Caribbean coral Porites astreoides. Glob. Chang. Biol. 17, 2478–2487. doi:10.1111/j.1365-2486.2011.02404.x
3. Alexander, L., Allen, S., Bindoff, N.L., 2013. Ocean Acidification: Summary for Policymakers. Natl. Cent. Inj. Prev. Control 1–36. doi:10.1017/CBO9781107415324.004
4. Alvarez-Filip, L., Alvarez-Filip, L., Dulvy, N.K., Dulvy, N.K., Gill, J.A., Gill, J.A., Côté, I.M., Côté, I.M., Watkinson, A.R., Watkinson, A.R., 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proc. Biol. Sci. 276, 3019–25. doi:10.1098/rspb.2009.0339
5. Arkema, K.K., Guannel, G., Verutes, G., Wood, S. a., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., Silver, J.M., 2013. Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Chang. 3, 913–918. doi:10.1038/nclimate1944
6. Armstrong, C.W., Holen, S., Navrud, S., Seifert, I., 2012. The Economics of Ocean Acidification – a scoping study 1–57.
7. Baker, A., Riegl, B., Glynn, P., 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. Estuar.

Coast. SHELF Sci. 80, 435–471. doi:http://dx.doi.org/10.1016/j.ecss.2008.09.003

8. Barbier, E.B., 2015. Valuing the storm protection service of estuarine and coastal ecosystems. Ecosyst. Serv. 11, 32–38. doi:10.1016/j.ecoser.2014.06.010
9. Bax, N., Williamson, A., Aguero, M., Gonzalez, E., Geeves, W., 2003. Marine invasive alien species: a threat to global biodiversity. Mar. Policy 27, 313–323. doi:10.1016/S0308-597X(03)00041-1
10. Beeden, R., Maynard, J., Johnson, J., Dryden, J., Kininmonth, S., Marshall, P., 2014. No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef. Australas. J. Environ. Manag. 21, 311–319. doi:10.1080/14486563.2014.881307
11. Bell, J.D., Ganachaud, A., Gehrke, P.C., Griffiths, S.P., Hobday, A.J., Hoegh-Guldberg, O., Johnson, J.E., Le Borgne, R., Lehodey, P., Lough, J.M., Matear, R.J., Pickering, T.D., Pratchett, M.S., Gupta, A. Sen, Senina, I., Waycott, M., 2013. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat. Clim. Chang. 3, 1–9. doi:10.1038/nclimate1838
12. Berkelmans, R., De'ath, G., Kininmonth, S., Skirving, W.J., 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: Spatial correlation, patterns, and predictions. Coral Reefs. doi:10.1007/s00338-003-0353-y
13. Betancur-R., R., Hines, A., Acero P., A., Ortí, G., Wilbur, A.E., Freshwater, D.W., 2011. Reconstructing the lionfish invasion: insights into Greater Caribbean biogeography. J. Biogeogr. 38, 1281–1293. doi:10.1111/j.1365-2699.2011.02496.x
14. Börger Nj; Pendleton, L; Boyle, Kj; Cooper, P; Fletcher, S; Haab, T; Hanemann, M; Hooper, Tl; Hussain, Ss; Portela, R; Stithou, M; Stockill, J; Taylor, T; Austen, Mc;, T.B., 2014. Incorporating ecosystem services in marine planning: The role of valuation. Mar. Policy Vol. 46 (pp 161-170). doi:http://dx.doi.org/10.1016/j.marpol.2014.01.019
15. Brander, L., Beukering, P. van, 2013. The Total Economic Value of U.S. Coral Reefs a Review of The Literature. Silver Spring, MD.
16. Brander, L.M., Rehdanz, K., Tol, R.S.J., Van Beukering, P.J.H., 2012. The economic impact of ocean acidification on coral reefs. Clim. Chang. Econ. 03, 1250002. doi:10.1142/S2010007812500029
17. Brewer, T.D., Cinner, J.E., Fisher, R., Green, A., Wilson, S.K., 2011. Market access , population density , and socioeconomic development explain diversity and functional group biomass of coral reef fish assemblages. Glob. Environ. Chang. 22, 399–406. doi:10.1016/j.gloenvcha.2012.01.006
18. Bruno, J.F., Precht, W.F., Vroom, P.S., Aronson, R.B., 2014. Coral reef baselines: How much macroalgae is natural? Mar. Pollut. Bull. 80, 24–29. doi:10.1016/j.marpolbul.2014.01.010
19. Bruno, J.F., Selig, E.R., 2007. Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. PLoS One 2. doi:10.1371/journal.pone.0000711
20. Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at risk Revisited, World Resources Institute. Washington, D.C. doi:10.1016/0022-0981(79)90136-9
21. Burke, L., Selig, E., Spalding, M., 2002. Reefs at Risk in Southeast Asia, World Fishing. World Resources Institute in collaboration with the United Nations Environment Programme-World Conservation Monitoring Centre, the World Fish Center, and the

International Coral Reef Action Network.

22. Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C. V, Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., Richardson, A.J., 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science (80-.). 334, 652–655. doi:10.1126/science.1210288
23. Caldeira, K., Wickett, M.E., 2003. Oceanography: Anthropogenic carbon and ocean pH. Nature 425, 365–365. doi:10.1038/425365a
24. Carrasquilla-Henao, M., Juanes, F., 2017. Mangroves enhance local fisheries catches: a global meta-analysis. Fish Fish. 18, 79–93. doi:10.1111/faf.12168
25. Census of Marine Life, n.d. Census of Coral Reef Ecosystems (CReefs) [WWW Document]. Coord. by a Secr. based Consort. Ocean Leadersh. Washington, D.C. URL http://www.coml.org/census-coral-reef-ecosystems-creefs (accessed 7.12.17).
26. Cesar, H., Beukering, P. van, Pintz, S., Dierking, J., 2002. Economic valuation of the coral reefs of Hawaii. The Netherlands.
27. Cesar, H., Burke, L., Pet-soede, L., 2003. The Economics of Worldwide Coral Reef Degradation. The Netherlands.
28. Cesar, H., Chong, C.K., 2004. Economic Valuation and Socioeconomics of Coral Reefs : Methodological Issues and Three Case Studies. World Fish Cent. 14–40.
29. Chen, P., Chen, C., Chu, L., Mccarl, B., 2015. Evaluating the economic damage of climate change on global coral reefs. Glob. Environ. Chang. 30, 12–20. doi:10.1016/j.gloenvcha.2014.10.011
30. Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., Pauly, D., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob. Chang. Biol. 16, 24–35. doi:10.1111/j.1365-2486.2009.01995.x
31. Cinner, J.E., Huchery, C., MacNeil, M.A., Graham, N.A.J., McClanahan, T.R., Maina, J., Maire, E., Kittinger, J.N., Hicks, C.C., Mora, C., Allison, E.H., D'Agata, S., Hoey, A., Feary, D.A., Crowder, L., Williams, I.D., Kulbicki, M., Vigliola, L., Wantiez, L., Edgar, G., Stuart-Smith, R.D., Sandin, S.A., Green, A.L., Hardt, M.J., Beger, M., Friedlander, A., Campbell, S.J., Holmes, K.E., Wilson, S.K., Brokovich, E., Brooks, A.J., Cruz-Motta, J.J., Booth, D.J., Chabanet, P., Gough, C., Tupper, M., Ferse, S.C.A., Sumaila, U.R., Mouillot, D., 2016. Bright spots among the world's coral reefs. Nature 1–17. doi:10.1038/nature18607
32. Cinner, J.E., McClanahan, T.R., MacNeil, M.A., Graham, N. a J., Daw, T.M., Mukminin, A., Feary, D. a, Rabearisoa, A.L., Wamukota, A., Jiddawi, N., Campbell, S.J., Baird, A.H., Januchowski-Hartley, F. a, Hamed, S., Lahari, R., Morove, T., Kuange, J., 2012. Comanagement of coral reef social-ecological systems. Proc. Natl. Acad. Sci. U. S. A. 109, 5219–22. doi:10.1073/pnas.1121215109
33. Cinner, J.E.F., Folke, C., Daw, T., Hicks, C.C.C., 2011. Responding to change: Using scenarios to understand how socioeconomic factors may influence amplifying or dampening exploitation feedbacks among Tanzanian fishers. Glob. Environ. Chang. 21, 7–12. doi:10.1016/j.gloenvcha.2010.09.001
34. Coker, D.J., Graham, N.A.J., Pratchett, M.S., 2012. Interactive effects of live coral and

structural complexity on the recruitment of reef fishes. Coral Reefs 31, 919–927. doi:10.1007/s00338-012-0920-1

35. Costanza, R., Arge, R., Groot, R. De, Farberk, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V, Paruelo, J., Raskin, R.G., Suttonkk, P., van den Belt, M., 1997. The value of the world ' s ecosystem services and natural capital. Nature 387, 253–260. doi:10.1038/387253a0
36. Côté, I.M., Gill, J.A., Gardner, T.A., Watkinson, A.R., 2005. Measuring coral reef decline through meta-analyses. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 360, 385–395. doi:10.1098/rstb.2004.1591
37. Crabbe, E., Garcia, C., Chub, J., Castro, L., Guy, J., Martinez, M., 2008. Growth modelling indicates hurricanes and severe storms are linked to low coral recruitment in the Caribbean. Mar. Environ. Res. 65, 364–368. doi:http://dx.doi.org/10.1016/j.marenvres.2007.11.002
38. Cruz-Trinidad, A., Aliño, P.M., Geronimo, R.C., Cabral, R.B., 2014. Linking Food Security with Coral Reefs and Fisheries in the Coral Triangle. Coast. Manag. 42, 160–182. doi:10.1080/08920753.2014.877761
39. Darling, E.S., Graham, N.A.J., Januchowski-Hartley, F.A., Nash, K.L., Pratchett, M.S., Wilson, S.K., 2017. Relationships between structural complexity, coral traits, and reef fish assemblages. Coral Reefs 36, 1–15. doi:10.1007/s00338-017-1539-z
40. De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proc. Natl. Acad. Sci. U. S. A. 109, 17995–9. doi:10.1073/pnas.1208909109
41. Deliotte, 2013. Economic Contribution of the Great Barrier Reef. Deloitte Access Econ.
42. Deloitte Access Economics, 2017. At what price? The economic , social and icon value of the Great Barrier Reef. Brisbane.
43. Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean Acidification: The Other CO2 Problem. Ann. Rev. Mar. Sci. 1, 169–192. doi:10.1146/annurev.marine.010908.163834
44. Donner, S.D., Potere, D., 2007. The Inequity of the Global Threat to Coral Reefs. Bioscience 57, 214. doi:10.1641/B570302
45. Dove, S.G., Kline, D.I., Pantos, O., Angly, F.E., Tyson, G.W., Hoegh-Guldberg, O., 2013. Future reef decalcification under a business-as-usual CO2 emission scenario. Proc. Natl. Acad. Sci. U. S. A. 110, 15342–7. doi:10.1073/pnas.1302701110
46. Dulvy, N., Allison, E., 2009. A Place at the Table ... [WWW Document]. Nat. Reports Clim. Chang. doi:10.1038/climate.2009.52
47. Ekstrom, J.A., Suatoni, L., Cooley, S.R., Pendleton, L.H., Waldbusser, G.G., Cinner, J.E., Ritter, J., Langdon, C., Van Hooidonk, R., Gledhill, D., Wellman, K., Beck, M.W., Brander, L.M., Rittschof, D., Doherty, C., Edwards, P.E.T., Portela, R., 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. Nat. Clim. Chang. 5, 207–214. doi:10.1038/nclimate2508
48. Fabricius, K.E., De''ath, G., Puotinen, M.L., Done, T., Cooper, T.F., Burgess, S.C., 2008. Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. Limnol. Oceanogr. 53, 690–704. doi:10.4319/lo.2008.53.2.0690
49. Fabricius, K.E., Okaji, K., De'ath, G., 2010. Three lines of evidence to link outbreaks of

the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. Coral Reefs 29, 593–605. doi:10.1007/s00338-010-0628-z

50. Fang, J.K.H., Mason, R.A.B., Sch??nberg, C.H.L., Hoegh-Guldberg, O., Dove, S., 2017. Studying interactions between excavating sponges and massive corals by the use of hybrid cores. Mar. Ecol. 38, e12393. doi:10.1111/maec.12393
51. Fernandes, J.A., Cheung, W.W.L., Jennings, S., Butensch??n, M., De Mora, L., Fr??licher, T.L., Barange, M., Grant, A., 2013. Modelling the effects of climate change on the distribution and production of marine fishes: Accounting for trophic interactions in a dynamic bioclimate envelope model. Glob. Chang. Biol. 19, 2596–2607. doi:10.1111/gcb.12231
52. Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 5, 3794. doi:10.1038/ncomms4794
53. Freeman Ja; Miller, Aj;, L.K., 2013. Coral Reef Habitat Response to Climate Change Scenarios. PLOS ONE DEC 5 2013 Vol. 8 Issue 12, pages 14 , N. e82404. doi:http://dx.doi.org/10.1371/journal.pone.0082404
54. Freeman, R.K., Valli?res, E., Verrier, E.D., Karmy-Jones, R., Wood, D.E., 2001. Coral bleaching: Interpretation of thermal tolerance limits and thermal thresholds in tropical corals. Coral Reefs 20, 51–65. doi:10.1007/s003380100146
55. Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A., Watkinson, A.R., 2003. Long-Term Region-Wide Declines in Caribbean Corals. Science (80-.). 301.
56. Gardner, T.A., Gill, J.A., Grant, A., Watkinson, A.R., Côté, I.M., 2005. Hurricanes and Caribbean coral reefs: immediate impacts, recovery trajectories and contribution to long-term decline. Ecology 86, 174–184. doi:10.1890/04-0141
57. Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.-O., Rogers, a. D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., 2015a. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. Science (80-.). 349. doi:http://dx.doi.org/10.1126/science.aac4722
58. Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.-O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., 2015b. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. Science (80-.). 349, aac4722. doi:10.1126/science.aac4722
59. Gattuso, J.-P., Allemand, D., Frankignoulle, M., 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry. Am. Zool. 39, 160–183. doi:10.1093/icb/39.1.160
60. Glynn, P., 1983a. Extensive “bleaching” and death of reef corals on the Pacific coast of Panama. Environ. Conserv. 10, 149–154. doi:10.1017/S0376892900012248
61. Glynn, P., 1983b. Extensive “bleaching” and death of reef corals on the Pacific coast of Panama. Environ. Conserv. 10, 149–154. doi:10.1017/S0376892900012248
62. Glynn, P.W., D’Croz, L., 1990. Experimental evidence for high temperature stress as the

cause of El Niño-coincident coral mortality. Coral Reefs 8, 181–191. doi:10.1007/BF00265009

63. Glynn, P.W., Manzello, D.P., 2015a. Bioerosion and Coral Reef Growth: A Dynamic Balance, in: Coral Reefs in the Anthropocene. Springer Netherlands, Dordrecht, pp. 67–97. doi:10.1007/978-94-017-7249-5_4
64. Glynn, P.W., Manzello, D.P., 2015b. Bioerosion and Coral Reef Growth: A Dynamic Balance, in: Coral Reefs in the Anthropocene. Springer Netherlands, Dordrecht, pp. 67–97. doi:10.1007/978-94-017-7249-5_4
65. Goreau, T.F., 1964. Mass Expulsion of Zooxanthellae from Jamaican Reef Communities after Hurricane Flora. Science (80-.). 145, 383–386. doi:10.1126/science.145.3630.383
66. Graham Sk; Pratchett, Ms; Polunin, Nvc; Spalding, Md;, [illegible] W.., 2009. Coral mortality versus structural collapse as drivers of corallivorous butterflyfish decline. Biodivers. Conserv. NOV 2009 Vol. 18 Issue 12, pages 12 (pp 3325-3336). doi:http://dx.doi.org/10.1007/s10531-009-9633-3
67. Graham, N.A.J., 2014. Habitat complexity: Coral structural loss leads to fisheries declines. Curr. Biol. 24, R359–R361. doi:10.1016/j.cub.2014.03.069
68. Graham, N.A.J., Wilson, S.K., Jennings, S., Polunin, N.V.C., Robinson, J., Bijoux, J.P., Daw, T.M., 2007. Lag effects in the impacts of mass coral bleaching on coral reef fish, fisheries, and ecosystems. Conserv. Biol. 21, 1291–1300. doi:10.1111/j.1523-1739.2007.00754.x
69. Greenfield, D.W., 2003. Coral reef fishes: dynamics and diversity in a complex ecosystem. Copeia. doi:10.1643/0045-8511(2003)003[0214:]2.0.CO;2
70. Grieve, B., Curchitser, E., Rykaczewski, R., 2016. Range expansion of the invasive lionfish in the Northwest Atlantic with climate change. Mar. Ecol. Prog. Ser. 546, 225–237. doi:10.3354/meps11638
71. Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A Global Map of Human Impact on Marine Ecosystems. Science (80-.). 319.
72. Harborne, A.R., Mumby, P.J., Kappel, C. V, Dahlgren, C.P., Micheli, F., Holmes, K.E., Brumbaugh, D.R., 2008. Tropical coastal habitats as surrogates of fish community structure,grazing, and fisheries value. Ecol. Appl. 18, 1689–1701. doi:10.1890/07-0454.1
73. Hargreaves-Allen, V., 2010. Economic values, distributional impacts and conservation outcomes for coral reef marine protected areas.
74. Heron, S., Johnston, L., Liu, G., Geiger, E., Maynard, J., De La Cour, J., Johnson, S., Okano, R., Benavente, D., Burgess, T., Iguel, J., Perez, D., Skirving, W., Strong, A., Tirak, K., Eakin, C., 2016. Validation of Reef-Scale Thermal Stress Satellite Products for Coral Bleaching Monitoring. Remote Sens. 8, 59. doi:10.3390/rs8010059
75. Hilmi, N., Allemand, D., Dupont, S., Safa, A., Haraldsson, G., Nunes, P. a L.D., Moore, C., Hattam, C., Reynaud, S., Hall-Spencer, J.M., Fine, M., Turley, C., Jeffree, R., Orr, J., Munday, P.L., Cooley, S.R., 2013a. Towards improved socio-economic assessments of ocean acidification's impacts. Mar. Biol. 160, 1773–1787. doi:10.1007/s00227-012-2031-5
76. Hilmi, N., Allemand, D., Dupont, S., Safa, A., Haraldsson, G., Nunes, P. a L.D., Moore,

C., Hattam, C., Reynaud, S., Hall-Spencer, J.M., Fine, M., Turley, C., Jeffree, R., Orr, J., Munday, P.L., Cooley, S.R., 2013b. Towards improved socio-economic assessments of ocean acidification's impacts. Mar. Biol. 160, 1773–1787. doi:10.1007/s00227-012-2031-5

77. Hock, K., Wolff, N.H., Beeden, R., Hoey, J., Condie, S.A., Anthony, K.R.N., Possingham, H.P., Mumby, P.J., 2016. Controlling range expansion in habitat networks by adaptively targeting source populations. Conserv. Biol. 30, 856–866. doi:10.1111/cobi.12665
78. Hoegh-Guldberg, O., 2016. Coral bleaching comes to the Great Barrier Reef as record-breaking global temperatures continue. Conversat. March.
79. Hoegh-Guldberg, O., 2015. The oceans are becoming too hot for coral, and sooner than we expected. Conversat. October.
80. Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. Mar. Freshw. Res. 50, 839. doi:10.1071/MF99078
81. Hoegh-Guldberg, O., Cai, R., Poloczanska, E.S., Brewer, P.G., Sundby, S., Hilmi, K., Fabry, V.J., Jung, S., 2014. The Ocean. Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part B Reg. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang. 1655–1732. doi:10.1017/CBO9781107415386.010
82. Hoegh-Guldberg, O., Cai, R., Poloczanska, E.S.S., Brewer, P.G.G., Sundby, S., Hilmi, K., Fabry, V.J.J., Jung, S., 2014. The Ocean, in: Press, C.U. (Ed.), C1001, R. (Tran.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655–1731.
83. Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E., 2007. Coral Reefs Under Rapid Climate Change and Ocean Acidification. Science (80-.). 318, 1737.
84. Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S., 2017. Coral Reef Ecosystems under Climate Change and Ocean Acidification. Front. Mar. Sci. 4. doi:10.3389/fmars.2017.00158
85. Hoegh-Guldberg, O., Smith, G.J., 1989. The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals Stylophora pistillata Esper and Seriatopora hystrix Dana. J. Exp. Mar. Bio. Ecol. 129, 279–303. doi:10.1016/0022-0981(89)90109-3
86. Hönisch, B., Ridgwell, A., Schmidt, D.N., Thomas, E., Gibbs, S.J., Sluijs, A., Zeebe, R., Kump, L., Martindale, R.C., Greene, S.E., Kiessling, W., Ries, J., Zachos, J.C., Royer, D.L., Barker, S., Marchitto, T.M., Moyer, R., Pelejero, C., Ziveri, P., Foster, G.L., Williams, B., 2012. The geological record of ocean acidification. Science (80-.). 335, 1058–1063. doi:10.1126/science.1208277
87. Hughes, S., Yau, A., Max, L., Petrovic, N., Davenport, F., Marshall, M., McClanahan, T.R., Allison, E.H., Cinner, J.E., Hughes A; Max, L; Petrovic, N; Davenport, F; Marshall, M; McClanahan, Tr; Allison, Eh; Cinner, Je;, S.Y., 2012. A framework to assess national level vulnerability from the perspective of food security: The case of coral reef fisheries. Environ. Sci. Policy 23, 95–108. doi:http://dx.doi.org/10.1016/j.envsci.2012.07.012

88. Hughes, T.P., 1994. Catastrophes, Phase Shifts, and Large-Scale Degradation of a Caribbean Coral Reef. Science (80-.). 265, 1547–1551. doi:10.1126/science.265.5178.1547
89. Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G., Wilson, S.K., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science (80-.). 359, 80–83. doi:10.1126/science.aan8048
90. Hughes, T.P., Kerry, J., Álvarez-Noriega, M., Álvarez-Romero, J., Anderson, K., Baird, A., Babcock, R., Beger, M., Bellwood, D., Berkelmans, R., Bridge, T., Butler, I., Byrne, M., Cantin, N., Comeau, S., Connolly, S., Cumming, G., Dalton, S., Diaz-Pulido, G., Eakin, C.M., Figueira, W., Gilmour, J., Harrison, H., Heron, S., Hoey, A.S., Hobbs, J.-P., Hoogenboom, M., Kennedy, E., Kuo, C.-Y., Lough, J., Lowe, R., Liu, G., Malcolm McCulloch, H.M., McWilliam, M., Pandolfi, J., Pears, R., Pratchett, M., Schoepf, V., Simpson, T., Skirving, W., Sommer, B., Torda, G., Wachenfeld, D., Willis, B., Wilson, S., 2017. Global warming and recurrent mass bleaching of corals. Nature. doi:10.1038/nature21707
91. Hughes, T.P., Kerry, J.T., Simpson, T., 2018. Large-scale bleaching of corals on the Great Barrier Reef. Ecology 99, 501. doi:10.1002/ecy.2092
92. Hungate, B.A., Hampton, H.M., 2012. Ecosystem services: Valuing ecosystems for climate. Nat. Clim. Chang. 2, 151–152. doi:10.1038/nclimate1398
93. IPCC, 2014. Summary for Policy Makers. Clim. Chang. 2014 Impacts, Adapt. Vulnerability - Contrib. Work. Gr. II to Fifth Assess. Rep. 1–32. doi:10.1016/j.renene.2009.11.012
94. IPCC, 2013. Climate Change 2013 The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Edited by. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
95. Jackson, J.B., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., Warner, R.R., 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. Science (80-.). 293, 629–637. doi:10.1126/science.1059199
96. Jackson, J.B.C., Donovan, M.K., Cramer, K.L., Lam, V., Lam, W., 2014. Status and Trends of Caribbean Coral Reefs : 1970-2012. Glob. Coral Reef Monit. Network, IUCN, Gland. Switz. 306
97. Jackson, J.B.C., Donovan, M.K., Cramer, K.L., Lam, W., 2014. Status and trends of Caribbean coral reefs: 1970-2012. GCRMN, Gland, Switzerland, IUCN.
98. Kennedy, E.V., Perry, C.T., Halloran, P.R., Iglesias-Prieto, R., Schonberg, C.H.L., Wisshak, M., Form, A., Carricart-Ganivet, J.P., Fine, M., Eakin, C.M., Mumby, P.J., 2013. Avoiding Coral Reef Functional Collapse Requires Local and Global Action. Curr. Biol. 23, 912–918. doi:10.1016/j.cub.2013.04.020
99. Kleypas, J.A., 1999. Geochemical Consequences of Increased Atmospheric Carbon

Dioxide on Coral Reefs. Science (80-.). 284, 118–120. doi:10.1126/science.284.5411.118

100. Kleypas, J.A., McManus, J.W., Meñez, L.A., 1999. Environmental limits to coral reef development: where do we draw the line? Am. Zool. 39, 146–159.

101. Knowlton, N., Brainard, R.E., Fisher, R., Moews, M., Plaisance, L., Caley, M.J., 2010. Coral Reef Biodiversity. Life World's Ocean. Divers. Distrib. Abundance 65–78. doi:10.1002/9781444325508.ch4

102. Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. Glob. Chang. Biol. 19, 1884–1896. doi:10.1111/gcb.12179

103. Lowe, P., Bruno, J., Selig, E., Spencer, M., 2011. Empirical models of transitions between coral reef states: Effects of region, protection, and environmental change. PLoS One 6. doi:http://dx.doi.org/10.1371/journal.pone.0026339

104. Maina, J., McClanahan, T.R., Venus, V., Ateweberhan, M., Madin, J., 2011. Global gradients of coral exposure to environmental stresses and implications for local management. PLoS One 6. doi:10.1371/journal.pone.0023064

105. Maire, E., Cinner, J., Velez, L., Huchery, C., Mora, C., Dagata, S., Vigliola, L., Wantiez, L., Kulbicki, M., Mouillot, D., 2016. How accessible are coral reefs to people? A global assessment based on travel time. Ecol. Lett. 19, 351–360. doi:10.1111/ele.12577

106. Mak, J., 2004. Tourism and the Economy: Understanding the Economics of Tourism. Honolulu, HI.

107. Mak, J., Moncur, J.E.T., 1997. Political economy of protecting unique recreational resources - Hanauma Bay, Hawaii (No. 97–8). Honolulu, HI.

108. Manzello, D.P., 2010. Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific. Coral Reefs 29, 749–758.

109. Martinez, M.L., Intralawan, A., V?zquez, G., P?rez-Maqueo, O., Sutton, P., Landgrave, R., 2007. The coasts of our world: Ecological, economic and social importance. Ecol. Econ. 63, 254–272. doi:10.1016/j.ecolecon.2006.10.022

110. McCulloch, M., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature 421, 727–730. doi:10.1038/nature01361

111. Millenium Ecosysetm Assessment, 2005. Ecosystems and Human Well-Being Synthesis. Washington, D.C.

112. Moritz, C., Vii, J., Lee Long, W., Tamelander, J., Thomassin, A., Planes, S., 2018. Status and Trends of Coral Reefs of the Pacific: Global Coral Reef Monitoring Network.

113. Mumby, P., Hastings, A., Edwards, H., 2007. Thresholds and the resilience of Caribbean coral reefs. Nat. NOV 1 2007 Vol. 450 Issue 7166, pages 4 (pp 98-101). doi:http://dx.doi.org/10.1038/nature06252

114. Mumby, P.J., Chollett, I., Bozec, Y.-M.M., Wolff, N.H., 2014. Ecological resilience, robustness and vulnerability: how do these concepts benefit ecosystem management? Curr. Opin. Environ. Sustain. 7, 22–27. doi:10.1016/j.cosust.2013.11.021

115. Mumby, P.J., Vitolo, R., Stephenson, D.B., 2011. Temporal clustering of tropical

cyclones and its ecosystem impacts. Proc. Natl. Acad. Sci. 108, 17626–17630. doi:10.1073/pnas.1100436108

116. Muscatine, L., 1990. The role of symbiotic algae in carbon and energy flux in reef corals. Ecosyst. world 25, 75–87.

117. Muscatine, L., Porter, J.W., 1977. Reef Corals: Mutualistic Symbioses Adapted to Nutrient-Poor Environments. Source Biosci. 27, 454–460. doi:10.2307/1297526

118. Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024. doi:10.1038/35016500

119. Nelson, E.J., Kareiva, P., Ruckelshaus, M., Arkema, K., Geller, G., Girvetz, E., Goodrich, D., Matzek, V., Pinsky, M., Reid, W., Saunders, M., Semmens, D., Tallis, H., 2013. Climate change's impact on key ecosystem services and the human well-being they support in the US. Front. Ecol. Environ. 11, 483–493. doi:10.1890/120312

120. Oxford Economics, 2009. Valuing the effects of Great Barrier Reef bleaching. Oxford, UK.

121. Pendleton, L., Comte, A., Langdon, C., Ekstrom, J.A., Cooley, R., Suatoni, L., Beck, M.W., Brander, L.M., Burke, L., Cinner, E., Doherty, C., Edwards, P.E.T., Gledhill, D., Jiang, L., Hooidonk, R.J. Van, Teh, L., Waldbusser, G.G., Ritter, J., 2016a. Coral Reefs and People in a High-CO 2 World : Where Can Science Make a Difference to People ? PLoS One 11, 1–21. doi:10.1371/journal.pone.0164699

122. Pendleton, L., Hoegh-Guldberg, O., Langdon, C., Comte, A., 2016b. Multiple Stressors and Ecological Complexity Require a New Approach to Coral Reef Research. Front. Mar. Sci. 3, 1–5. doi:10.3389/fmars.2016.00036

123. Pendleton, L.H., Hoegh-guldberg, O., Langdon, C., Comte, A., 2016. Multiple stressors and ecological complexity require a new approach to coral reef research 3, 1–5. doi:10.3389/fmars.2016.00036

124. Perry, C.T., Murphy, G.N., Kench, P.S., Edinger, E.N., Smithers, S.G., Steneck, R.S., Mumby, P.J., 2014a. Changing dynamics of Caribbean reef carbonate budgets: emergence of reef bioeroders as critical controls on present and future reef growth potential. Proc. R. Soc. London B Biol. Sci. 281.

125. Perry, C.T., Murphy, G.N., Kench, P.S., Edinger, E.N., Smithers, S.G., Steneck, R.S., Mumby, P.J., 2014b. Changing dynamics of Caribbean reef carbonate budgets: emergence of reef bioeroders as critical controls on present and future reef growth potential. Proc. R. Soc. London B Biol. Sci. 281.

126. Poloczanska, E., Brown, C., Sydeman, W., 2013. Global imprint of climate change on marine life. Nat. Clim. 3, 919–925.

127. Prastiyo, Hakim, L., Batoro, J., 2015. Mangrove biodiversity as tourism attraction: the perspective of tourist. J. Biodivers. Environ. Sci. 6, 89–98.

128. Pratchett, M.S., Hoey, A.S., Wilson, S.K., 2014. Reef degradation and the loss of critical ecosystem goods and services provided by coral reef fishes. Curr. Opin. Environ. Sustain. 7, 37–43. doi:10.1016/j.cosust.2013.11.022

129. Pratchett, M.S., Munday, P.L., Wilson, S.K., Graham, N.A.J., Cinnerm, J.E., Bellwood, D.R., Jones, G.P., Polunin, N.V.C., McClanahan, T.R., 2008. Effects of climate-induced coral bleaching on coral-reef fishes - Ecological and economic

consequences. Oceanogr. Mar. Biol. An Annu. Rev. 46, 251–296.

130. Prayaga, P., Rolfe, J., Stoeckl, N., 2010. The value of recreational fishing in the Great Barrier Reef, Australia: A pooled revealed preference and contingent behaviour model. Mar. Policy 34, 244–251. doi:10.1016/j.marpol.2009.07.002

131. Raven, John, Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., Watson, A., 2005. Ocean acidification due to increasing atmospheric carbon dioxide. R. Soc. 1–68.

132. Reaka-Kudla, M.L., Wilson, D.E., 1997. Global biodiversity of coral reefs: a comparison with rainforests., Biodiversity II: Understanding and Protecting Our Biological Resources. Joseph Henry Press.

133. Reyes-Nivia, C., Diaz-Pulido, G., Dove, S., 2014a. Relative roles of endolithic algae and carbonate chemistry variability in the skeletal dissolution of crustose coralline algae. Biogeosciences 11, 4615–4626. doi:10.5194/bg-11-4615-2014

134. Reyes-Nivia, C., Diaz-Pulido, G., Dove, S., 2014b. Relative roles of endolithic algae and carbonate chemistry variability in the skeletal dissolution of crustose coralline algae. Biogeosciences 11, 4615–4626. doi:10.5194/bg-11-4615-2014

135. Richardson, L.E., Graham, N.A.J., Pratchett, M.S., Hoey, A.S., 2017. Structural complexity mediates functional structure of reef fish assemblages among coral habitats. Environ. Biol. Fishes 100, 193–207. doi:10.1007/s10641-016-0571-0

136. Riebesell, U., Gattuso, J.-P., 2015. Lessons learned from ocean acidification research. Nat. Clim. Chang. 5, 12–14. doi:10.1038/nclimate2456

137. Riegl, B., 2003. Climate change and coral reefs: different effects in two high-latitude areas ({Arabian} {Gulf}, {South} {Africa}). Coral Reefs 22, 433–446. doi:10.1007/s00338-003-0335-0

138. Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., Worm, B., Castilla, J.C., 2017. Marine reserves can mitigate and promote adaptation to climate change. Proc. Natl. Acad. Sci. 201701262. doi:10.1073/pnas.1701262114

139. Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature. doi:10.1038/nature18307

140. Rogers, A., Blanchard, J.L., Mumby, P.J., 2014. Vulnerability of coral reef fisheries to a loss of structural complexity. Curr. Biol. 24, 1000–1005. doi:10.1016/j.cub.2014.03.026

141. Saunders, M.I., Leon, J., Phinn, S.R., Callaghan, D.P., O'Brien, K.R., Roelfsema, C.M., Lovelock, C.E., Lyons, M.B., Mumby, P.J., 2013. Coastal retreat and improved water quality mitigate losses of seagrass from sea level rise. Glob. Chang. Biol. 19, 2569–2583. doi:10.1111/gcb.12218

142. Saunders, M.I., Leon, J.X., Callaghan, D.P., Roelfsema, C.M., Hamylton, S., Brown, C.J., Baldock, T., Golshani, A., Phinn, S.R., Lovelock, C.E., Hoegh-Guldberg, O., Woodroffe, C.D., Mumby, P.J., 2014. Interdependency of tropical marine ecosystems in response to climate change. Nat. Clim. Chang. 4, 724–729. doi:10.1038/NCLIMATE2274

143. Sherwood, A., Bradley, M., Rossi, L., Guiam, R., Melliker, B., 2015. Resolving Displacement : Insights from the Philippines after Typhoon Haiyan 1–82.

144. Spalding, M., Burke, L., Wood, S.A., Ashpole, J., Hutchison, J., zu Ermgassen, P., 2017. Mapping the global value and distribution of coral reef tourism. Mar. Policy 82, 104–113. doi:https://doi.org/10.1016/j.marpol.2017.05.014

145. Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A., Lombana, A., Lourie, S.A., Martin, K.D., Mcmanus, E., Molnar, J., Recchia, C.A., Robertson, J., 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57, 573. doi:10.1641/B570707

146. Speers, A.E., Besedin, E.Y., Palardy, J.E., Moore, C., 2016a. Impacts of climate change and ocean acidification on coral reef fisheries: An integrated ecological-economic model. Ecol. Econ. AUG 2016 Vol. 128, pages 11 (pp 33-43) 128, 33–43. doi:http://dx.doi.org/10.1016/j.ecolecon.2016.04.012

147. Speers, A.E., Besedin, E.Y., Palardy, J.E., Moore, C., 2016b. Impacts of climate change and ocean acidification on coral reef fisheries: An integrated ecological-economic model. Ecol. Econ. 128, 33–43. doi:10.1016/j.ecolecon.2016.04.012

148. Strong, A.E., Barrientos, C.S., Duda, C., Sapper, J., 1997a. Improved satellite techniques for monitoring coral reef bleaching, in: Proceedings of the 8th International Coral Reef Symposium. pp. 1495–1498.

149. Strong, A.E., Barrientos, C.S., Duda, C., Sapper, J., 1997b. Improved satellite techniques for monitoring coral reef bleaching, in: Proceedings of the 8th International Coral Reef Symposium. pp. 1495–1498.

150. Sumaila, U.R., Lam, V., Le Manach, F., Swartz, W., Pauly, D., 2016. Global fisheries subsidies: An updated estimate. Mar. Policy 69, 189–193. doi:10.1016/j.marpol.2015.12.026

151. Talbot, F., Wilkinson, C., 200 . Coral Reefs, Mangroves and Seagrasses: A sourcebook for managers. Townsville, Australia.

152. Teh, L.S.L., Teh, L.C.L., Sumaila, U.R., 2013. A global estimate of the number of coral reef fishers. PLoS One 8. doi:10.1371/journal.pone.0065397

153. van Wesenbeeck, B.K., Balke, T., van Eijk, P., Tonneijck, F., Siry, H.Y., Rudianto, M.E., Winterwerp, J.C., 2015. Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty. Ocean Coast. Manag. 116, 466–469. doi:10.1016/j.ocecoaman.2015.09.004

154. Wachenfeld, D., 1997. Long-term trends in the status of coral reef-flat benthos–the use of historical photographs, in: State of the Great Barrier Reef World Heritage Area Workshop. Great Barrier Reef Marine Park Authority, Townsville, Australia, pp. 134–148.

155. Whitfield, P., Gardner, T., Vives, S., Gilligan, M., Courtenay Ray, W., Ray, G., Hare, J., 2002. Biological invasion of the Indo-Pacific lionfish Pterois volitans along the Atlantic coast of North America. Mar. Ecol. Prog. Ser. 235, 289–297. doi:10.3354/meps235289

156. Wilkinson, C., 2008. Status of Coral Reefs of the World: 2008. GCRMN, Townsville, Australia.

157. Wilkinson, C., Salvat, B., 2012. Coastal resource degradation in the tropics: Does the tragedy of the commons apply for coral reefs, mangrove forests and seagrass beds.

Mar. Pollut. Bull. 64, 1096–1105. doi:10.1016/j.marpolbul.2012.01.041

158. Wilson, S.K., Fisher, R., Pratchett, M.S., Graham, N.A.J., Dulvy, N.K., Turner, R.A., Cakacaka, A., Polunin, N.V.C., 2010. Habitat degradation and fishing effects on the size structure of coral reef fish communities. Ecol. Appl. 20, 442–451. doi:10.1890/08-2205.1

159. Yahya, F., Parameswaran, A., Ahmed, I., Sebastian, R., 2005. The economic cost of tourism in Maldives. Tour. 53, 33–44.

Figures and legends

Figure 1: (a) Symbiotic dinoflagellates (*Symbiodinium)* from reef-building coral (Allison M Lewis, Creative Commons), (b) Deep water non-symbiotic coral, *Lophelia pertusa* (USGS Public Domain), (c) Annelid worm skeletal borer (Photo: OHG), (d) Bumphead Parrotfish (Flickr: Jenny Huang), (e) Non-carbonate coral reef at Cocos Island, Costa Rica (Photo: OHG), and Carbonate coral reefs at Heron Island (Photo: OHG).

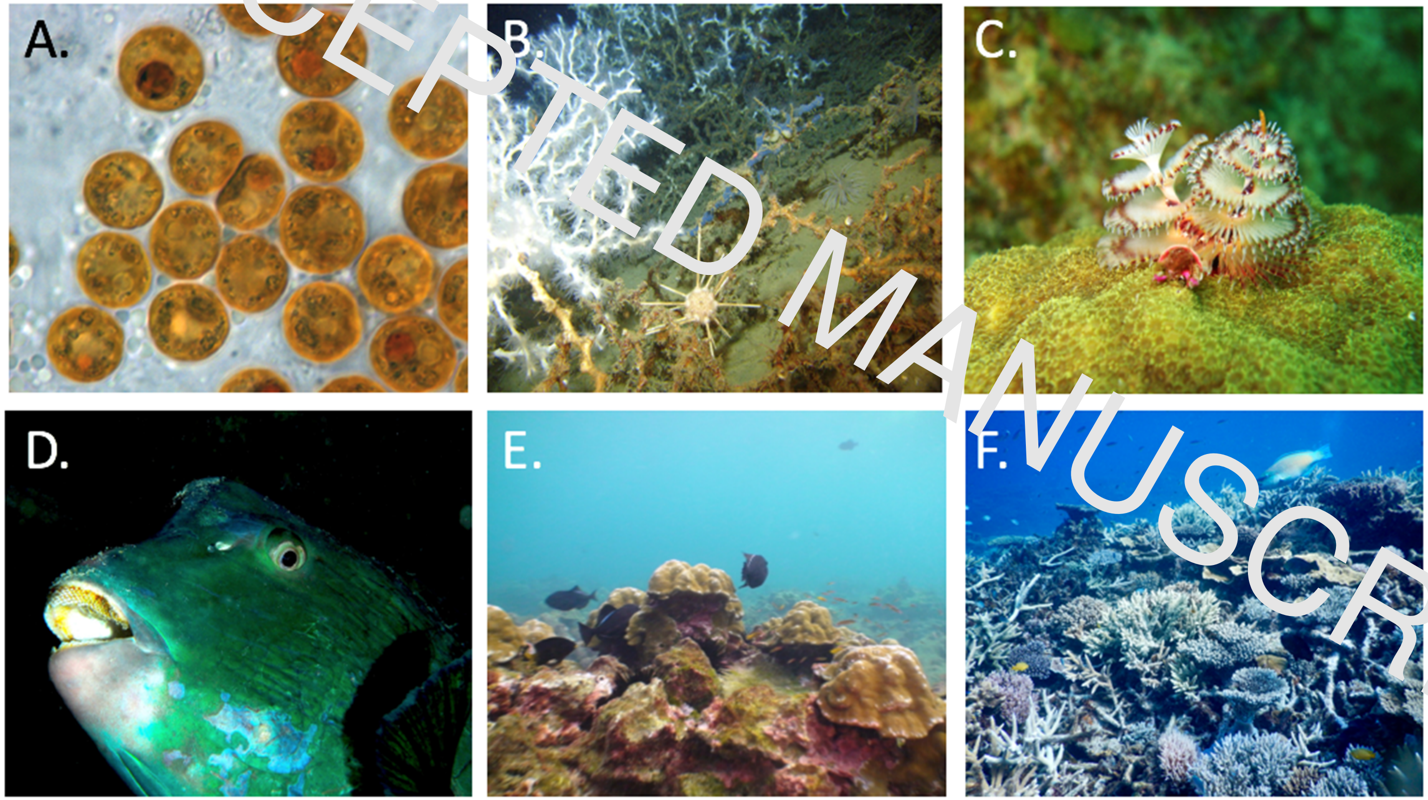


Figure 2. Global map showing selected coral reef carbonate budgets, Related to Figure 1 Values (in blue) indicate estimated net reef carbonate budgets, in kg CaCO3 m-2 year-1; below this is the publication and year. From Figure S1 in Kennedy et al. (2016).

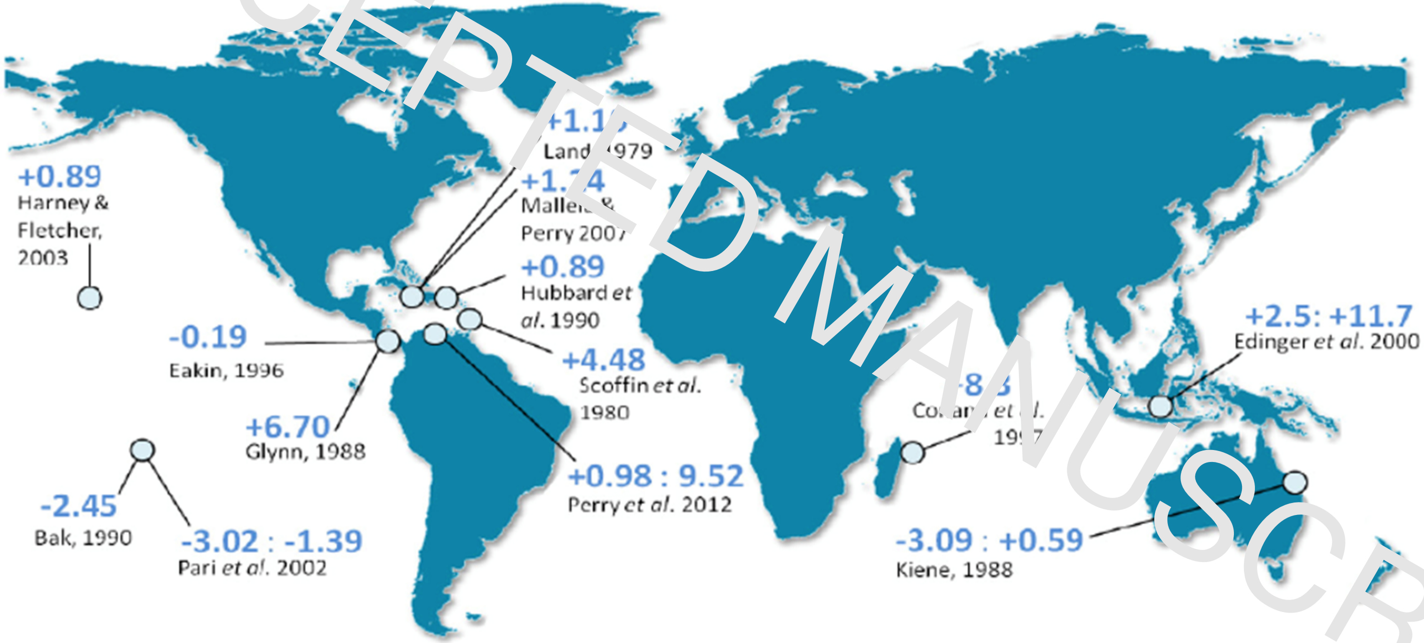


Figure 3. Main actors and relationships in the effect of local and global factors along typical tropical coastal areas involving coral reefs and other ecosystems. From Pendleton et al (2016).

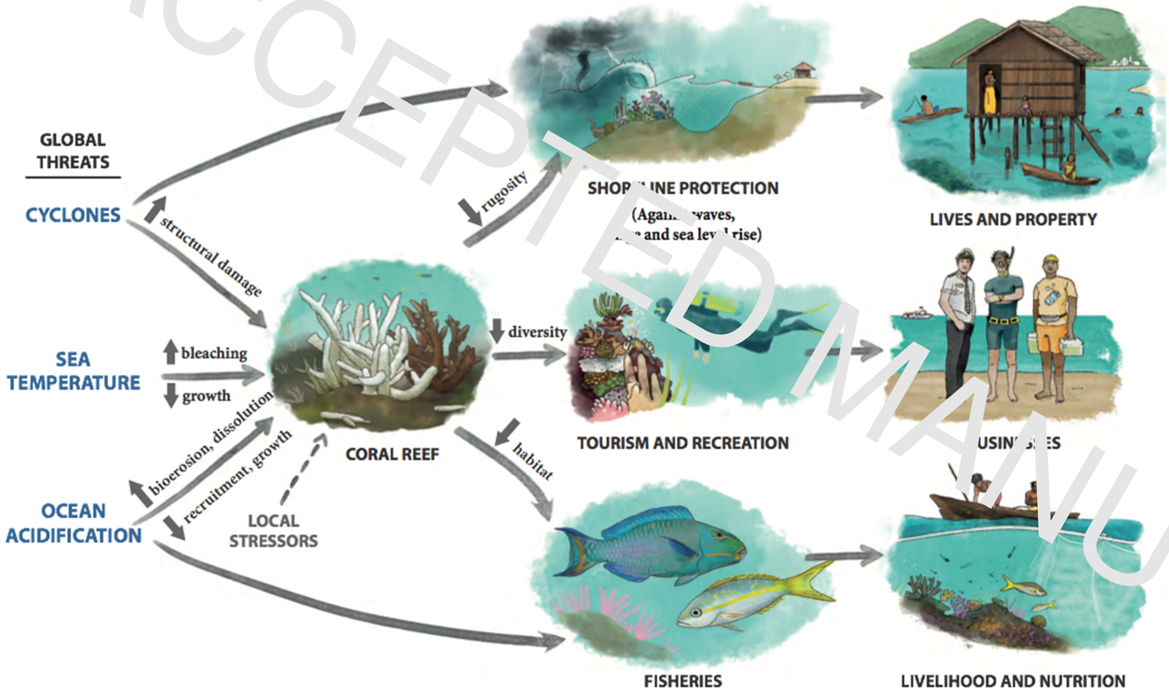


Fig 4. A. Projected concentrations (EPA, US) of CO2 equivalents under different emission scenarios (IPCC AR5, WG I); B. Concentrations of CO2 in the atmosphere and seawater, as well as C. pH (Modified from Doney et al (2006); Land and ocean anomalies in 2016; and D. Bleached coral in May 2016, at Lizard Island on the Great Barrier Reef, with permission of The Ocean Agency.

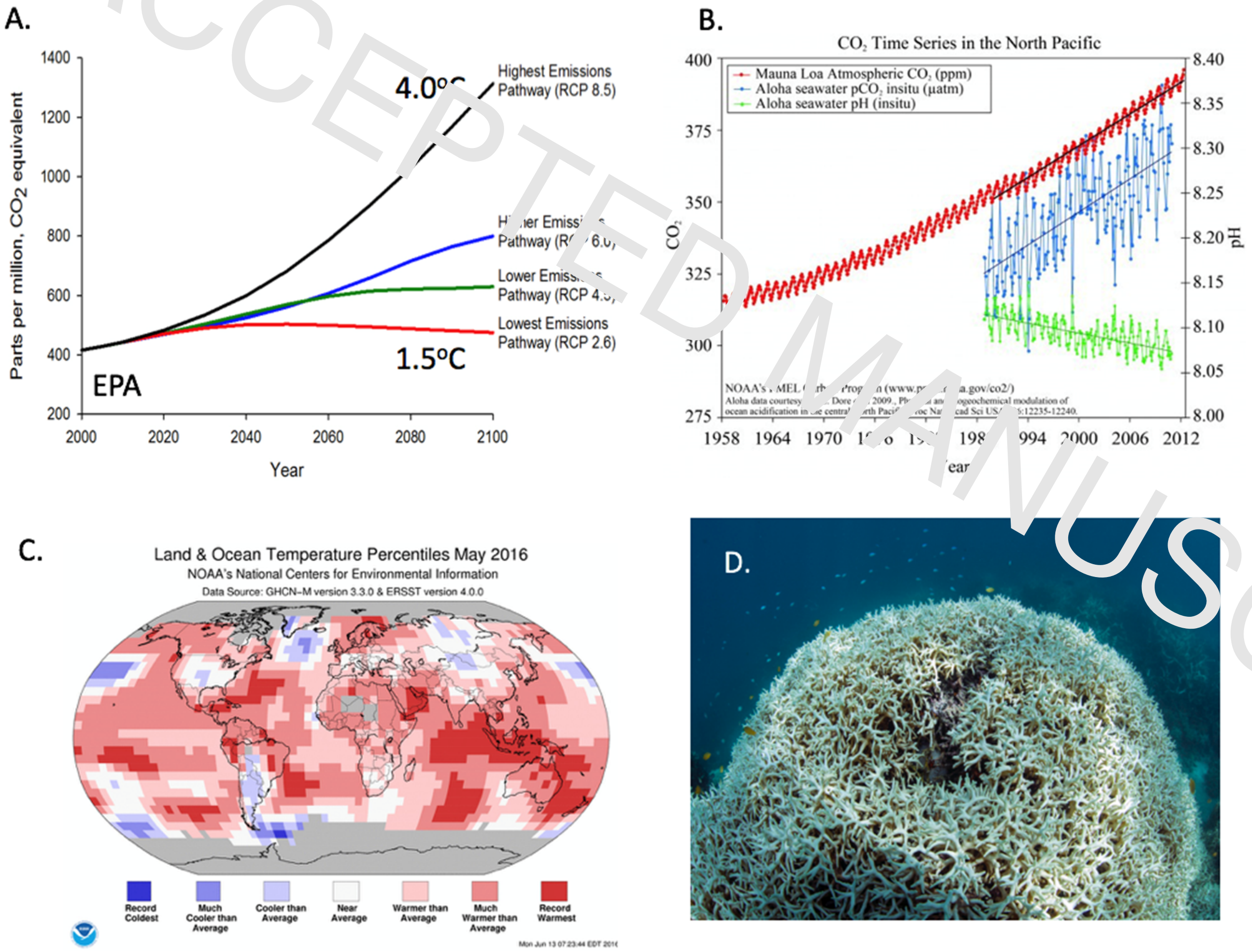
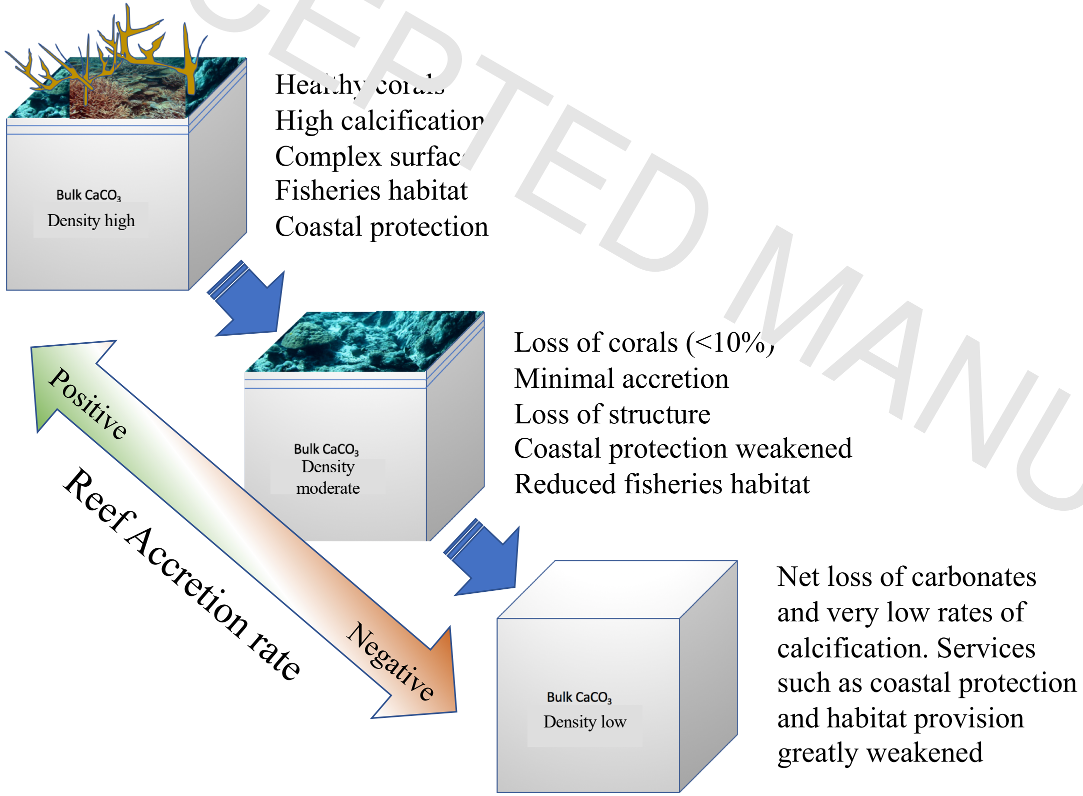
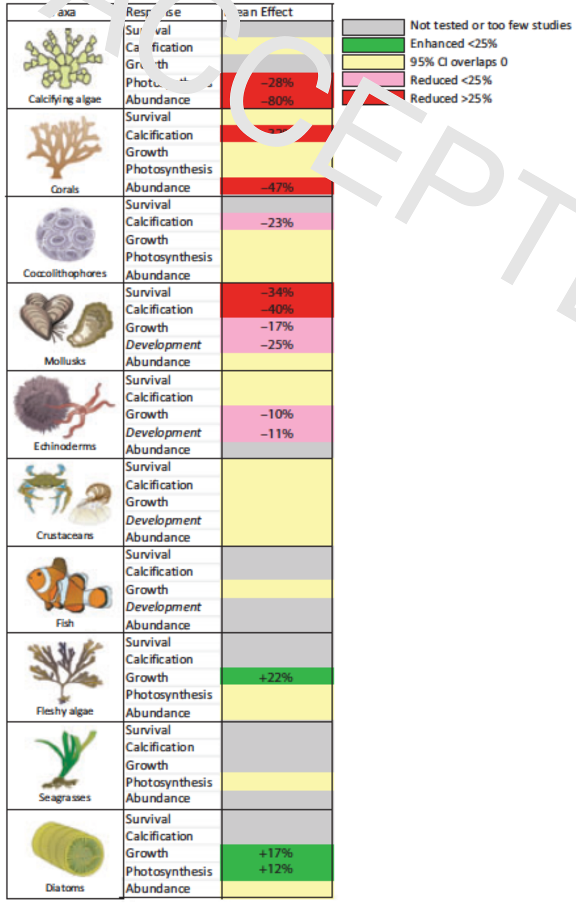


Figure 5. Conceptual diagram illustrating the changes in the characteristics of intact carbonate coral reefs (top left-hand corner) to the bottom right-hand corner. This transition is driven by changes to ocean chemistry and strengthening storms, and depends on the equilibrium between processes (positive net accretion) that lead to calcification versus those that result in decalcification (negative net accretion).



Tables and captions

Table 1. Organisms and process affected by ocean acidification (Kroecker et al. 2013)



Taxa	Response	Mean Effect
Calcifying algae	Survival	⬜
	Calcification	🟨
	Growth	⬜
	Photosynthesis	🟥 −28%
	Abundance	🟥 −80%
Corals	Survival	🟨
	Calcification	🟥 [illegible]
	Growth	🟨
	Photosynthesis	🟨
	Abundance	🟥 −47%
Coccolithophores	Survival	⬜
	Calcification	🟪 −23%
	Growth	🟨
	Photosynthesis	🟨
	Abundance	🟨
Mollusks	Survival	🟥 −34%
	Calcification	🟥 −40%
	Growth	🟪 −17%
	Development	🟪 −25%
	Abundance	🟨
Echinoderms	Survival	🟨
	Calcification	🟨
	Growth	🟪 −10%
	Development	🟪 −11%
	Abundance	⬜
Crustaceans	Survival	🟨
	Calcification	🟨
	Growth	🟨
	Development	🟨
	Abundance	🟨
Fish	Survival	⬜
	Calcification	⬜
	Growth	🟨
	Development	⬜
	Abundance	⬜
Fleshy algae	Survival	⬜
	Calcification	⬜
	Growth	🟩 +22%
	Photosynthesis	🟨
	Abundance	🟨
Seagrasses	Survival	⬜
	Calcification	⬜
	Growth	⬜
	Photosynthesis	🟨
	Abundance	⬜
Diatoms	Survival	⬜
	Calcification	⬜
	Growth	🟩 +17%
	Photosynthesis	🟩 +12%
	Abundance	🟨

⬜ Not tested or too few studies
🟩 Enhanced <25%
🟨 95% CI overlaps 0
🟪 Reduced <25%
🟥 Reduced >25%

Table 2. Fishing jobs and revenue as a function of lost reef productivity

Fishing Revenues and Jobs as a Proportion of Current Output (From Teh et al. 2013 and Pendleton et al. 2016)								
	Current Output		80%		50%		20%	
	revenues from reef fish harvest (million US$)	fisher livelihoods from coral reef fishing, # of fishers (thousands)	revenues from reef fish harvest (million US$)	fisher livelihoods from coral reef fishing, # of fishers (thousands)	revenues from reef fish harvest (million US$)	fisher livelihoods from coral reef fishing, # of fishers (thousands)	revenues from reef fish harvest (million US$)	fisher livelihoods from coral reef fishing, # of fishers i(thousands)
Brazilian Province	180	144	144	116	90	72	36	29
Caribbean	727	277	581	221	363	138	145	55
Central Indian Ocean	169	621	135	497	84	310	34	124
Central Pacific	2	25	1	20	1	13	0	5
Eastern Pacific	17	23	14	18	9	12	3	5
Great Barrier Reef	414	225	331	180	207	113	83	45
Micronesia	12	72	9	58	6	36	2	14
Middle East	669	345	535	276	335	173	134	69
Polynesia	17	85	14	68	9	42	3	17
South East Asia	3768	3972	3014	3177	1884	1986	754	794
Western Australia	46	3	37	2	23	2	9	1
Western Indian Ocean	66	228	53	182	33	114	13	46

Table 3. Low Elevation Population That Depends on Coral Reefs for Shoreline Protection

Ocean Province	Low Elevation Population That Depends on Coral Reefs for Shoreline Protection (Pendleton et al. 2016) – # people in 2007 living less than 10m above sea level and 3 km from a coral reef
Brazilian Province	1,239,637
Caribbean	8,300,897
Central Indian Ocean	5,054,227
Central Pacific	1,536,879
Eastern Pacific	108,616
Great Barrier Reef	1,441,968
Micronesia	407,388
Middle East	6,535,613
Polynesia	809,403
South East Asia	33,187,672
Western Australia	30,990
Western Indian Ocean	4,271,981
Total	62,925,271

Table 4. Reef-related Visitor Expenditure within the ten jurisdictions with the highest total values. Data from Spalding et al. (2017) Table 2 (Spalding et al. 2017). Data retrieved for years 2008-2012 where possible. Local currency data was converted to US$ values for 30 June of relevant year and these values were then converted to 2013 values using the Consumer Price Index (CPI) price deflator.

Country	Proportion of tourism which is coastal, non-urban	Reef-adjacent tourism value (Million US$ per year)	Proportion of reef-coast tourism assigned as on-reef	On-reef tourism value (Million US$ per year)	Total tourism value (Million US$ per year)
Egypt	44%	948	53%	4,520	5,467
Indonesia	29%	1,106	20%	1,991	3,098
Mexico	27%	1,657	9%	1,343	3,000
Thailand	34%	1,332	9%	1,079	2,410
Australia	24%	473	40%	1,703	2,176
China	13%	1,348	2%	88	1,435
Philippines	30%	451	23%	934	1,384
USA (Hawaii)	58%	680	9%	551	1,231
Japan	10%	543	13%	635	1,178
USA (Florida)	11%	851	4%	306	1,157