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Underreported Stories on Climate Change and Coral Reefs in These Times of Diminishing International Reporting: Mining the Scholarly Literature Through Regular Annotated Bibliographies

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by

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By Lucy A. Higgins

Has been approved for Journalism and Mass Communication

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(Sandra Fish)

Date _______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet the acceptable presentation standards of scholarly work in the above mentioned *discipline.*

Lucy A. Higgins (M.A., Mass Communication and Research with a certificate in the Environment, Policy, and Society, School of Journalism and Mass Communication)

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Thesis direction by Bella Mody

ABSTRACT

The goal of this project is to explore solutions to the increasingly difficult challenge of covering international environmental topics, such as coral reefs and climate change, during times of constrained budgets, shrinking environmental reporting, and disappearing foreign news bureaus. In this context of limited resources, this study explores whether the periodic bibliographic review of scholarly literature may offer a low-expense avenue for news organizations to sustain or even increase the breadth and depth of coverage of these important topics. This study compares coverage of coral reefs and climate change in scholarly journal articles (2007-2011) to those in the popular press (2007-2012) using the *New York Times (NYTimes)* as an exemplar of the latter. The extra year in the latter was to allow for a possible time lag in information moving from the scholarly literature to the popular press. Articles on coral reefs and climate change identified in the scholarly literature (239) revealed numerous possibilities for stories that were not covered in the 22 annotated articles on this topic that appeared in the *NYTimes*. Whereas the most frequently discussed topics in the scholarly literature were the

relationship between herbivorous fish and coral health, sea surface temperatures (SST), coral bleaching, and the resilience, recovery, and acclimation processes of coral reef ecosystems, the *NYTimes's* articles focused on conservation, tourism, SST, and broad discussion of climate change and how it might affect coral reef ecosystems. Additionally, of the 22 *NYTimes* articles on coral reefs and climate change, only three (14%) included hyperlinks to scholarly articles and 12 (55%) included at least one scientific reference. Overall, this study demonstrates that during these times of declining resources for on-the-spot reporting, scholarly literature represents an affordable but currently underutilized means for news organizations to continue providing wide ranging and detailed coverage of international environmental issues.

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CHAPTER 1: INTRODUCTION

Coral reef ecosystems are increasingly threatened worldwide by rising sea temperatures and ocean acidification, coupled with other human factors such as sedimentation and pollution, overfishing and destructive fishing, coastal development, and marine pollution and damage (Burke, 2011). At the same time, many US news organizations that could increase awareness and understanding of these threats are downsizing their global operations. For example, Bill Keller (Keller, 2012), the former editor of *the New York Times (NYTimes)*, wrote,

> News organizations began their retreat from the world a long time ago, driven by economics and a wrongheaded belief that Americans don't care that much about foreign news…two years ago 18 American newspapers and two entire newspaper chains had closed every one of their overseas bureaus. Other news outlets, including most TV networks, have downsized or abandoned full-time bureaus in favor of reporters or anchors who parachute in when there's a crisis. They give spurts of coverage…but much less of the ongoing attention that would equip us to see crises coming and understand them when they erupt…Tweets are no substitute for being there… it's possible we miss a layer of an immensely complicated story when we are not (there)… the price we pay for not being where news happens can be reckoned not only in less good journalism, but in less good policy. Because, make no mistake, some portion of the information governments call 'intelligence' is nothing more than an attentive reading of the news.

In January of 2013, the *NYTimes,* Keller's organization, announced that it was dismantling its nine-person environment desk further reducing availability of resources for adequately reporting on these important environmental developments.

Colleges and universities often offer online resources, such as JSTOR, that consolidate scholarly journals, primary sources, and books. Google Scholar also offers readily available scholarly journal articles, many of which can be accessed without a journal subscription. Open databases are becoming more prevalent with the growing debate about whether online journal articles should be free; PLoS (Public Library of Science) is a nonprofit that publishes open-access articles to the public (PLoS, 2013).

Rather than continue to bemoan global environmental threats and shrinking foreign and environmental correspondence, I investigate unreported stories journalists might gain from freely available scholarly literature. Consistent with Thomas E. Patterson's advocacy of knowledge-based journalism, this thesis presents a comparative study of popular press coverage of coral reefs and climate change against coverage in scholarly journal articles over a six-year period, from 2007-201 to benefits that could potentially arise from greater utilization of the scholarly literature in times of declining foreign and environmental correspondence. The purpose of this study is to demonstrate a potential avenue for continuing to provide detailed and accessible information to the public on a global level, despite shrinking foreign and environmental bureaus. It points to reporter-friendly annotated bibliographic research of the scientific literature that may provide a practical strategy for financially strapped news organizations to bolster the breadth and depth of coverage of global environmental impacts. Scientific literature is readily available to writers and news organizations through public libraries and online journals.

The specific focus on coral reefs in this project is based on my own professional interest in this topic. I developed awareness in environmental conservation early on, having grown up in rural northern Vermont where conservation efforts are quite prevalent. This interest was further developed during my time at Brown University, where I majored in environmental studies. During my time at Brown, I completed an internship on The Ocean Project, an organization focused on increasing oceanic conservation awareness by using zoos, aquariums, and museums to educate the public. That was followed by a three-month stay in a Belize study-abroad program, where I was exposed to the biodiversity and natural beauty of coral reefs and a summer in Madagascar where I helped to create a marine protected area off the country's northeastern coast. These educational experiences served to enhance my knowledge of the scientific foundation of coral reefs and threats to their future and instilled a desire to examine important potential future direction in providing appropriate, in-depth news coverage on global environmental challenges.

As discussed in greater detail below, coral reefs worldwide are being impacted by climate change, which is of grave concern as they are important to biodiversity, protection of coastal areas, nurturing of fish species important to commercial fishing, and support tourism and economic development. A recent University of Florida study showed the dependence of decapods (shrimp, lobster, and crab species) on coral reefs, by connecting the sharp decline of coral reefs 150 million years ago to the corresponding decline in decapods (*Geology*, 2013). It is predicted that as much as 20% of coral reefs may collapse within 40 years, which has present-day implications to the survival of decapod species (shrimp, lobster, and crab species), for both biodiversity and as a food source for millions (*Geology*, 2013). Coral reefs and their dependent biota are also highly photogenic and charismatic, allowing journalists to relate climate change impacts to readers's interests (e.g snorkeling, scuba diving). Larger effects of climate change, e.g ocean acidification and sea surface temperature, can be connected to coral reefs to help give attention to a global phenomenon.

While this project offers a thematic approach to better understanding a global topic despite limited foreign correspondence, there are currently other potential solutions to the challenge of diminishing international coverage. Increasingly, academic institutions are stepping in to help meet this need (Zasloff, 2013). These academic resources include The *Harvard Journalist's Resource*, *The New England Center for Investigative Reporting* at Boston University, the *Schuster Institute* at Brandeis, and the *Hechinger Report* at Columbia University (Zasloff, 2013). These brief reports hint at the proliferation of data generated by scholars and industry organizations; they are starting points with a few scholarly articles and helpful information for jouranlists, such as advice on how to read a scholarly article, and why such literature is important to reading. While academic institutions offer at least a partial solution to the decrease in foreign correspondence and science and environmental reporting, topics may need investigating beyond what these institutions provide. This project is advocating for regular reviews of comprehensive online academic databases by news organizations. The scholarly articles made available via academic resources are generally hand selected by the sites' staff, and thus do not represent a systematic search of available knowledge on a subject. In the *Harvard Journalist's Resource,* for example, there is little information available under the topic of coral reefs. A search on their site using the term "coral reef," for example, turned up only a single scientific article (Harvard Journalist's Resource, 2013).[1] Such academic resources for news organizations work well in providing journalists with a starting point for amassing scholarly background material, but they should not be considered an alternative to the strategy of developing and using annotated bibliographic

[1] Coral reefs ecosystems boast high levels of biodiversity and species richness, and are the most diverse marine ecosystem. Coral reef ecosystems also provide a source of food and coastal protection on a global level.

searches on a regular basis (my proposal). Period-specific annotated bibliographies use the scholarly literature to provide a more thorough, detailed characterization of knowledge in a topic area.

Conducted on a regular basis, annotated bibliographies of scholarly literature offer opportunities for news organizations to uncover new topics within a particular field of study and to more fully understand a phenomenon by examining developments and discerning trends over a specific time period. Annotated bibliographies could be utilized by newspaper organizations and freelance journalists to create detailed and varied news stories about important global environmental topics. As reporters or other news staff create annotated bibliographies and update them over time (e.g., yearly), there is potential for developing a library of scientifically supported references for future reporting. My interest is in global environmental coverage: the proposed annotated bibliographies could provide individual reporters and news organizations with a cheap alternative for covering international news without sacrificing in-depth coverage. By examining scholarly journal articles on the topic of climate change and coral reefs over a period of five years and comparing that to the coverage of the same topic in the *NYTimes* over a six-year period (extra year to allow for lag in scholarly information to reach news organizations), the present study proposes that an important next step in providing quality foreign coverage of environmental issues might be right at our fingertips.

CHAPTER 2: LITERATURE REVIEW

This section first introduces the context: the economic problems of news organizations in general and international reporting. It is crucial to understanding the need to expand upon current news sources and topics being discussed by news organizations. The next part focuses on a topic of global ecological significance: the impacts of climate change and the current state of coral reefs.

2.1 The Context: A Reconfiguration of the Media and a Decline in Media Coverage of Climate Change

Mass media serves as a crucial connection between scientific discussion and public knowledge. The public largely gains its scientific understanding via newspapers, television, magazines, radio, and online news (Boykoff and Yulsman, 2013). Newspapers have historically served as a source of accountable information and a means for national conversation and debate (Boykoff and Yulsman, 2013). Despite this, U.S newspapers have been facing disinvestment and declines in newsroom staffing since 2006. Newspaper staffing is as low as it's been in thirty-five years, creating additional travel, monetary, and time constraints on remaining staff (Boykoff and Yulsman, 2013). Cutting costs has also resulted in fewer news organizations, resulting in a handful of organizations influencing media output (Remler, et al; 2013). As newsroom budgets continue to shrink, investigative reporting has taken a turn for the worse. As Boykoff and Yulsman note in their 2013 paper, *Political Economy, Media, and Climate Change: Sinews of Modern Life*:

> A report by the Pew Research Center's Project for Excellence in Journalism (PEJ) found that even by 2008, only 8% of newspaper editors surveyed said their papers had dedicated more resources to covering science since three years prior, whereas 24% said resources dedicated to the topic had declined. The same survey also found that nearly 50% of newspaper editors considered coverage of science and technology to be 'nonessential.' In 2009, a survey in *Nature* of 493 science journalists found that many jobs in that field were being lost; yet, those who remained found that their workloads increased… Another measure of the decline of science coverage in the context of corporate disinvestment in newsrooms has been the decline in the number of dedicated science sections… By 2006, only 34 daily U.S newspapers featured science sections dedicated in some way to science, and those that did often had a concentration on health and lifestyle.

These factors have resulted in oversimplified scientific material (Boykoff and Yulsman, 2013). Reporters are stressed for time and resources: travel budgets are limited, which translates into an increase in second-hand reporting and a heavy reliance on wire copy. As the ways in which reporters cover topics such as climate change increasingly face budget contraints, certain news organizations have adapted. *The NYTimes* rid itself of its environmental desk and its *Green Blog* in an effort to integrate environmental issues through out the paper. Nonprofit academic resources are also adapting; sources such as the *Harvard Journalist's Resource* select articles that aim to provide reporters with accessible and intellectual information.

Nonetheless, there has been a significant change in the ways in which climate change specificially is being reported. For a brief period in U.S newspaper history, there was a dramatic increase in climate change coverage: climate change articles rose from roughly 20 articles per month in 2004 to around 100 articles per month in 2007 (Boykoff and Yulsman, 2013). During this time period, 2005 was the hottest year on record and the Intergovernmental Panel on Climate Change (IPCC) had released two reports and an assessment report (Boykoff and Yulsman, 2013). These environmental and political events did not have long-lasting effects: in 2007 the economic recession began shrinking budgets, and climate change stories began to diminish as well (Boykoff and Yulsman, 2013). Specific environmental issues, such as coral reef ecosystems, also still remain minor news stories, if mentioned at all (Boykoff and Yulsman, 2013). Issues become oversimplified and disorted by skewed debates. If it is the job of the reporter to move beyond the biases, simplification, and budget constraints of the 21st century, it will require knowledge of covering nuanced topics and of science itself (Boykoff and Yulsman, 2013).

News organizations are facing increasing difficulties in knowledge-based reporting, and meanwhile academia is perhaps not presenting its research in accessible language (Remler, et al; 2013). While journalism may not dedicate enough time and newspaper space to complex topics, academia is often high inaccessible (Remler, et al; 2013). Academics generally write for specific audiences, and in doing so rely heavily on jargon and complex explanations to new ideas (Remler, et al; 2013). When this is coupled with time and budget-stressed reporters, news stories become increasingly oversimplified, or important topics or disregarded altogether.

As the newspaper model evolves from paper-based organizations to an online media resource, foreign bureaus have dropped dramatically. A report conducted by the *American Journalism Review* in 2011, for example, found that the number of full-time correspondents employed by U.S newspapers declined steeply since 2003 (Martin, 2012). Despite this steep decline, news organizations still present themselves as global news organizations, while often only assigning one foreign correspondent to an entire bureau (Martin, 2012). Twenty American papers and companies have cut their foreign bureaus since the first *American Journalism Review* was conducted on foreign correspondents in 1998 (Kumar, 2011).

Reliance on printing wire service copy does not “allow for alternate views of the news” (Fitzgerald, 2009). Researchers have long advocated for the use of non-official sources to encourage a diversity of ideas. Hansen (1991), for example, noted that stories that won Pulitzer or other enterprise journalism awards were less likely to use official sources and more likely to mine documentary sources compared to usual stories. Unfortunately, Stephen Hess’ (1981) well-regarded study of Washington reporters found no documentary sources in almost three quarters of the stories examined. That practice appears to be continuing. For example, Mody’s (2010) study of coverage of genocide in Sudan by ten news organizations (including the BBC and *The NYTimes*) found minimal in-depth attention to causes of the conflict across news organizations, missing the opportunity for explanatory and potentially preventive journalism. In *Educating Journalism Students to do Comprehensive Reporting* (2011), Mody advocated educating journalists in research skills to enable them to study what has been published on an issue before doing any reporting. This direction is consistent with Harvard University’s publication of the *Journalist’s Resource* launched to assist news organizations with background research on today’s news stories. The annotated bibliographic strategy being examined in the present study takes this further.

2.2 The Decrease in Foreign Correspondents

Many challenges of global ecological significance, such as climate change and its impact on coral reef ecosystems are found in tropical regions, often an expensive plane ride away for news organizations in the global North. The shrinking presence of foreign correspondents could leave immense gaps in public knowledge on such important topics. Reporters can function as a link between the world of scientific academia and the public on these important matters. In the United States, public scientific literacy is relatively high (Raloff, 2010). Despite falling behind European and other industrialized countries in many aspects of educational achievement, the United States scores well in scientific literacy, trailing only Sweden and surpassing Denmark, Finland, Norway, and the Netherlands (Miller, 2007; cited in Raloff, 2010). While it is still only about 28% of the United States public who are judged to be scientifically literate, that relatively high rate is attributed to the practice of requiring general education courses in the sciences as part of standard undergraduate education. Importantly, this suggests that the general readership of mainstream newspapers like the *NYTimes* can handle detailed or in-depth environmental news coverage. Unfortunately, trends in the mainstream press raise questions about how much this opportunity is being leveraged. For example, the *NYTimes* killed its *Green Blog* in early 2013, after discontinuing its environmental desk less than two months prior, as was mentioned above (Hein, 2013). On a positive note, the *NYTimes* did keep its prestigious weekly Science section. Claiming budget cuts as the reasons for both the *Green Blog's* and the environmental desk's demise, it should not go unmentioned that the *NYTimes* has nevertheless maintained its blogs for the Red Carpet, Baby Boomers, and multiple sports blogs (The New York Times, 2013; Hein, 2013). The stated purpose behind elimination of the *Green Blog* and environmental desk was to also disperse environmental coverage throughout the paper, instead of congregating it into a few sections. This is contrary to the design of topic-specific and page-specific packages of news on a topic that is the current practice. The upcoming years will suggest whether this tactic is successful, or whether scientific and environmental news will be minimized both in terms of coverage of global as well as regional and local issues. As news organizations continue to shift into becoming online media resources, blogging may continue to become more prestigious. Already, talented journalists, such as Andy Revkin of the *NYTimes DotEarth* blog, are contributing valuable, edited pieces of journalism to news organizations.

For reporters to effectively share scientific knowledge, they must first have a firm grasp on the language and construction of scientific data (White, 2013). Given that reporters often must cover a variety of stories, even within a “science” or “environmental” beat, it is likely that they will run into required knowledge that goes beyond their experience (White, 2013). As this may be the case with reporting on topics such as climate change and coral reefs, maintaining an up-to-date annotated literature review offers a tactic whereby reporters and news organizations can amass enough scientific articles to provide an in-depth background understanding of a topic, before reporting on it.

If serious scholarship and serious journalism go hand-in-hand, then it is imperative that journalism make use of the breadth of scientific literature being published on environmental issues, especially with funding for foreign correspondence and environmental and other scientific news coverage decreasing. Annotative literature reviews, such as on climate change and coral reefs as illustrated in the present study, has the potential to promote broader and more in-depth coverage of important and timely global environmental topics.

2.3 Overview on Coral Reefs and the Impact of Climate Change

For the purpose of this paper, coral reef ecosystems and the impact of climate change are important in highlighting an international topic that is nuanced and affects a large portion of the world's population. Coral reef ecosystems are the most diverse marine ecosystem and are also the largest shore structures created by plants and animals (Anthony, 2009). They boast high levels of biodiversity and species richness, which is often the result of symbiotic relationships between the coral invertebrate species that comprise coral reefs and countless reef organisms (Stella, et al., 2010). In a recent study that measured the diversity and community structure among various coral species, a single coral colony that had a mere 20-centimeter diameter hosted 73 individuals and 24 species (Stella, et al., 2010). Different coral species are able to host varying assemblages of species, and are thought to harbor potential specialist species (Stella, et al., 2010). In addition to abundant biodiversity and species richness in coral reef ecosystems, there are approximately 500 million people who are reef dependent vis-à-vis activities ranging from fishing to tourism (Cinner et al, 2009; Hoegh-Guldberg, 2011); the highest rates of dependence are in Southeast Asia, the Indian Ocean, and the Atlantic (Burke, 2011).

The conservation of coral reef ecosystems is imperative as evident in the abundance of species, including humans, who rely on coral reefs for survival. Unfortunately, although reef ecosystems boast high productivity, biodiversity, and species richness, they are also easily overexploited by local and global factors and require management and mitigation to achieve a sustainable yield (Hodgson, 1997). The largest and most pressing concern regarding the conservation of coral reefs is their high sensitivity to climate change, although this differs by susceptibility, resilience, and region (Baker, 2008; Barshis, et al, 2010).

Coral reefs react negatively to rising sea temperatures and ocean acidification that are the result of rising carbon dioxide in the ocean, and the rate of degradation is exacerbated by concurrent local pressures, such as overfishing, pollution, and sedimentation (Anthony, et al., 2011). As an outcome of rising sea surface temperatures, reefs are experiencing mass coral bleaching, which occurs when the symbiotic relationship between corals and zooxanthellae, a type of algae, is disrupted. The zooxanthellae are expelled from the coral host, leading to photosynthetic pigment loss, hence the term "bleaching" (Jokiel, 2004). This is fatal if the symbiotic relationship is not quickly restored, and that can only occur if sea surface temperatures do not remain at the elevated levels it took to produce bleaching (Crabbe, 2008; Jones, 2008). Mass bleaching events are occurring with increasing frequency and across a growing geographic distribution (Jokiel, 2004). There are differences in coral sensitivity, yet since the 1980s mass coral bleaching has occurred in almost every coral reef throughout the world (Hoegh-Guldberg and Hutchings, 2009).

Ocean acidification is the other main natural occurrence that is disrupting the functioning of coral reefs. With the increase of carbon dioxide (CO_2) released into the atmosphere, the ocean sequesters increasing amounts of this compound. Coral reefs are unable to survive in atmospheric concentrations greater than 450 parts per million (ppm) (Hoegh-Guldberg and Hutchings, 2009). With greater concentrations of CO_2 in water, corals undergo calcification and are unable to survive (Hoegh-Guldberg and Hutchings, 2009).

Rising sea surface temperatures and ocean acidification are processes that occur naturally but are exacerbated by an increase of greenhouse gases in the atmosphere. Indeed, global climate change is the main contributor to declines in coral cover, and this is occurring at rates that have not been previously geologically recorded (Lesser, 2011).

In addition to the unprecedented rates of coral mortality due to rising sea surface temperatures and ocean acidification, stressors on local and regional spatial scales are also contributing to declining coral reef health. Human impacts on coral reefs have been a concern for decades, especially overfishing and pollution. Additional human factors include sedimentation and coastal development (Burke, 2011).

The discussion surrounding coral reefs and the impacts of climate change is complex and constantly evolving. As news organizations face increasing financial decline and a decrease in foreign correspondents, annotated bibliographies serve as a cost-effective tool that does not compromise, and may in fact increase, the complexity and depth of reporting on this dynamic topic.

CHAPTER 3: METHODS

The purpose of this thesis is to conduct a comparison between the coverage of climate change and coral reefs in the scholarly literature and the popular press. To keep the scope of the effort to something that could be managed as part of an MA thesis, the review of the scholarly journal articles has been limited to five years (2007-2011) and the coverage of the mainstream press has been limited to one high-impact newspaper (*NYTimes)*, and a six-year period (2007-2012). The extra year included in the review of *NYTimes* articles is to account for any time lapse that might occur between publication of scholarly literature and its review by news organizations for publication in the popular press.

3.1 The Time Period

The starting date for the literature covered in the present study is January 1, 2007. In 2007, the Intergovernmental Panel on Climate Change (IPCC) released its fourth assessment report on climate change, which aimed to provide a work of reference for policymakers, scientists, and other experts and students (IPCC, 2007). The release of the IPCC was expected to be a contributing factor to publications in both the scholarly literature and popular press regarding the topic of climate change and its impact on coral reefs.

3.2 Scholarly databases

The databases GREENR and Web of Science were selected to access scholarly journal articles. GREENR is a global database specifically for topics touching on the environment, energy, and natural resources. The advanced search option in GREENR was employed to identify peer-reviewed articles for this project's specific topic. The search focused on articles that were published between the years 2007 to 2011, using the search terms "climate change" and "coral reefs." This process generated four articles. Of the four articles, three were relevant to this particular study; the fourth was based on the impact of climate change on sea turtle nesting sites.

The Web-of-Science is an online, subscription-based citation indexing service that gives access to multiple databases and disciplines. The specified search terms were again "climate change" and "coral reef," as was the case with GREENR, and the time period was again 2007-2011. This search identified 336 peer-reviewed articles. I then reviewed the abstract or introduction of each article identified in the search to affirm that they addressed climate change and coral reefs. That revealed 236 articles that pertained to the overall topic of climate change and coral reefs.

After saving the combined 239 articles in the *Refworks* bibliographic software, I was able to prepare a citation list for each article in the widely used format of the American Psychological Association (APA). Next, each article was annotated on the following dimensions: summary, researchable questions, research method, findings, and quotable quotes. The purpose of annotating the literature was to make the findings of each article accessible in an efficient reporter-friendly manner and to also facilitate comparisons to articles that appeared in the popular press. With the abolition of foreign beats and environmental desks, compiling the data sources in this manner permits reporters to be assigned to this topic without any background scholarly work.

3.3 The Popular Press: *The New York Times* as an Exemplar

After the scholarly literature was annotated, focus was then directed to the popular press. As noted earlier, this study focuses specifically on the *NYTimes*, as opposed to including other news organizations that are also generally considered to be major "popular press" organizations as well (e.g., *USA Today*, *Washington Post*, *Wall Street Journal*). After carefully considering including these other news organizations in the study, I decided against it due in part to the relatively small number of relevant articles appearing in these outlets. Searching the *USA Today*'s website for articles that discussed coral reefs between 2007 and 2012, for example, yielded only two articles discussing coral reefs (*USA Today*, 2013). A search of *USA Today* articles published in 2013 identified seven articles on coral reefs. While this increase in 2013 represents a potentially promising direction for more coral reef coverage, it did not change the fact that only two articles were identified within the relevant time period of the present study (2007-2012), making it difficult to compare to the breadth of coverage in the scholarly literature. Likewise, a search of *the Wall Street Journal* turned up only five articles that pertained to coral reefs, although their coverage of climate change was quite extensive, resulting in identifying 252 articles turned up in the search. Unfortunately, these articles did not go into any detail about the effects of climate change on coral reefs. *The Washington Post* had more to offer on the topics of climate change and coral reefs, with

22 articles published between 2007 and 2012 mentioning climate change and coral reefs, although many were not sufficiently focused on this topic area to be relevant to the present study. Despite this relatively high number, *the NYTimes* was clearly the news organization that produced the largest number of articles on this topic, and was thus selected to be the focus of this study. A search in Lexus Nexus Academic identified 44 articles published in the *NYTimes* that mentioned both climate change and coral reefs. Among those 44 articles, 22 went beyond simply mentioning coral reefs to discuss a topic within coral reefs and climate change. It is worth mentioning that these searches covered all sections of each newspaper. In addition to being part of the popular press, the *NYTimes* is also responsible for setting the agenda for other news media. Their national and global influence also sets the *NYTimes* apart as a worthy news organization to focus this study on.

While the present study focused only on *articles* that appeared in the *NYTimes*, it is important to note that during the time period covered by this study, there was a high volume of blogging conducted by the *NYTimes* staff on climate change and effects on coral reefs. Highly educated and prolific writers, such as Andy Revkin, provided high quality journalism that discussed a variety of topics within the broad scope of climate change and coral reefs. Blog posts were excluded from the present study because they only appeared online, and although they were informative and well written, they are opinion columns, rather than edited and institutionally sanctioned reports of the news organization. Often, the *NYTimes* places one writer as the forerunner for an entire blog, such as Andy Revkin's *DotEarth* and Nate Silver's *FiveThirtyEight* Blog. This is not to detract from the value that these blog postings provide, but what they do differs from the supervised and less opinionated reporting of the news organization.

As with the articles from the scholarly literature discussed above, the *NYTime*s articles were put into *Refworks*, thereby producing a list of citations in APA style, with which I was then able to create an annotated bibliography, included in Appendix C. Annotation addresses these specific topics: a summary of the article, any notable quotes, the number of pages, scholarly citations or hyperlinks within the articles, scientific sources or scientists cited, and themes that the articles focused on within the overarching category of climate change and coral reefs.

Upon completing annotation of the articles from the two literatures, an Excel table was created to compare the various topics that were included. Topics (e.g., ocean acidification, fish and herbivory, and coral bleaching) were identified based on the title, abstract, questions the article aimed to answer, and findings of each article. Next, the frequency of topics discussed in the scholarly literature and the popular press were quantified by year and compared to deduce any gaps or similarities across them.

CHAPTER 4: RESULTS

This section is divided into three parts. The first section discusses the topics covered in the scholarly literature. The second section addresses the *NYTimes* coverage of climate change and coral reefs, and the third section compares the coverage in the scholarly literature to that in the *NYTimes*.

4.1 Topics Covered in the Scholarly Literature

The goal of this section is to characterize how the scholarly literature discussed climate change and coral reefs. It highlights what was discussed and the frequency at which the various topics were discussed during the study period. A review of the 239 articles identified in the search of *GREENR* and *Web of Science* revealed coverage of approximately 34 different aspects of the general topic of climate change and coral reefs. Appendix A shows a complete list of the topics covered, including: coral reef resilience; ocean acidification; coral bleaching; rising SST; the relationship between herbivorous fish and coral reefs and climate change; species predation and/or domination; the symbiotic relationship between coral and algae; broad ecosystem and climate change discussion; scientists' perspectives; modeling; historical analysis; habitat loss and fragmentation; policy involvement and implications; phase and regime shifts; local stressors and socio-economic impacts; disease; calcification; hydrodynamics; water quality; storms; marine reserves and conservation; biodiversity; coral mortality and productivity; future predictions and long-term impacts; plasticity; reproduction; algae blooms; and tourism. Topics also included the following case studies: The Great Barrier

Reef and Australia at large; the Caribbean and Atlantic; Indo-Pacific and the South Pacific; the U.S (including Hawaii); and the Red Sea.

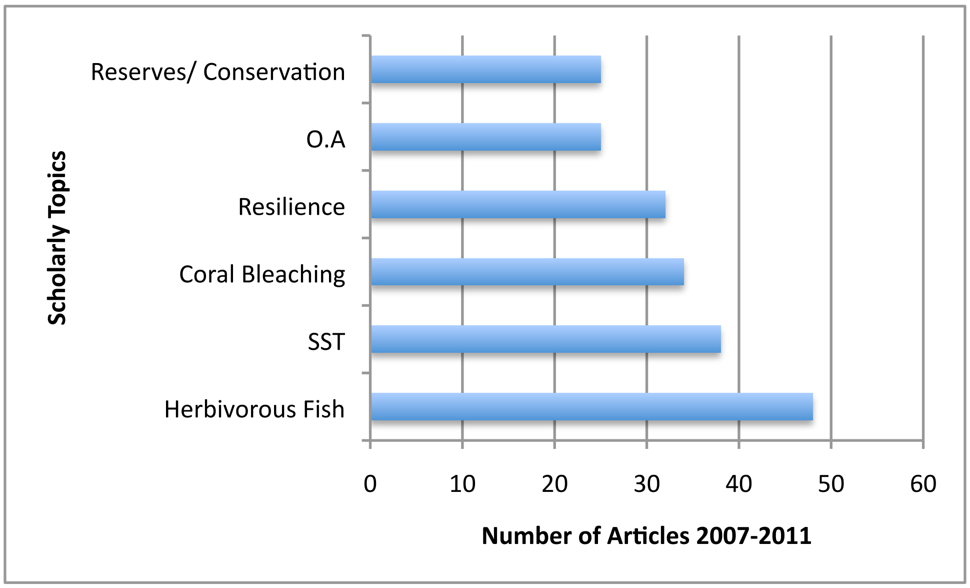

FIGURE 1. Most commonly published topics (the relationship between herbivorous coral reef fish and climate change, sea surface temperatures, coral bleaching, the resilience and/or recovery process of coral reef ecosystems, and ocean acidification and marine reserves and/or conservation efforts) in the scholarly literature between the years 2007-2011.

Figure 1 shows the majority of these articles fall into six topic areas. Herbivorous coral reef fish and their role in coral reef ecosystems during climate change was the most frequent (48/239 (20%)). This was followed by sea surface temperature, with 38 mentions in 239 articles (16%). The third most frequent mention was coral bleaching, with 34 mentions in 239 articles (14%). The fourth most frequent mention was coral reef resilience, with 32 mentions in 239 articles (13%). The fifth and sixth most frequent mentions were ocean acidification and marine reserve/conservation, with 25 mentions in 239 articles (10%).

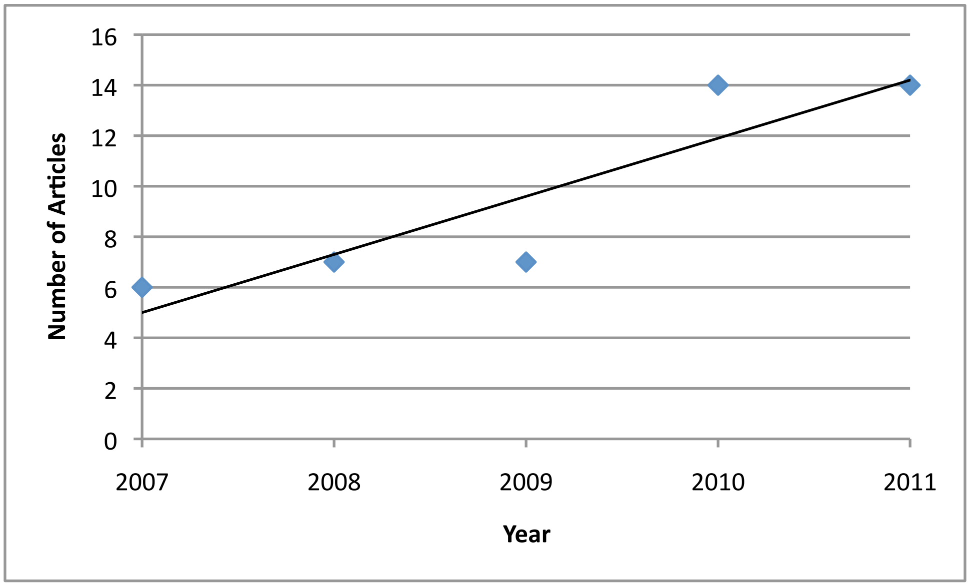

FIGURE 2. An increasing trend of scholarly journal articles that discuss the topic of herbivorous coral reef fish between the years 2007-2011.

4.1.1 Herbivorous Fish and Coral Reefs

The topic of herbivorous fish and coral reefs had an increasing trend across years, with 28 of those 48 (58%) articles appearing in 2010 and 2011, suggesting that this is likely to remain a topic of considerable interest (Figure 2). This strong focus on herbivorous fish is understandable as they are crucial to coral reef health and resilience. When there are large-scale disturbances, as with climate change, coral reefs tend to shift from coral-dominated to macroalage-dominated ecosystems (Adam, et al.; 2011). A consequence of the declining health of corals is an increase in algae cover. Herbivorous fish can be key actors in curbing algae cover and maintaining reefs in a coral-dominated state, thereby supporting structural complexity within a region and reef-fish species richness (Graham, et al.; 2008). Herbivorous fish graze on algae, which creates space for invertebrate larval settlement (Graham, et al.; 2008). After a disturbance, herbivory is the primary driver in controlling algal communities, and thus aiding coral reef ecosystem resilience (Green and Bellwood, 2009). Resilience can be defined as the ability of an ecosystem "to maintain its key ecological functions and processes after disturbances by either resisting or adapting to change" (Green and Bellwood, 2009).

Different functional groups of herbivorous fish can have varying effects on coral reef ecosystems depending on how they consume algae (Ceccarelli, et al., 2011). Certain types of algae are more damaging to coral survival and regeneration than others; thick turfs and "fleshy microalgae" are especially detrimental to corals after a disturbance (Ceccarelli, et al., 2011). There are generally two types of herbivorous fish: "foragers," such as parrotfish, that traverse over large areas, and "farmers," which include damselfish, that primarily guard their territory against foragers and consume the algae within the protected area (Ceccarelli, et al., 2011). Farmers have a different and more dramatic effect on algae and coral reef ecosystems than foragers, with the capacity to suppress the growth of fleshy algae completely (Ceccarelli, et al., 2011). Farmers manipulate their surrounding algae environment, given their dietary preferences and the availability of food algae in the nearby environment (Ceccarelli, et al., 2011). As coral reef ecosystems undergo environmental disruption as a result of climate change, farmer herbivores will be key to ensuring coral reef resilience. This is especially interesting when considering the anthropogenic local impacts to coral reefs, such as overfishing and sedimentation, and how that may impact the coral reef fish populations.

Just as herbivorous fish impact the health of coral reef ecosystems, the ecosystem, and any disruptions to it, can in turn influence the abundance and species richness of coral-associated reef fish (Bonin, et al, 2011). Interestingly, a recent experimental study conducted by Bonin, et al. (2011) suggested that there are positive effects of coral reef fragmentation on certain coral reef fish species. Bonin et al. examined the potential independent and interactive effects of habitat loss versus fragmentation on survival, abundance, and species richness. The results showed a negative impact of habitat loss on survival of key fish such as damselfish and species richness but a positive effect of fragmentation. Hypotheses as to why this difference occurred included a reduced interference competition from other species on the damselfish with fragmentation, as well as differences in predator distribution between fragmented and non-fragmented coral reefs. Unfortunately, the positive impact of fragmentation waned over several months while the negative impact of habitat loss worsened with time. Nevertheless, this study presents a twist to the typically adverse consequences of climate change habitat disruptions and at a minimum illustrates the complexities involved in habitat disruptions; there may be species, such as the damselfish, that can derive at least some time-limited benefit from habitat disruptions. Studies such as this offer an interesting and complex angle for news coverage, as they could potentially add nuanced information into the public dialogue.

4.1.2 Sea Surface Temperature, Thermal Stress, and Rising Sea Level

While the scholarly literature from 2007 to 2011 discussed the topic of herbivory and its relationship with coral reef ecosystems most frequently, the literature also had a high count of articles (38/239 or 16%) addressing the related topics of rising sea surface temperature (SST), thermal stress, and rising sea level--these three sub-categories were included under the same heading in Appendix B, given their interconnectivity. As sea temperatures rise, so do sea levels: an increase in sea temperatures can result in glacier melt, thus raising sea levels and creating thermal stress on various ocean ecosystems, including coral reefs. As was the case with the topic of herbivorous fish and coral reef in the scholarly literature, there has been an increase in the number of publications dedicated to SST, thermal stress, and sea level rise.

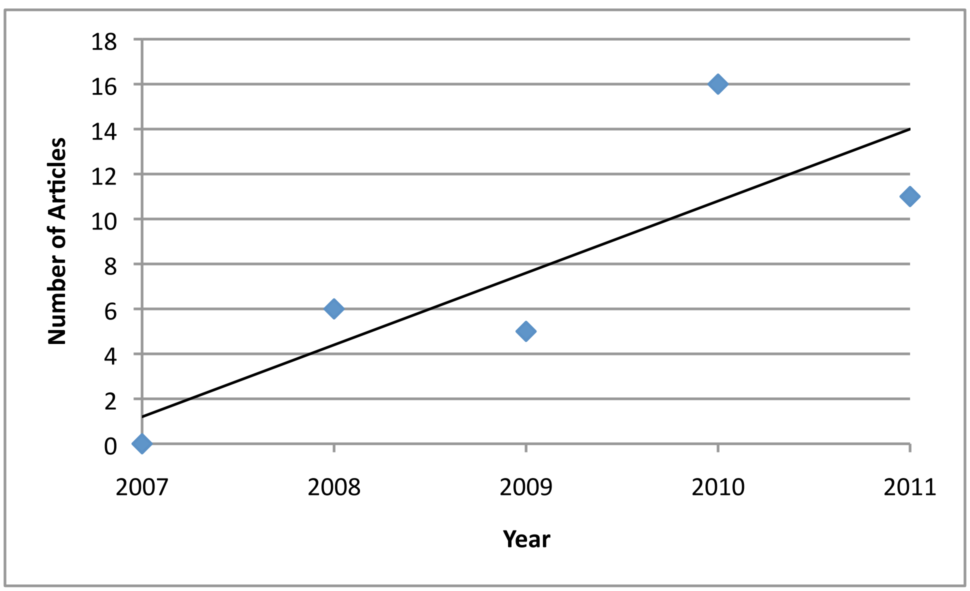

FIGURE 3. Scholarly journal articles that discussed sea surface temperature, thermal stress, and rising sea levels 2007-2011.

This is evident in Figure 3, which shows that between 2007-2009 there were 11 articles dedicated to SST, sea level rise, and thermal stress while in 2010 and 2011 there were 27 articles devoted to that topic area. This increasing trend suggests that this topic is also likely to remain a topic of considerable interest.

The growth and health of coral reefs are adversely impacted by multiple factors, including sedimentation, turbidity, temperature, and overfishing, and changes to these processes affect how well corals calcify and survive (Crabbe, 2008). Currently, coral reefs are under pressure from all of these factors, and temperature increase is occurring on a global scale (Crabbe, 2008). The ability for corals to calcify and extend has been correlated strongly with rising SST (Crabbe, 2008). SST is a main environmental component in coral growth (De'ath, et al., 2009), and it increases as a positive function of increasing atmospheric greenhouse gas concentrations (Klyepas, et al., 2008). One of the most important outcomes of SST on coral reefs is coral bleaching (Donner, 2011).

4.1.3 Coral Bleaching

Coral bleaching was the third most frequent topic covered, with 34 of the 239 (14%) annotated articles discussing the impact of bleaching on reef ecosystems. There were no discernible increasing or decreasing trends in coverage of this topic across the 5-year study period. Coral bleaching occurs when a host coral is no longer able to maintain a symbiotic relationship with dinoflaggellates (a type of zooxanthellae), which typically survive within coral tissue (Donner, 2011). Coral bleaching is generally expected to occur when SST increases by 1˚C above an average summer temperature for more than one month (Donner, 2011; and Hoegh-Guldberg, 2009). The maximum SSTs in the ocean should not exceed 30˚ to 31˚C, as has been supported through theory and direct observation (Kleypas, et al., 2009). The Intergovernmental Panel on Climate Change has predicted that there will be an increase of SST by at least 2˚C in the 21st century

(Spillman, 2011). This is expected to have a substantial detrimental effect on coral reefs, pushing them over their threshold and resulting in an increase in bleaching and further compromising of their ability to recover from disturbances (Spillman, 2011). Coral bleaching has been an ongoing problem since the 1980's in the tropic and sub-tropic seas (Baker, et al., 2008). Baker, et al. note that bleaching is "episodic, with the most severe events typically accompanying coupled ocean-atmosphere phenomena, such as the El Nino-Southern Oscillation (ENSO)" (Baker, et al., 2008). The recovery of coral reefs after a bleaching event varies by region, and is contingent upon multiple factors. Coral reef survival hinges upon how much coral was lost, and which species were exterminated (Baker, et al., 2008). It is important to note the ability of the remaining corals to adapt and/or acclimatize to higher temperatures (Baker, et al., 2008). Thermal bleaching occurs when corals are exposed to abnormal temperatures, which require additional energy from corals and reduce coral biomass (Crabbe, 2008). Coral recovery also depends on other factors of ecosystem resilience, such as herbivory and coral recruitment. That is, the various processes of coral survival and adaptation to climate change overlap.

4.1.4 Coral Reef Resilience and Recovery

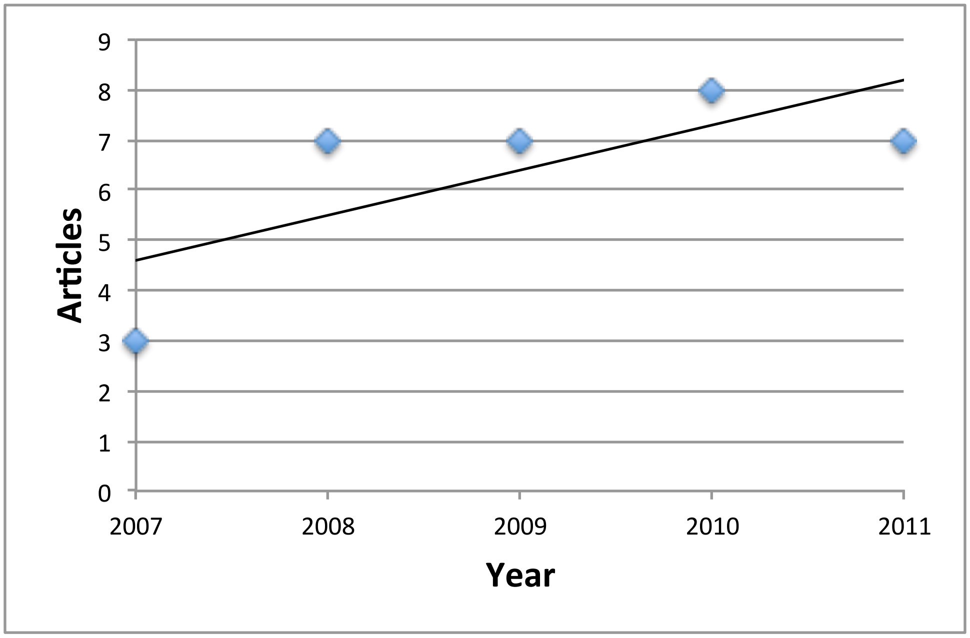

FIGURE 4. An increasing trend in scholarly journal articles on coral reef resilience, recovery and acclimation between the years 2007 and 2011.

Coral reef resilience, recovery, and acclimation were often discussed in papers that went into detail about coral bleaching and represented the fourth most frequent topic covered. Figure 4 shows 32 (13%) of the 239 annotated articles involved the response of corals to negative climate impacts, with a relatively steady trend of publication after an initial increase of articles from 2007 to 2011. Coral reef resilience, or the "capacity …to absorb disturbance without shifting to an alternative state and losing function and services," (Cote and Darling, 2010), is impacted by both global and local factors (Anthony, et al., 2011). Coral reefs that are already facing herbivore overfishing and nutrification are more likely to be impacted by climate change (Anthony, et al., 2011).

Although local factors may influence the resilience of coral reefs, this is not to say that reducing local stressors will eliminate climate change impacts, but it can bolster coral reef resilience between climate disturbances (Cote and Darling, 2010). Marine reserves may help in this process, as they have shown higher coral recruitment and coral species diversity (Cote and Darling, 2010). Threats to coral reef resilience should be reduced by establishing no-take marine reserves, improving management of land-based threats, such as sedimentation, and incorporating an ecosystem approach to fisheries management (Green and Bellwood, 2009). An additional factor that is useful for enhancing coral reef resilience includes bioerosion, which removes dead coral and in doing so provides substratum for benthic organisms to colonize (Green and Bellwood, 2009).

4.1.5 Other Topics in the Scholarly Literature: Ocean Acidification and Marine Reserves and Conservation

In annotating the scholarly literature, the fifth and sixth most discussed topic areas across the articles were ocean acidification and marine reserves/conservation, each being covered in 25 (11%) of the 239 articles, with no discernable increasing or decreasing trends in the number of articles published on these topics over the study period. Ocean acidification, like coral bleaching, is a large-scale phenomenon that is occurring due to an increasing amount of CO_2 in the atmosphere and ocean. Ocean acidification is the result of an increase in release of CO_2 into the atmosphere, primarily through human fossil fuel combustion (Anthony, et al., 2011). Approximately one-third of excess CO_2 is absorbed by the ocean, making it a natural sink (Doney, et al., 2009). The influx of CO_2 in the ocean created a change in the seawater chemistry; there is a decrease in the pH and carbonate ion concentration, coupled with an increase in hydrogen ion and bicarbonate ion (Fabry, 2008). Acidifying oceans results in a decrease of calcite and aragonite, two types of calcium carbonate that are important to the health of the ocean's biota (Fabry, 2008). As acidification increases and calcium carbonate saturation states decrease, organisms that create shells, such as corals, molluscs, and crustaceans, are negatively impacted and face reduced calcification and growth rates (Doney, et al., 2009). It is unknown how such organisms will adapt to consistently rising acidification.

While ocean acidification presents a global threat to the ability of corals to calcify and grow, marine reserves take into account the mitigation strategies that can be enacted on a local and regional scale to minimize the compounding impacts on coral reef ecosystems. Management strategies are in agreement that there is a positive correlation between resilience and sustainability, making it necessary to reduce negative impacts on coral reefs such as overfishing and pollution (Cote and Darling, 2010). Although marine protected areas and no-take zones do not reduce the likelihood that a region will face thermally-induced bleaching or mortality from bleaching, such reserves offer increased rates of coral recovery and higher coral recruitment (Cote and Darling, 2010). This is thought to be due to the high species diversity within reserves, which serves to create functional redundancy: multiple species conduct the same ecological function, so a loss of one species is not immediately detrimental to resilience (Cote and Darling, 2010). As important as marine reserves are in promoting coral reef resilience in a time of declining coral health, this form of management should be conducted in conjunction with other management strategies, such as minimizing sedimentation and pollution (Keller, et al., 2009).

4.1.6 Research Methods Used in Scholarly Studies

It is notable that a significant proportion of the scholarly journal articles are based on case studies conducted across the globe (Figure 5). Overall, 68 (29%) of the scholarly articles discussed a specific place in which a study took place; the remaining articles focused on species or overarching phenomena that were not specific to one particular location. Sixteen (24%) of those 68 articles referred to studies conducted on the Great Barrier Reef and Australian coral reefs, while 12 (18%) were based on the Caribbean and Atlantic coral reefs and 7 (10%) narrowed in upon U.S (including Hawaii) corals. The Pacific/South Pacific proved to be the area of greatest focus, with 29 (43%) articles discussing the impact of climate change on coral reefs in this region.

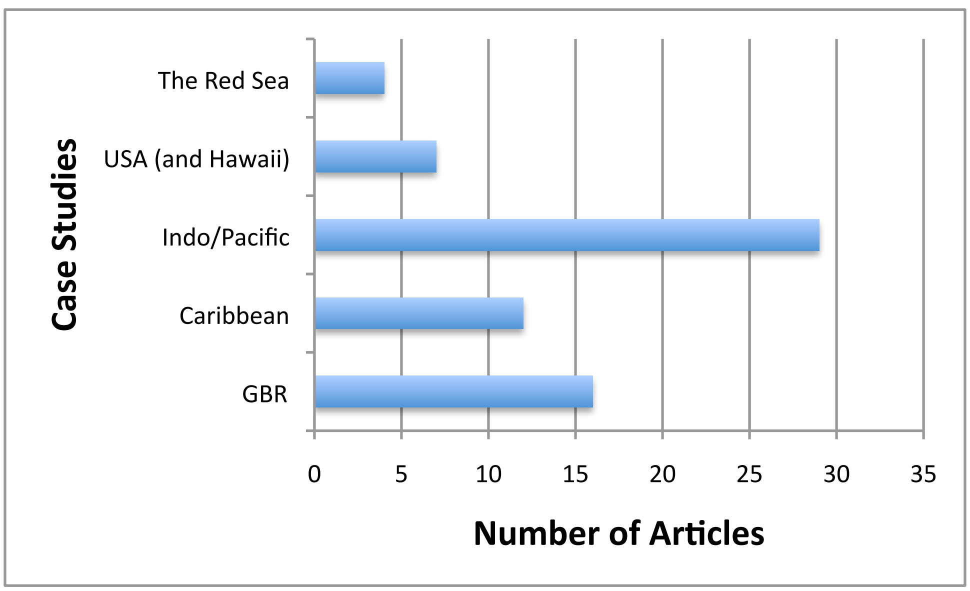

FIGURE 5. Number regional case studies in the scholarly literature (The Great Barrier Reef/ Australia, The Caribbean/ Atlantic, The Indo/Pacific Ocean, the U.S and Hawaii, and the Red Sea).

4.2. Topics Covered in the *New York Times*

As is detailed below, the *NYTimes* articles mainly focused on four topics in relation to climate change and coral reefs: conservation, tourism, SST, and broad discussions of climate change and/or global warming. Conservation is a logical topic for news organizations to address, in that it focuses on the application of scientific knowledge. While there was relatively limited reporting devoted to new scientific knowledge or discoveries in the scholarly literature, as illustrated by the absence of fish/herbivory coverage in the selected news articles, the *NYTimes* instead more heavily reported on topics that were of more immediate potential practical utility to its readers. Conservation or impacts of climate change on tourism, for example, are covered with greater frequency than more nuanced and scientifically based topics. The rise of sea surface temperature and broad coverage of climate change in how it relates to coral reefs are both topics that are perhaps less nuanced and require less detail, and thus precious newspaper space, than topics such as herbivory or fish species diversity.

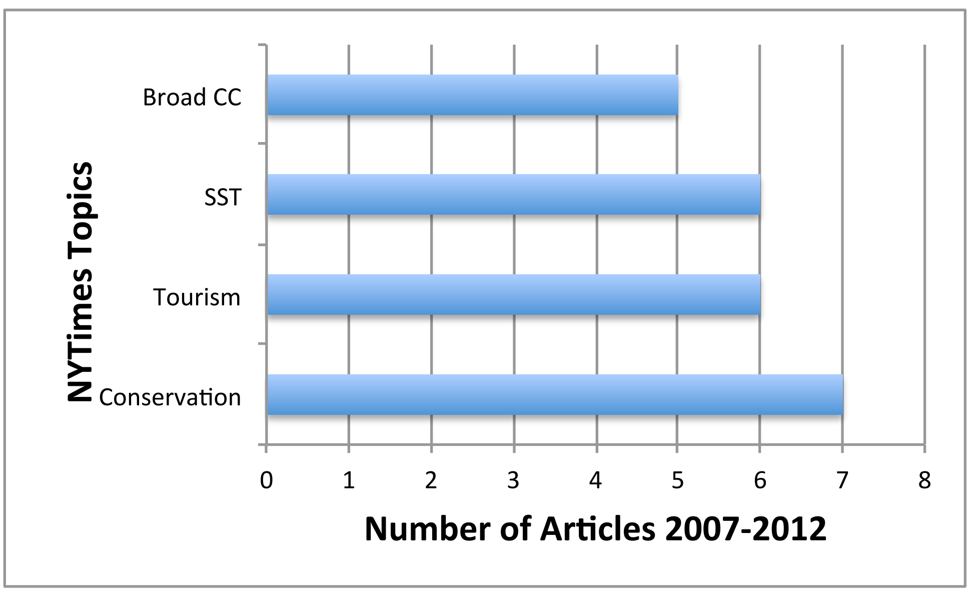

FIGURE 6. Most commonly published topics (conservation, tourism, SST, and broad climate change discussion) in the *NYTimes* 2007-2011.

Turning to specifics on the *NYTimes* search of articles spanning 2007 to 2012: 44 articles were identified with 22 (50%) of those being judged to be relevant to this particular study in that they discussed both climate change and coral reefs. The 22 *NYTimes* articles addressed 23 topics within the overarching subject of climate change and coral reefs. These topics included: broad discussion of climate change and/or global warming; artificial reefs; sea surface temperature; acidification; bleaching; historical analysis and comparison; tourism; zoos and aquariums; conservation; coral reef health; local threats (not including overfishing); overfishing; policy; species extinction; resilience; increased storm intensity; reproduction; and case studies conducted in the Great Barrier Reef, the Indian Ocean, the Caribbean, the Indo-Pacific region, Haiti, and the U.S. These topics were addressed a total of 57 times across the 22 annotated articles. These topics can be further analyzed within Appendix B.

Among the 23 topics covered across the 22 *NYTimes* articles, eight topics were only addressed in one article, and six topics were addressed twice. This means that just over half of the 23 topics were mentioned two or fewer times across a six-year period, from 2007 to 2012. The remaining topics were largely shared across the four previously mentioned topics: conservation, tourism, SST, and broad climate change impacts on coral reefs

4.2.1 Conservation

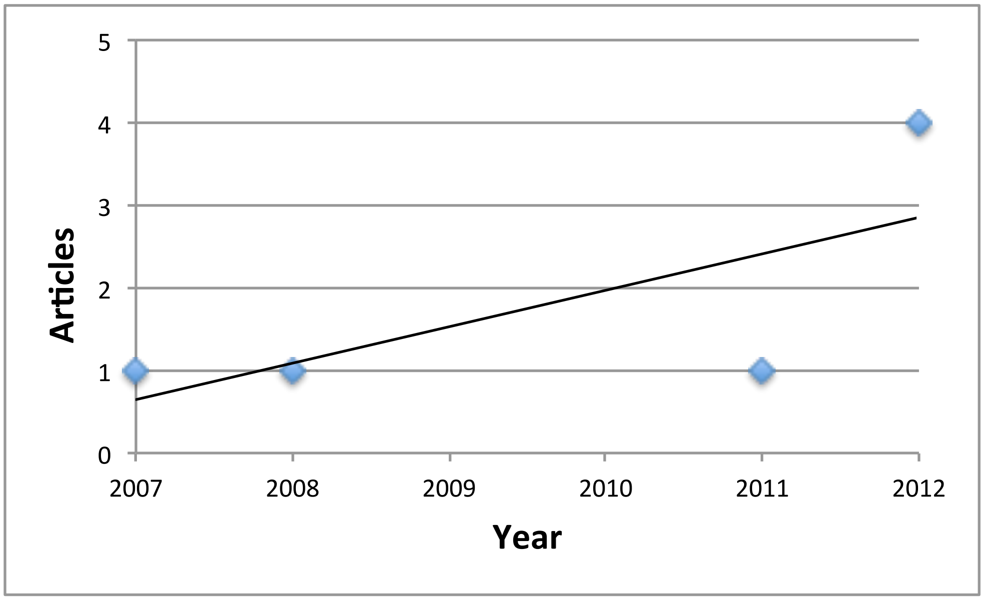

FIGURE 7. An increasing trend on the topic of conservation occurring in *NYTimes* articles published between 2007 and 2012.

Conservation was covered in a variety of ways, and was mentioned in seven (32%) of the 22 annotated articles. This can be expected to increase, considering that of the seven conservation articles, four (57%) were published in 2012, as shown in Figure 7. A 2012 article written by Archibold, for example, discussed the artificial reef being constructed off the coast of Puerto Morelos, Mexico and its potential as an alternative dive site for tourism. The artificial reef was created by the artist Jason deClaires Taylor. Taylor crafted sculptures of local fishermen and villagers, only to sink them into the surrounding water for the purpose of drawing divers' attention away from the MesoAmerican Reef (Archibold, 2012). Seaweed, algae, and corals have already begun to overtake the sculptures. Despite Taylor's efforts to deviate attention from the

MesoAmerican Reef to another site, scientists have little hope that this will offer any huge positive benefit for the MesoAmerican Reef, although it is helpful to have an alternative dive site. This article clearly focused on both potential conservation via artificial reefs, and a potential solution to the often negative impacts of tourism.

Another example of the manner in which conservation was covered in the *NYTimes* dealt with a more educational approach. The New England Aquarium was discussed in a 2012 article by Kaufman that went into detail about the efforts of the aquarium to teach children about climate change in a non-threatening or alienating approach (Kaufman, 2012). In 2008, a coalition of aquariums devised a method to communicate with visitors about climate change without discouraging them. The method largely relied on explaining facts about species and construction of reefs before delving into the various impacts of ocean acidification and coral bleaching on the health of coral reef ecosystems. Despite mentioning how to communicate the impacts of climate change to an audience, the article did not go into detail over what the impacts of ocean acidification and bleaching involved (Kaufman, 2012).

A third article discussed conservation tactics around climate change and the coral reefs surrounding Haiti's coast. It's estimated that 85% of the coral reef along the Haitian coast has died; in a reaction to this, Reef Check, a non-profit organization, has taken it upon themselves to incorporate Haitian fishermen and villagers into monitoring the health of coral reefs (McDonald, 2011). These locals will monitor improvements in the numbers of local edible fish as a method of encouraging local fisherman that conservation is having a positive impact on restoring local fishing stocks. Overfishing is a detrimental problem to Haitian coral reefs, but the poverty rates are so high that it is difficult to get local buy-in around environmental concerns and the critical importance of conservation to combating coral reef degradation and restoring fish stocks (McDonald, 2011).

4.2.2 Tourism

Among the seven articles that discussed conservation, three (42%) addressed the impact that climate change may have on the large tourism industry that thrives on coral reefs. Indeed, a total of six (27%) of the 22 *NYTimes* articles identified in this search focused on tourism. Interestingly, three of the articles that mentioned tourism were published in the first year of the search (2007), and the remaining three were published in the final year (2012), leaving no noticeable trend in publication frequency. An example of an article that discussed both conservation and tourism was Tsui's (2007) article on climate change as a tourism priority, given the annual economic value of coral reefs worldwide. While the Great Barrier Reef has considerable conservation initiatives in place, such as no-take zones and eco-friendly tourism practices, other tourism "hot spots," such as the Caribbean and the Coral Triangle in Southeast Asia, are facing increasing threat from overfishing and coastal development and have relatively few conservation policies in place (Tsui, 2007).

Yet another article talked about climate change in relation to tourism, but discussed tourism on a broader scale before considering the impacts that climate change specifically may have to coral reef tourism. The article, written in 2007 by Rosenthal, began by discussing the potential impacts that climate change may have on the ski industry. From this, Rosenthal moved on to mention that developing countries often rely on their natural environment to promote revenue, yet cannot afford to "make eco-friendly changes to their industry" (Rosenthal, 2007). Clear examples of this from Seychelles and the Maldives were noted; they cannot sacrifice the arrival of carbon dioxide-emitting airplanes for the sake of protecting their coral reefs, although the CO_2 is in turn having a long-term negative impact on reef health. Conservation is not always so easily adapted into tourism.

Tourism was also discussed in relation to a specific place, as was the case in Gies' 2012 travel piece on the Adaman and Nicobar Islands located in the Bay of Bengal. Tourism brought in local jobs to the islands, although resorts are now grappling with coral bleaching that is occurring as a result of rising sea temperatures. Gies reassures the reader that there are still reefs worth seeing despite bleaching episodes. An early 2007 article, written by Bowermaster for the Travel Desk, also focused on a particular region to report upon the impacts of climate change and how it might relate to travel. Tahiti, which contains 77 coral atolls, is threatened by climate change. Bowermaster notes that the beauty of Tahiti's beaches and coral reefs, once renowned by the western hemisphere, may soon be decimated due to pollution, rising sea levels, and increased frequency and intensity of storms. The local population is anecdotally portrayed as being largely unaware of global warming.

4.2.3 Sea Surface Temperature

Sea surface temperature was represented in 27% of NYTimes articles (six articles). Interestingly, one article was produced in 2007 and 2008, zero articles were published in 2009 and 2010, three in 2011, and one more in 2012. This indicates there is no noticeable trend in the publication of *NYTimes* articles discussing SST. Gillis (2011) offered a straightforward report regarding the figures of global climate change, mentioning that the year 2010 had tied 2005 as the hottest year on record. The article goes on to state that scientists say that this is due to humans "releasing heat-trapping gases like carbon dioxide into the atmosphere" (Gillis, 2012). The result is increased sea surface temperatures, coral reef die-off, and the trend is expected to continue.

Sea surface temperature was again mentioned in 2011 by Rudolf, this time to discuss the impacts of coral bleaching that have resulted from increasing ocean temperatures. The record-hot summer of 2010 resulted in global bleaching episodes, which killed 10% of shallow water corals. Overall, three quarters of reefs are threatened by degradation, and in response coastal communities have taken conservation efforts to participate in sustainable fishing and agriculture practices (Rudolf, 2011).

4.2.4 Climate Change in General

A category of broad climate change and/or global warming was created due to a number of the articles present in the *NYTimes* study sample that reviewed climate change in relation to coral reefs, but did not go into depth about any particular outcome of climate change, such as ocean acidification, coral bleaching, or resilience. Other articles did go into some detail about the outcomes of climate change, while also devoting a section to broader implications of climate change. The five articles (23%) that comprise this topic appeared constitute 23% of the articles published in 2007 and 2011-2012; from 2008 until 2010 there were no publications that broadly covered climate change and how it relates to coral reefs. As was the case with the topic of SST, there is no noticeable trend in the number of articles published on the topic of broad climate change discussion.

4.2.5 NYTimes Sources and Hyperlinks

As part of the annotation process for the *NYTimes* articles, any hyperlinks or references to scholarly journal articles were noted, as were any scientific expert sources who were interviewed for the articles. Of the 22 articles, three (14%) included hyperlinks to scholarly articles. The earliest article was a 2008 article by C. Dean: *"The Preservation Predicament"* on the topics of overfishing, population, and coral reef health. It included one reference to a PLoS research article, although it linked to the PLoS database homepage without linking to the article itself.

The next article that included hyperlinks and references to scholarly journal articles was in 2011 and written by J. Collins Rudolf entitled *"Under the Sea, Hot, White Reefs."* This article cited three scholarly reports. The first was a report conducted by the World Resources Institute, the second was a report from the Global Coral Reef Monitoring Network, and the third was more vaguely mentioned as a "new study" by an international research team that was linking coral reef damage to carbon emissions (Rudolf, 2011). The reports were included in the annotation as a scholarly resource, because they linked to scientifically-supported written pieces about climate change and coral reefs.

The third article that linked to scholarly journal articles was also published in 2011. It was a piece written by Carl Zimmer entitled "*Multitude of Species Face Threat of Warming*" and was on species extinction, warming oceans, and adaptation. In contrast to the vast majority of *NYT*imes articles published across the span of the present study, this article linked to six scholarly journal articles. The article first linked to *Nature,* a highly regarded scientific journal, but did not go to a specific article. After this initial hyperlink, three subsequent hyperlinks led to *Nature* articles published by Camille Parmesan and Chris D. Thomas. The remaining two articles were published in *Science* and *Biology Letters* by Terence Dawson and Michael R. Kearney, respectively. Although this article linked to six journal articles, none were present in the scholarly annotated bibliography. One of the articles did have an author, Terence Dawson, who was cited in the annotated bibliography, although for a different paper. Two of the linked articles were from 2003 and 2004, nine and eight years before the newspaper article was published, respectively.

It is worth mentioning that although the majority of the *NYTimes* articles did not link to a scholarly journal or journal article, some did include links to organizations, websites, and institutes that promoted the health and study of coral reefs. These included hyperlinks to the Flower Garden Banks National Marine Sanctuary, the Nature Conservancy, and the Coral Reef Watch.

A more common approach across the *NYTimes* articles was to include interviews from scientific sources, including biologists, oceanographers, and physicists. Overall, 12 (55%) of the 22 annotated articles, included a reference to a scientific source. Including interviews and first hand sources is a more typical practice than is citing specific scholarly articles. No obvious trends across time in this practice were noted. The articles published in 2007 did not include any interviews from scientific sources, nor did they provide information about any scientist's coral reef research. In 2008, however, three articles included scholarly references. 2009 and 2010 resulted in a slight decline in coral reef expert references; 2009 had one article that referenced a “coral expert” and a chemical oceanographer, and 2010 had two articles that referenced a total of four sources. 2011 and 2012 were on par with 2008, in that they too included three articles each year that noted a scientific source.

4.3 Comparing the Scholarly and *NYTimes* Literatures

The scholarly and *NYTimes* literatures vary in the topics that are covered at the greatest frequency. In the scholarly literature, the most prevalent topics discussed were the relationship between herbivorous fish and coral health; SST; coral bleaching; and the resilience, recovery, and acclimation processes of coral reef ecosystems. On the other hand, *NYTimes* articles had four main topics that focused on conservation, tourism, SST, and broad discussion of climate change and how it might affect coral reef ecosystems.

While the impact on coral reef fish from climate change and the interrelationships between herbivorous fish, algae, and corals is well documented in the scholarly literature, there is no mention of this aspect of coral reefs and climate change in the *NYTimes* between 2007 and 2012. The lack of coverage of this topic in the *NYTimes* could reflect the relatively few published scholarly journal articles on this topic during the 2007-2009 period. Yet there is an increase between 2009 and 2010 in the number of published scholarly articles that discuss the impact of climate change on coral reef herbivorous fish, without a corresponding increase in coverage in the *NYTimes*. This discrepancy illustrates that there is ample information available in the scholarly literature that can be mined to further enhance popular press articles. The lack of coverage of this topic is also correlated with the decline in foreign correspondence and the decision at the *NYTimes* to separate their environmental information into blogs including the *Green Blog* and *Dot Earth*. The importance of reporting on herbivory and coral reef fish lies in the implications this topic has to coral reef recovery and resilience in a time of increasing coral bleaching, rising sea surface temperatures, and ocean acidification.

Herbivory and coral reefs may be a nuanced and technical topic to cover in the limited space that is allocated to popular press reporters, but it does not have to necessarily be so. There are scholarly journal articles, such as Green and Bellwood's 2009 paper that clearly defines ecosystem resilience and the role of herbivory in coral reef recovery and resilience in a manner that should be accessible to a general audience. In fact, it states in its title that the research presents a practical guide for coral reef managers, suggesting that this article would play to the already popular topic of conservation while introducing a slightly more nuanced discussion (Green and Bellwood, 2009). Using scholarly papers that are not overly complex in popular press articles represents a potential strategy to increase knowledge-based journalism without overextending shrinking budgets.

While the most readily discernible overlap between the two literature sources appears to be the focus on SST, there is also overlap between the topic of resilience and recovery in the scholarly literature and conservation in the NYT literature, in that both are examining the recovery of coral reef ecosystems. Although conservation was a prevalent topic in the *NYTimes* literature being mentioned in 5 (23%) of the 22 articles, there was no in-depth coverage of the possibility of natural resilience within coral reef ecosystems. Conversely, 32 (14%) of the 239 scholarly articles discussed the potential for coral reef ecosystems to rebound successfully, and what could potentially help or hinder such a process. A key difference in the discussion of resilience and conservation in the scientific literature and in the *NYTimes* revolves around the proactive or reactive efforts being promoted. Focusing on increasing the resilience of a coral reef ecosystem is a proactive measure that is currently being emphasized in the scholarly literature to ensure that reef ecosystems are at optimal health before facing any disturbances (Hughes, et al. 2007). The *NYTimes* articles largely reported on the current state of coral reefs that are undergoing disturbances, and the reactive conservation methods that have been assigned to address the problems at hand. Clearly, there is ample scholarly material available for reporters in the *NYTimes* to call on to weave a more proactive, preventative slant involving resilience into their reporting on protecting coral reefs. This is not to say that a reactive coverage of coral reefs is necessarily insufficient, but a proactive approach may elicit a more progressive stance on climate change, and shows the broad range of possible solutions to climate change impacts on coral reefs.

The frequent coverage of SST in both the scholarly literature and the *NYTimes* articles could be due to a multitude of reasons. Rising ocean temperatures is a global phenomenon, so it is likely that it will be covered across case studies and reporter angles. SST is also a catalyst for other coral reef problems, such as coral bleaching, and offsets the symbiotic relationship between corals and algae. This topic is also a relatively easy concept for the public to understand: carbon dioxide emissions are making oceans warmer, and this is negatively impacting coral reefs. Given the charismatic species and natural beauty associated with coral reefs, the public generally cares about the implications of SST for coral reefs; conserving corals also means that coral reef destinations and the $9.6 billion dollar tourism industry it supports will also survive.

Tourism made up only 0.5% of the topics covered in the scholarly literature compared to 27% in the *NYTimes*. Tourism is an easy way to relate an unfamiliar phenomenon to a readership that may not have in-depth experience with the science associated with climate change and coral reefs. This certainly is not to suggest that scientific explanation should be excluded from popular press articles, but tourism may be a means of sparking the public's interest in climate change and coral reefs. Another potential upside to a tourism angle in the *NYTimes* articles is that it offers the opportunity to use scholarly cases studies. Across all of scholarly annotated literature, there were 68 articles that were on the Great Barrier Reef, the Caribbean, Atlantic, the Red Sea, and U.S coral reefs. These articles offer supplementary, current information on highly popular tourism destination sites that can be accessed without the cost of foreign bureaus or correspondence. For the purpose of this study, case studies were discussed via the region that the article pertained to, but there were additional case studies on particular coral reef species, such as damselfish, parrotfish, and coral species that also could offer fresh insights into the resilience of coral reef tourism destinations.

The *NYTimes* literature used interviews with scientific coral experts in 54% of the annotated articles. How then does this compare to the breadth of public in the scholarly journal literature? The 12 *NYTimes* articles included input from a variety of scientists and coral reef experts, with some articles using multiple sources. Overall, the 12 articles relied on 27 interviewees to supplement their story. Of the 22 sources used, 6 of those sources were also found in the scholarly literature that was annotated between 2007 and

2011. The scholarly literature at this time produced 239 scientific articles on this topic, often with multiple authors for each article. These sources included Jeremy B.C Jackson, a coral expert at the Scripps Institution of Oceanography in San Diego; Mark Eakin of the Coral Reef Watch; Clive Wilkinson, the director of the Global Coral Reef Monitoring Network; Katharina Fabricius, a coral reef ecologist with the Australian Institute of Marine Science; and Terence Dawson, a professor at the University of Southampton's School of Geography. These six sources were mentioned across a five-year period of 2008-2012. The *NYTimes* articles published in 2007 did not use any scholarly sources.

Less encouraging was that only 14% of *NYTimes* articles included hyperlinks or citations to scholarly articles. This is an area where availability of an annotated bibliography might allow reporters to connect their readership with more detailed or in-depth reports than might be appropriate for an article in the popular press. Having such an explicit connection to original research may also increase the likelihood that reporters will take care to carefully represent the scientific evidence supporting their report. That, of course, is the intent behind the required use of citations in the scientific literature. It promotes closer adherence to the evidence.

4.3.1 Possible Explanations for Differences

The comparison between the scholarly literature and the *NYTimes* coverage of climate change and coral reefs shows topics that are being underreported in the latter, such as herbivory, and other topics, such as tourism, where the quality of reporting could be strengthened with the use of additional scholarly resources. The *NYTimes* is a highly regarded news organization and has won 112 Pulitzer Prizes, the most prestigious

American journalism award (The New York Times Company, 2013). Despite this record of outstanding accomplishments the *NYTimes* is nevertheless dealing with a shrinking staff, as shown by the dismantling of the Environmental Desk, as well as their environmental blogs. Without a staff designated to cover environmental topics, scientific nuances can slip through the cracks. Annotating scholarly literature and utilizing the plethora of scholarly reports, journals, and even abstracts may offer a cheap and quick alternative to underreporting.

The *NYTimes* articles that were annotated for the purpose of this study demonstrated that scholarly journal articles are often not used. As was discussed above, only three (14%) of the 22 annotated articles included mention of or hyperlinks to scholarly journal articles. While sites like the *Harvard Journalist's Resource* represent one method to facilitate knowledge-based reporting, it is only one strategy and only provides limited direct connection to the scholarly literature. Such academic sites are a phenomenal complimentary tool to what is being advocated in the present study for reporters in a time of declining foreign correspondence and diminished budgets, but as has been made evident with the topic of climate change and coral reefs, is not a substitute for the annotated bibliography strategy.

It may be beneficial to look closer at how the science of climate change and coral reefs has been covered in the *NYTimes*. Although the science itself is not incorrect, it is often less detailed than perhaps it could be. While some of this is by design to assure accessibility to its readers, the *NYTimes* should not downplay a topic that is occurring on a global scale and within our lifetime. It should also not ignore the relatively high rates of scientific literacy among its U.S. readership (Raloff, 2010). In Bowermaster's 2007 article on Tahiti's coral reefs, for example, he writes: "'Global warming?' the bus driver pondered, scratching his head. 'No, don't know what that is, never heard of it.' The reality is that if tropical storms and hurricanes increase as is predicted, things here will change very quickly." (Bowermaster, 2007). This quote shows that Bowermaster is discovering a once-pristine coral region now damaged, and goes so far as to note the public's lack of education on what may be driving such changes. Bowermaster could readily cite a scholarly resource at this point to elaborate on the damaging impacts of global warming and the rise in frequency of tropical storms and hurricanes. A more positive example of utilizing a scientific resource is seen in Gillis' 2010 article for the Foreign Desk section. Gillis writes, "Coral bleaching occurs when high heat and bright sunshine cause the metabolism of the algae to speed out of control, and they start creating toxins. The polyps essentially recoil. ' The algae are spat out,' Dr. Wilkinson said" (Gillis, 2010). Gillis relied on Wilkinson, who was also annotated in the scholarly literature for this project.

Unfortunately, there are more negative examples than positive. Dean's 2010 *NYT*imes article on ocean acidification reads, "ocean acidification may render most regions chemically inhospitable to coral reefs by 2050." The group said that acidification could be controlled only by limiting future atmospheric levels of the gas" (Dean, 2010). This is not poor writing and it is not inaccurate science: there just is not much explanation. Calling on information from Joan Kleypas, for example, who published the first scholarly journal article on ocean acidification in 2006 and is considered a leader in the field of coral reefs and climate change, would be a perfect addition to more thoroughly explain the processes and impact of ocean acidification.

The *NYTimes* has been used for this project because it is considered to be among the best news organizations in the United States and globally. If there are gaps within the *NYTimes* coverage of topics such as climate change and coral reefs, it is likely that other news organizations are exhibiting similar limitations. Put differently, if an influential outlet like the *NYT*imes adopts practices involving greater use of the scholarly literature in its environmental reporting, it seems likely that other news organizations may follow suit. The issue of the lack of journalism resources that has arisen along with the decline of knowledge-based journalism could perhaps be reversed if measures such as annotating scholarly literature were used.

CHAPTER 5: CONCLUSION

The present study is a demonstration of the advantages of knowledge-based journalism in a time of declining foreign correspondence (Patterson, 2013). I have used the example of climate change and coral reefs to illustrate the current information gaps that are occurring between scholarly literature and a highly recognized popular press organization out of my own professional interest and because of its unquestionable global impact. In a time of downsizing and abandoned foreign news coverage, important and timely topics, such as climate change and coral reefs, deserve to be covered with more frequency and detail. Access to bi-annual reviews of the scholarly literature in journalist-friendly formats present the opportunity to utilize a wide breadth of in-depth and nuanced information for reporting, especially in longer forms of journalism, such as feature pieces. Considering that most reefs are located along the coast of developing, faraway countries, and are at risk of local and global environmental degradation, this topic is up against both the decline in foreign correspondence and a decline in environmental coverage.

In creating an annotated bibliography for scholarly journal articles and *NYTimes* articles during a time span of 2007-2012, I was able to compare the topics covered in both resources. There did prove to be some overlap in the discussions, such as the frequent mention of SST and some overlap between scholarly literature's focus on coral reef recovery and resilience and the *NYT's* frequent discussion of conservation. The *NYTimes* was relatively successful in its use of scientific first hand sources, as 12 (54%) of the 22 annotated articles quoted or mentioned a coral reef expert or relevant scientist.

That being said, that still leaves 46% of the articles without any sort of scientific source to add in new discussion points or nuances to the writing piece. Additionally, very few (3 out of 22 or 14%) articles included a link to relevant scholarly articles. This could be drastically improved and lead to more detailed and groundbreaking reporting, without tying down the piece with unnecessary or dry facts.

In a time of declining foreign correspondence and the Internet changing the way in which news information is transmitted, there does not need to be a decline in the quality of reporting on foreign and nuanced topics. Annotating scholarly literature on specialized topics, e.g. the environment, may provide a possible solution to maintaining knowledge-based journalism. It also suggests an entrepreneurial opportunity. The *NYT*imes is recognized as one of the best news organizations in America, yet is currently undergoing transitions that may threaten the quality of reporting on environmental and foreign topics. Annotated bibliographies are cheap, in that they are both time effective and rely on a readily available source of information. Instead of staffing foreign bureaus or budgeting the expenses for a journalist to fly to a destructed coral reef, news organizations can rely on the steady, up-to-date information that is readily available via scholarly studies. Assuming news staffs are scientifically literate, it should take roughly fifteen to twenty minutes to read and annotate a scholarly article. When considering the number of hyperlinked articles that were present in the *NYT* articles, this would equate to anywhere from fifteen minutes to an hour and a half of research time. Considering this level of quick access to a fantastic database to the time and expenses of overseas reporting and annotated bibliographies clearly begin to appear to be a helpful tool to reporters. There is no question that journalists face serious time constraints around their deadlines, but there are also countless numbers of journalism students and niche specialists in international fields who may be willing to contribute a small segment of their time to be associated with an organization as prestigious as the *NYTimes*. An option is to outsource the preparation annotated bibliographies of research to contractors who would supply multiple news organizations for a subscription price that would be smaller than the cost of travelling overseas. Prospective bibliography developers might want to first conduct market research to assess demand and then tailor a *beta* version of this trial service for a specific beat. Annotators could then design the annotations accordingly so that they provide information for news organizations that is easily translatable into stories.

During this period where news organizations are facing enormous financial constraints and unprecedented challenges, this project serves to demonstrate that free and accessible scholarly journal articles that are available through public libraries and online databases may provide a cost-effective means for helping to sustain knowledge-based international and environmental journalism during this time of budget cuts and shrinking news staffs.

FURTHER RESEARCH

Annotated bibliographies are not the only solution to the problem of declining journalism resources, funding, and staffing. The purpose of this study was to suggest *one* way to provide scholarly knowledge-based journalism in these times of declining international reporting. As science communication research *qua* research with no practical agenda, there are many ways in which this study could have been enhanced. Firstly, a comparative study of the coverage in scholarly literature, the popular press, and highly regarded environmental and science blogs was possible. Likewise, it would also be interesting to examine trade press content on climate change and coral reefs, that is, magazines and news outlets that are devoted to coverage of the environment, the ocean, coral reefs, and related topics. Further research could also include a look into how journalists conduct their work, and how their methods might be best partnered with academic research. This would include interviewing journalists who are facing problems in these times of international reporting. They could add valuable insight into the potential usefulness of annotated bibliographic reviews of scholarly literature.

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APPENDIX A: Table of Scholarly Literature

Topics	2007	2008	2009	2010	2011	Total*
C.R. resilience/recovery/acclimation	3	7	7	8	7	32
O.A	1	9	4	4	7	25
C.B	3	11	10	3	7	34
Rising SST/thermal stress/rising sea-level	0	6	5	16	11	38
Herbivorous Fish	6	7	7	14	14	48
Species dominance/predation	0	0	2	2	3	8
Symbiotic C.R. and algae	5	3	3	6	5	12
Broad C.R and C.C. Discussion	1	4	4	5	4	18
Scientists' perspectives	1	0	0	0	0	1
Modeling	2	6	7	1	4	20
Historical Analysis	0	1	2	3	3	9
Habitat loss and fragmentation	1	0	2	3	3	9
Policy involvement/implications	0	0	1	0	0	1
Phase shifts/regime shifts	2	1	3	1	2	9
Local stressors/socio-econ impacts	1	5	2	2	1	11
Disease	0	0	5	1	2	8
Calcification	0	2	0	0	1	3
Hydrodynamics	0	0	0	0	1	1
Water quality	0	0	2	0	0	2
GBR/Australia	2	1	3	8	2	16
Caribbean/Atlantic	0	5	2	3	2	12

Indo-Pacfic/ South Pacific	1	4	4	12	6	29
USA (including Hawaii)	0	0	2	1	4	7
The Red Sea	0	0	0	2	2	4
Storms (hurricanes and cyclones)	1	2	0	1	2	6
Marine reserves/conservation/management	0	3	8	8	6	25
Biodiversity	1	2	3	2	1	9
Coral mortality/ productivity	0	2	3	3	7	15
Future predictions/ outlooks/ long-term impacts	1	3	4	0	5	12
Coral structure/ genetic stucture	1	0	2	3	3	9
Placticity	0	0	0	1	2	3
Reproduction (corals, fish, algae)	0	0	1	1	2	4
Algae blooms	0	0	0	2	0	2
Tourism	0	0	0	0	1	1

*Article may have more than one topic

Topic abbreviations:
C.R: coral reef
O.A: ocean acidification
C.B: coral bleaching
C.C: climate change
GBR: Great Barrier Reef

APPENDIX B: Table for *NYTimes* Articles

Topics	2007	2008	2009	2010	2011	2012	Total*
Broad climate change/ global warming	2				2	1	5
Artificial reefs						1	1
SST	1	1			3	1	6
Acidification			1			1	2
Bleaching				1	1		2
Historical analysis/ comparison						1	1
Tourism	3					3	6
GBR	1						1
Indian Ocean						1	1
Caribbean	1			1			2
Indo-Pacific	1			1			2
Haiti					1		1
U.S.						2	2
Zoos and aquariums						1	1
Conservation	1	1			1	4	7
Coral reef health	1	1					2
Local threats (besides overfishing)	1	1				1	3
Overfishing		1			1		2
Policy/IPCC	2			1			3
Species extinction					1		1
Resilience		1			1	2	4
Increased storm intensity	1						1
Reproduction						1	1

*Article may have more than one topic

Topic Abbreviations:
SST: sea surface temperature
GBR: Great Barrier Reef

APPENDIX C: *NYTimes* Annotated Bibliography

Archibold, R. C. (2012). Trying to protect a reef with an otherworldly diversion. *The New York Times, Section A* (Column 0)

Summary:
Jason deClaires Taylor has been creating concrete sculptures of local fishermen and villagers of Puerto Morelos, Mexico. The goal of his artwork is to attract tourists who may otherwise be drawn to the Mesoamerican reefs. Eventually, corals will overtake the sculptures- today seaweed, coral, and algae have already begun to do so.

Taylor uses marine-grade concrete to cater to coral, it's close to a neutral pH

Provides an alternative dive site- that aspect is more helpful than the natural reef it may one day create

National Marine Park wants Taylor to contribute to an artificial aquatic preserve off of Cancun to preserve the natural reserve nearby

Quotes:
"'It is neither a benefit nor a harm to the reef, but I do not see it as a conservation project,' said Roberto Iglesias Prieto, a scientist in Cancún who studies the reef."

"'I have seen the pictures, and it looks intriguing,' Richard E. Dodge, executive director of the National Coral Reef Institute in Florida, said of the museum. 'If it is not so extensive that it impinges hugely on the natural reef, it does help by providing an alternative dive site.'"

Electronic Pages: 1

Scholarly citations/hyperlinks (to outside the NYT): 0

Scientific Sources: 2

Themes: artificial reefs, conservation, tourism

Bakalar, N. (2012). Coral shows resilience in face of hostile climate. *The New York Times, Section D* (Science Desk), 3.

Summary: Reefs stopped growing (based on sampling off Panama) around 4,000 years ago and took 2,500 years to recover. The beginning of 2,500-year period coincided with the start of a series of extremely strong El Niño effects, elevations of water temperature every three to seven years that cause long-term changes in weather. Also was a La Nina period (unusually cold ocean temps) that could have also affected coral health ~3,800 to 3,200 years ago. Reefs could potentially recover if we stop the increase of greenhouse gases and conserve on a local scale; reef have shown past recovery/resilience

Quotes: "Similar growth hiatuses have been recorded at other locations, generally attributed to local conditions. But these researchers conclude that the phenomenon was more likely a result of Pacific-wide climatic changes disrupting many reefs at the same time."

Electronic pages: 1

Scholarly citations/ hyperlinks (to outside the NYT): 1

Scholarly Sources: 0

Themes: resilience/ historical analysis/ global and local conservation

Barringer, F., et al. (2010). Seeking answers on oil spill as questions mount. ***The New York Times, Section A*****(National Desk), 11.**

Summary: the impact of the Gulf Coast oil spill has not been uniform: oil heads in all directions at the same time, affecting some places much more than others. (Questions and answers about various impacts the oil might have on the ocean and surrounding states) Scientists are worried about the reefs, the ones in the greatest risk are the deep reefs closest to the gushing well Florida keys reefs: scientists not unanimous- oil may be diluted enough by currents that there will be little harm done to organisms there

Quotes: "Because the well is so deep, some toxins that would rise to the surface and evaporate in a shallow oil spill are instead dissolving into the water. The worry is that they may kill or weaken deepwater marine organisms. But even relatively near the well, the concentrations of these toxins in deep water are relatively low, so there is reason to hope for the best."

Electronic pages: 1

External citations/hyperlinks (to outside the NYT): 0

Scholarly Sources: 0

Themes: local threats to reefs

Bowermaster, J. (2007). The fragile paradise that tahiti used to be. *The New York Times, Section 5*(Travel Desk), 12.

Summary: Tahiti, once considered a Paradise by westerners, is now polluted and heavily populated. Along with this, there is the threat of a loss of culture and damage to the coast due to climate change. Tahiti consists of 77 coral reef atolls, which were originally colonized by the French, are now facing threats from the black pearl industry, airstrips, and tourism. The reporter goes into detail about the beauty of the beaches and the grandeur of diving off the coast. With current climate change predictions, the reefs and their reliant populations are at danger from increasing sea levels and increased frequency and intensity of storms. This was briefly mentioned, and it was also noted annecdotally that a bus driver was not concerned about the weather. The remainder of the article discussed travel accomodations.

Quotes: "'Global warming?' the bus driver pondered, scratching his head. 'No, don't know what that is, never heard of it.' The reality is that if tropical storms and hurricanes increase as is predicted, things here will change very quickly."

Electronic pages: 1

External citations/hyperlinks (to ouside the NYT): 0 (but did link to climate change section within NYT)

Scientific sources: 0

Themes: tourism/travel; CC-related storms; local population

Broder, J. M. (2010). Negotiators at global climate talks continue past the deadline for an agreement. The New York Times, Section A(Foreign Desk), 12.

Summary: Negotiators failed to meet a self-imporsed deadline at the 16th U.N Framework Convention on Climate Change in Cancun, Mexico. They were working toward an agreement for 200 participating countries. Despite reaching an agreement, the conference did result in additonal amendments eing included in the Copenhagen Accord (2009). Without reaching any sort of negotition, negotiators worried that future progress may be halted. Havard University's director of Environmental Economics Robert Stavins had another approach, noting that countries are already working on their own carbon reductions, and that this may be more effective than an overarhcing, top-down approach. While negotations were at a standstill, the climate was not; 2010 experienced the warmest year in a 130-year climate record.

Quotes: "High sea temperatures were also blamed for a global bleaching of coral reefs." (ONLY MENTION)

Electronic pages: 1

External citation/hyperlinks (to outside the NYT): 0

Scientific sources: 2 (Robert N. Stavins, director of the environmental economics program at Harvard University; Kevin Trenberth, head of climate analysis at the National Center for Atmospheric Research in Boulder, Colo)

Themes: policy; international; UN

Dean, C. (2008). Coral reefs and what ruins them. The New York Times, Section F Science Desk), 3.

Summary: In the Pacific Ocean, researchers from the Scripps Institute of Oceanography studied the northern Line Islands, which is a chain of islands south of Hawaii. Reefs on the northernmost, least populated islands have a variety of predators and robust corals. The southern islands are the most populated and have the least healthy reefs- fleshy algae and planton-eating fish. Scientists disagree over the importance of local factors vs. global factors (climate change and ocean acidification). Line Islands will help solve this- scientists noticed varying fish communities in the reefs.

Quotes: "'Reefs without people' were healthier than populated reefs, they say in a report to be posted Wednesday in the online journal PLoS ONE.'

Hyperlink and/or outside citations: 3 Smithsonian Institute, Fish and Wildlife Services, PloS

Scholarly journals cited: 1: PLoS

Scientific sources: 2 Nancy Knowlton; Jeremy B. C. Jackson- Scripps and Smithsonian Institute

Notes from online published scholarly lit- ton and Jeremy B. C. Jackson, coral experts at Scripps and the Smithsonian Institution, said the new work was notable because it produced data at sites "across a full spectrum of human impacts." Without this kind of data, they write, studying coral reefs is like trying to discern the ecological structure of the Amazon rain forest by looking at the cattle ranches and soybean fields that have replaced much of it.

Themes: overfishing/ population density/ reef health

Dean, C. (2008). The preservation predicament. *The New York Times, Section F*(Science Desk), 1.

Summary: Is conservation worth it? How will landscapes under preservation change with climate change? Conservationists and scientists must guess which sites are going to be worthy of conservation in the near future as well as in the upcoming (50, 100) years. Current land conservation isn't worthless, because preserved ecosystems will help ecosystem resilience. What reefs did the best in the Caribbean with the El Nino event of 1999? Resilient strains could be used to restore damaged reefs. Coastal ecosystems are the first to have conservation problems with sea level rise. Important for coastal wetlands and beaches. Should coral reefs be focused on, because they could potentially be wiped out with warming waters? Should conservation efforts focus on resilience or triage?

Quotes: "We said, 'Why did they survive, and are they the ones most likely to survive in the future?' " Mr. Stanley said. Resilient strains could be used to restore damaged reefs. "The same approach could translate to the land," he said.

Electronic pages: 1

External hyperlinks/ citations to sources (outside NYT): 0

Scientific sources: 5 Healy Hamilton, director of the Center for Biodiversity Research and Information at the California Academy of Sciences; Bill Stanley, who directs the global climate change initiative at the Nature Conservancy; Dan Kimball, superintendent of Everglades National Park; David S. Wilcove, a conservation biologist at Princeton; Asbury H. Sallenger, an oceanographer at the United States Geological Survey and an expert on coastal hazards

Themes: conservation; resilience; sea level rise

Dean, C. (2009). Rising acidity is threatening food web of oceans, science panel says. ***The New York Times, Section A*****(Foreign Desk), 12.**

Summary: Ocean acidity is a growing threat to ocean health. There are detectable traces in shellfish and shell weights, and coral skeleton growth is affected.

Quotes: "According to the declaration, "ocean acidification may render most regions chemically inhospitable to coral reefs by 2050." The group said that acidification could be controlled only by limiting future atmospheric levels of the gas."

Electronic pages: 1

External hyperlinks/ citations to sources (outside NYT): 0

Scientific Sources: Jeremy B. C. Jackson, a coral expert at the Scripps Institution of Oceanography in San Diego; James Orr, a chemical oceanographer at the Marine Environmental Laboratory in Monaco

Themes: ocean acidification; conservation

Editorial. (2007). At humanity's doorstep. ***The New York Times, Section 4*** **(Editorial Desk)**

Summary: Increased carbon emissions are resulting in rising sea levels, more powerful hurricanes, and disappearing reefs

Electronic pages: 1

External hyperlinks/ citations to sources outside the NYT: 0

Scientific Sources: IPCC

Themes: policy/ global warming

Editorial. (2008). A new respect for science. *The New York Times, Section A* (Editorial Desk), 32.

Summary: Barack Obama appointed two sub-cabinet choices: Jane Lubchenco, marine biologist at Oregon State to run NOAA and John Holdren- Harvard physicist. Lubchen's expertise are ocean acidification (which is destroying coral reefs) and hypoxia (fish not getting enough O2 to survive).

Electronic pages: 1

External hyperlinks/ citations to sources outside the NYT: 0

Scientific Sources: Jane Lubchenco- marine biologist at Oregon University- runs NOAA; John Holdren- Harvard physicist and presidential science advisor

Themes: policy/ coral reef health/advocacy

Gies, E. (2012). Holding on to what was in the Adamans. *The New York Times, Section TR*(Travel Desk), 12.

Summary: Gies embarks on a diving expedition in the Bay of Bengal, off the coast of Havelock. Despite their relative proximity to millions of South Asians, the 572 Andaman and Nicobar islands were largely ignored until the 21st century. Just 38 are inhabited, and most are protected from development by the Indian government, leaving endemic fauna and flora untouched, and some native tribes off limits. The country was exposed to tourism as a result of 2004 hurricanes. The results of tourism are to provide local populations with resort jobs. The resorts are grappling with coral bleaching as a result of warming ocean temps- although the reefs still boast some coral reef life.

Quotes: "there were plenty of reef dwellers among the bleached coral: parrotfish, butterflyfish, purple-lipped clams, sea slugs and Christmas tree worms. Farther down, as we had seen during our scuba trip, ocean life remains spectacular. Bright, jumbo-size Moorish idol fish trail dorsal fins longer than their bodies; dotting the seascape are healthy corals and fat purple barrel sponges, some occupied by spotted groupers."

Electronic pages: 1

External hyperlinks/ citations outside of NYT: 0

Scholarly sources: 1 Terry Gosliner, an expert in Indian and Pacific coral reefs and their biodiversity with the California Academy of Sciences

Themes: tourism; sea level rise/warming; coral bleaching; India

Gillis, J. (2010). Extreme heat bleaches coral, and scientists see global threat. *The New York Times, Section A* (Foreign Desk), 1.

Summary: The extreme heat of climate change is affecting coral reefs, both as ecosystems hosting high biodiversity and as fisheries. Coral reefs are bleaching as a result of high temperatures; scientists suggest that this is linked to climate change. 1998 has gone as record as the hottest year yet for ocean temperatures. The first eight months of 2010 matched temperatures in 1998. Bleaching has occurred intermittently since a 1983 disaster, which was the result of an El Nino event. Climate change has increased baseline temperatures, making coral reefs more susceptible to bleaching (bleaching is when polyps expel the algae they rely on and thus die). Coral bleaching is occurring in Southeast Asia, the Pacific, and the Caribbean.

Quotes: Coral bleaching occurs when high heat and bright sunshine cause the metabolism of the algae to speed out of control, and they start creating toxins. The polyps essentially recoil. "The algae are spat out," Dr. Wilkinson said.

Electronic pages: 1

External hyperlinks/ citations outside of NYT: 4 Global Coral Reef Monitoring Network; Flower Garden Banks National Marine Sanctuary- NOAA; Prince of Songkla University (Thailand); Great Barrier Reef Organization

Scientific Sources: 2- Clive Wilkinson- director of Global Coral Reef Monitoring Network; C. Mark Eakin- Coral Reef Watch- NOAA; James True- biologist- Songkla University

Themes: Coral bleaching; mention of Indonesia and Philippines and Caribbean

Gillis, J. (2011). Figures on global climate show 2010 tied 2005 as hottest year on record. ***The New York Times, Section A*** **(Foreign Desk), 4.**

Summary: 2010 was the wettest year on record, tied with 2005 since record-keeping began in 1880 (says NOAA and NASA). 9 out of the 10 hottest years have occurred since 2001. The United States was wetter and hotter last year than the average values for the 20th century, but over all the year was not as exceptional in this country as for the world as a whole.

Quotes: "a large majority of climatologists say that is because humans are releasing heat-trapping gases like carbon dioxide into the atmosphere. The carbon dioxide level has increased about 40 percent since the Industrial Revolution."

"The new figures confirm that 2010 will go down as one of the more remarkable years in the annals of climatology … a severe die-off of coral reefs; and a continuation in the global trend of a warming climate."

Electronic pages: 1

Hyperlinks/external sources outside the NYT: 1; NOAA News

Scientific Sources: David R. Easterling- scientist NOAA's National Climate Data Center

Themes: Rising sea temperatures

Kaufman, L. (2012). Intriguing habitats, and careful discussions of climate change. ***The New York Times, Section A*****(Column 0)**

Summary: The New England Aquarium, located in Boston, is doing its part to teach children about how carbon dioxide emissions are impacting the ocean. Many zoos and aquariums now work with conservation organizations and private parties who advocate teaching children about climate change, so the New England Aquarium is attempting to incorporate those values into their presentations. The catch is to do this without alienating visitors. In 2008, a coalition of aquariums carefully constructed a way to communicate with visitors so that they would be intrigued and not discouraged. The association (224 members) has had mostly positive reviews. Studies found that word choice is extremely important. In the case for coral reefs, it has been helpful at the New England Aquarium to give some information about reef and the species that habitat them before launching into the impacts of ocean acidification and bleaching.

Quotes: "A few minutes passed before she told the crowd that corals around the world are bleaching and dying because of a pronounced rise in ocean temperature and acidity."

"Upon leaving, the visitors were briefed on positive steps they could take, like using public transportation or bikes and being cautious about energy consumption."

Electronic pages: 1

Hyperlinks/external sources outside the NYT: 1 National Science Foundation

Scientific Sources: 0

Themes: tourism, zoos and aquariums, conservation, climate change

McDonald, B. (2011). Volunteer Haitian divers hope to aid ailing coral reef, and themselves. *The New York Times, Section A*(Foreign Desk), 9.

Summary: Reef Check, a non-profit organization in California that monitors reef health around the globe, has made a special effort to mitigate the coral reefs along Haiti's coast. It is estimated that roughly 85% of the coral reef surrounding the island has died. Grouper and snapper populations have dwindled, and algae is taking over. There are no marine-protected areas where fishing is restricted, let alone off-limits. Overfishing is a problem, but with Haiti's poverty rates, there is no set regulation to be enforced. Reef Check's program is attempting to use incentive- by protecting the reefs, fishermen will have an opportunity to see the reefs flourish and produce more fish for them to harvest. Through Reef Check, volunteers are mapping reefs foot by foot and creating species counts.

Quotes: "Its extensive coral reef system, an attraction to foreign scuba divers in the 1970s and '80s, has largely died off — partly from sedimentation and climate change, but mostly from overfishing.

Electronic pages: 1

Hyperlinks and external scholarly citations: 0

Scientific sources: 0

Themes: conservation/ Haiti/ overfishing

Nijhuis, M. (2012). Frozen sperm offer a lifeline for coral. *The New York Times, Section D*(Science Desk), 1.

Summary: Dr. Mary Hagedorn is a reproductive physiologist with Smithsonian Institute, who is currently working at the Hawaii Institute of Marine Biology. She is collecting and freezing coral reef sperm and eggs, in a hopeful attempt to restore and possibly rebuild damaged coral reefs. She collects her samples from the Caribbean, Hawaii, and Australia. Coral sexual reproduction maintains genetic diversity within populations, which is linked to a species' ability to adapt to change. Rising sea temperatures have resulted in coral bleaching and disease. Acidification is also a threat. Although marine reserves have been created by various conservation efforts, only 27% of reefs lie within reserve boundaries. Freezing and thawing sperm has had mixed results, and is contingent on the species. "Coral sex is poorly understood;" the spawning phases are closely tied to moon cycles, although researchers are still unsure why. This makes collecting sperm and eggs very difficult, although Hagedorn has been able to collect what she thinks is close to a trillion samples overall.

Quotes: Though Dr. Hagedorn supports these traditional conservation strategies, she is preparing for their failure. While she freezes coral sperm and eggs for future use, colleagues are refining techniques for raising coral in captivity and for reintroducing young corals to their natural habitats.

But she and her colleagues have to struggle to raise money for her efforts, which are often seen as a distraction from the more immediate job of habitat protection. "In an ideal world, we would do both," said Stephen Palumbi, director of the Stanford University Hopkins Marine Station. "Of course, in an ideal world, there would be no funding constraints."

Electronic pages: 1

Hyperlinks/ external links to scholarly sources: 0

Scientific sources: 4; Hagedorn; Greta Abey- biologist at "dockside laboratory on Coconut Island; Stephen Palumbi- director of Stanford University Hopkins Marine Station; Kenneth Storey- crypopreservation reearcher at Carleton University in Ottawa

Themes: reproduction, resilience. conservation,

Rosenthal, E. (2007). How do you ski if there is no snow? *The New York Times, Section C*(Business/Financial Desk), 3.

Summary: Resort owners and tour operators will be strongly affected by climate change, given that their livelihoods are directly related to weather. Scuba clubs will have to adapt to warmer and stormier seas, just as ski resorts may have to accommodate for the bottoms of mountains being without snow. Poor countries that rely on tourism as a main source of income often do not have enough money to make eco-friendly changes to their industry.

Quotes: "It's nice to talk about reducing air travel, but many nation-states depend on it," Mr. Lipman said. "Think about what happens to New Zealand and Australia. More important, what happens to poor countries — the Maldives, Seychelles and Africa — who need it because it is the only way to get tourists in."

Electronic pages: 1

Hyperlinks/ external scholarly sources: 0

Scientific Sources: 0

Themes: tourism/ sea temperature rise/ climate change

Rudolf, Collins, J. (2011). Under the sea, hot, white reefs. *The New York Times, Section WK*(Week in Review), 3.

Summary: Reefs have long faced the damaging impacts of local populations interacting with reefs, such as sedimentation, pollution, and overfishing, Now coral reefs must also combat global warming. The summer of 2010 offered one of the worst recorded episodes of coral bleaching that affected reefs globally. This impact may be as damaging as the only other global-scale bleaching event- 10% of shallow-water corals were killed by heat. 3/4 of reefs are at risk of degradation. Rising carbon dioxide makes the ocean more acidic, which in turn kills corals. In the past two decades, significant conservation efforts have been made to educate coastal communities about sustainable fishing, agriculture, and development practices.

Quotes: "Coral reefs, which cover barely 0.2 percent of the ocean floor but contain roughly 25 percent of the ocean's biodiversity, provide a crucial source of protein for an estimated 500 million people, protect shorelines from tsunamis and tropical storms and attract tourists that sustain coastal economies with tens of billions of dollars in annual revenue."

Electronic pages: 1

Hyperlinks/ external links outside NYT: 0

Scientific Sources: 2 Nancy Knowlton- marine biologist at Smithsonian Institute; Katharina Fabricius- coral reef ecologist with Australian Institute of Marine Science; Lauretta Burke- reef biologist (from where??)

Studies mentioned: report by World Resources Institute; report by Global Coral Reef Monitoring Network; a "new study" by an international research team linking coral reef damage to carbon emissions;

Themes: Sea temperature rise/ coral bleaching/ carbon emissions and broad CC discussion

Tsui, B. (2007). Saving coral reefs becomes a tourism priority. *The New York Times, Section 5*(Travel Desk), 13.

Summary: The tourism industry is trying to halt climate change, which makes sense when you consider the enormous impact that coral reefs can contribute to the industry. The GBR alone draws 1.9 million visitors annually, and the annual economic value of coral reefs to worldwide tourism is $9.6 billion. The GBR is not the most threatened, because it has marine management and conservation efforts including no-take zones, environmental tourist fees, and eco-certification programs for tourism operators within the park. The MesoAmerican Reef, however, is very threatened bicoastal development and overfishing, as is the Coral Triangle in Southeast Asia.

Quotes: All three reef systems — the Great Barrier Reef, the Mesoamerican Reef and the Coral Triangle — are jeopardized by the threat of global warming, which kills coral and leads to a bleaching effect. And while tourism cannot solve the problem of rising sea temperatures, the industry's cooperation to eliminate specific pressures — by establishing a well-enforced no-take zone, or reducing wastewater pollution, for example — helps reefs recover from bleaching and disease. The contribution of conservation fees to support the protected areas, which many businesses have long resisted, is also important.

Hyperlinks/ external links outside NYT: 0

Scientific Sources: 0

Themes: tourism/ conservation/ GBR, Caribbean, Coral Triangle

Zimmer, C. (2011). Multitude of species face threat of warming. *Section D, Section D* (Science Desk), 1.

Summary: Scientists have been suggesting that humans are paving the way for a 6th mass extinction, and scientists at UC Berkeley are testing this hypothesis. The current rate of extinction is far above normal., and the Berkeley scientists suggest that they may be underestimating the rate of extinction. Scientists are pushing back against detailed timelines for when and how many species will go extinct. In 2003, a study showed that 1,700 species' ranges were moving toward the poles and up mountain slopes. Conisdering this a global phenomenon, the scientists linked it to global warming. Other studies suggest that individual species may be adapting to temperatures increases, such as the brown butterfly. But attributing individual biological changes to global warming is argued to be the wrong way to go. Individual species offer a complicated, blurry lens to climate change, but an overarching picture shows that they are adapting.

Quotes: "'We need to stand firm about the real complexity of biological systems and not let policy makers push us into simplistic answers,' said Camille Parmesan, a biologist at University of Texas. She and others studying climate's effects on biodiversity are calling for conservation measures that don't rely on impossible precision."

"Scientists in Australia have found that coral reefs are more resilient against global warming, for example, if they're protected from overfishing. The warming oceans stimulate the growth of deadly algae on the reefs. But grazing fish can keep the algae in check."

Electronic pages: 1

Hyperlinks/external links: 7- Nature Journal;

Parmesan, Camille. (2003). A Globally Coherent Fingerprint of Climate Change Impacts Across Natural Systems. Nature 421, 37-42.

Kearney, et al. (2010). Early Emergence in a Butterfly Casually Linked to Anthropogenic Warming. Biology Letters.

Parmesan, Camille, et al. (2011). Overstretching attribution. *Nature Climate Change* **1**, 2–4

Thomas, Chris D., et al. (2004). Extinction risk from climate change. Nature 427, 145-148

Dawson, Terence, et al. (2011). Beyond Predictions: Biodiversity Conservation in a Changing Climate. Science 332 (6025); pp 55-58

Scientific Sources: 6- UC Berkeley scientists; Camille Parmesan- U of Texas biologist; Michael Kearney of the University of Melbourne; Richard Pearson, the director of biodiversity informatics research at the American Museum of Natural History; Dáithí Stone, a climate scientist at the University of Cape Town in South Africa; Georgina Mace of Imperial College London

Themes: species extinction/ climate change/ warming ocean/ adaptation

APPENDIX D: Scholarly Journal Articles Annotated Bibliography

Adam, T. C., Schmitt, R. J., Holbrook, S. J., Brooks, A. J., Edmunds, P. J., Carpenter, R. C., & Bernardi, G. (2011). Herbivory, connectivity, and ecosystem resilience: Response of a coral reef to a large-scale perturbation. *PLoS One, 6*(8).

Abstract: Coral reefs world-wide are threatened by escalating local and global impacts, and some impacted reefs have shifted from coral dominance to a state dominated by macroalgae. Therefore, there is a growing need to understand the processes that affect the capacity of these ecosystems to return to coral dominance following disturbances, including those that prevent the establishment of persistent stands of macroalgae. Unlike many reefs in the Caribbean, over the last several decades, reefs around the Indo-Pacific island of Moorea, French Polynesia have consistently returned to coral dominance following major perturbations without shifting to a macroalgae-dominated state. Here, we present evidence of a rapid increase in populations of herbivorous fishes following the most recent perturbation, and show that grazing by these herbivores has prevented the establishment of macroalgae following near complete loss of coral on offshore reefs. Importantly, we found the positive response of herbivorous fishes to increased benthic primary productivity associated with coral loss was driven largely by parrotfishes that initially recruit to stable nursery habitat within the lagoons before moving to offshore reefs later in life. These results underscore the importance of connectivity between the lagoon and offshore reefs for preventing the establishment of macroalgae following disturbances, and indicate that protecting nearshore nursery habitat of herbivorous fishes is critical for maintaining reef resilience.

Questions this article answers: what are the processes that affect the capacity of ecosystems to return to coral dominance after disturbances? How do herbivorous fish impact recovery ecosystems?

Methodology: time series data collections from six sites around Moorea, French Polynesia; field experiment on the forereef for herbivorous fish

Findings:

- Crown-of-thorn starfish (COTS) began increasing in density in 2007 (peak density 2008 and 2009) then declined in 2010
- The cover of live coral on the forereef declined by ,90%, from ,40% in 2005 to ,5% in 2010
- By 2010, macroalgae had returned to predisturbance levels, and ,90% of the substrate on the forereef was occupied by closely cropped filamentous turfing algae and/or crustose coralline algae
- Temporal patterns of abundance in the lagoons differed sharply from those on the forereef

- COTS were an order of magnitude less abundant on the backreef and fringing reef compared to the peak densities observed on the forereef
- Following the decline in cover of live coral, the herbivore assemblage on the forereef became increasingly dominated by parrotfish
- Parrotfish biomass was dominated by two species, Chlorurus sordidus and Scarus psittacus: together accounted for ,80% of the total parrotfish biomass on the forereef in 2010.
- Some reefs have exhibited the capacity to return to coral dominance following large-scale perturbations, others have failed to do so, and many of these have become dominated by macroalgae (easier to prevent macroalgae than reverse it)
- After near complete loss of coral, the forereef community on Moorea has not become dominated by macroalgae.
    - Coral decline was accompanied by a rapid and sustained increase in populations of herbivorous fish (particularly parrotfish) whose intense grazing has kept algae in a closely cropped state
- Results strongly suggest that herbivorous fish were food limited prior to the COTS outbreak and that an increase in benthic primary production associated with coral decline stimulated rapid population growth

Quotes:
"Importantly, our results demonstrate that increases in the biomass of herbivorous fishes on the forereef of Moorea were due to population growth and increases in biomass of individuals, and not simply redistribution among habitats."

"Indeed, habitat-providing species in inshore nurseries are likely to respond differently to perturbations— including those associated with climate change—than corals on offshore reefs [44]. For example, our results indicate that corals in inshore nurseries in Moorea underwent strikingly different dynamics in response to the COTS outbreak than corals on nearby offshore reefs, with coral cover in the lagoon changing little despite near complete loss of coral along ,50 km of coastline on the forereef."

Anthony, K., Maynard, J. A., Diaz-Pulido, Guillermo., Mumby, P. J., Marshall, P. A., Cao, L., & HOEGH‐GULDBERG, O. V. E. (2011). Ocean acidification and warming will lower coral reef resilience. *Global Change Biology*, *17*(5), 1798-1808.

Source type: journal article

Abstract: Ocean warming and acidification from increasing levels of atmospheric CO_2 represent major global threats to coral reefs, and are in many regions exacerbated by local-scale disturbances such as overfishing and nutrient enrichment. Our understanding of global threats and local-scale disturbances on reefs is growing, but their relative contribution to reef resilience and vulnerability in the future is unclear. Here, we analyse

quantitatively how different combinations of CO_2 and fishing pressure on herbivores will affect the ecological resilience of a simplified benthic reef community, as defined by its capacity to maintain and recover to coral-dominated states. We use a dynamic community model integrated with the growth and mortality responses for branching corals (*Acropora*) and fleshy macroalgae (*Lobophora*). We operationalize the resilience framework by parameterizing the response function for coral growth (calcification) by ocean acidification and warming, coral bleaching and mortality by warming, macroalgal mortality by herbivore grazing and macroalgal growth via nutrient loading. The model was run for changes in sea surface temperature and water chemistry predicted by the rise in atmospheric CO_2 projected from the IPCC's fossil-fuel intensive A1FI scenario during this century. Results demonstrated that severe acidification and warming alone can lower reef resilience (via impairment of coral growth and increased coral mortality) even under high grazing intensity and low nutrients. Further, the threshold at which herbivore overfishing (reduced grazing) leads to a coral–algal phase shift was lowered by acidification and warming. These analyses support two important conclusions: Firstly, reefs already subjected to herbivore overfishing and nutrification are likely to be more vulnerable to increasing CO_2. Secondly, under CO_2 regimes above 450–500 ppm, management of local-scale disturbances will become critical to keeping reefs within an *Acropora*-rich domain.

Questions this article answers: How do global impacts affect local stressors? How do different combinations of CO2 and fishing pressure on herbivores affect ecological resilience of a simplified benthic reef community?

Methodology: Analytical approach: We extend an existing model (Mumby *et al*., 2007) to analyze how increasing CO_2 and the local-scale disturbances overfishing and nutrification operate mechanistically in defining coral resilience.Approach does not provide absolute measures of coral and macroalgal abundance with high confidence, but allows an analytical comparison of the relative roles of environmental and ecological processes as drivers of resilience patterns

Findings:

- Ocean acidification and warming are critical drivers of resilience via impacts on coral growth rates and survivorship
- The predicted loss of corals didn’t lead to increase in macroalgae, instead lead to increase in free space
- A key result of our analyses was that warming and acidification interact with reduced grazing rates (due to overfishing or disease of herbivores) in the decline of coral resilience (i.e. referring to the probability patterns of coral abundance)
- For the modelled system, moderate to high herbivore grazing intensity can prevent losses in coral resilience under intermediate CO_2, but maximum grazing rates are required to maintain coral-dominated states under the very high CO_2 levels representative of the end point of the A1FI scenario
- By reducing coral growth (due to acidification) and survivorship (due to warming), increasing CO_2 will lower the threshold value at which local and regional processes like herbivore overfishing and nutrification drive the study

community from predominantly coral-dominated to predominantly algal-dominated states
- Therefore, warming, acidification, overfishing and nutrification all drive the dynamics of the system in the same direction, suggesting that reduced coral resilience in a high-CO_2 world is likely to be a consequence of both global threats and local-scale disturbances.

Quotes:

- "These findings have far-reaching implications for the health of coral reefs in the future for at least two reasons. Firstly, under a fossil-fuel intensive carbon emission path (the A1FI scenario by the IPCC) – the current global trajectory – acidification effects on coral calcification and increased coral mortality from bleaching may potentially reduce *Acropora* abundance to less than half the current abundances despite high rates of grazing and low levels of nutrification"
- Based on the likely shift from coral dominance to algal dominance under the high CO_2 and low grazing scenario in Fig. 4c, it can be inferred that coral reefs in developing nations, where most of the world's reefs occur and overfishing and nutrification remain key concerns (Silvestre & Pauly, 1997; McClanahan, 1999; Jackson *et al*., 2001; Knowlton & Jackson, 2008), are particularly vulnerable to acidification and warming.
- "While coral dominance is possible in our model projections under high CO_2 and high grazing, the combination of high CO_2 and low grazing (herbivore loss) leads to severe coral loss even under the highly conservative assumptions made here."

Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S., & Hoegh-Guldberg, O. (2008). Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences*, *105*(45), 17442-17446.

Abstract: Ocean acidification represents a key threat to coral reefs by reducing the calcification rate of framework builders. In addition, acidification is likely to affect the relationship between corals and their symbiotic dinoflagellates and the productivity of this association. However, little is known about how acidification impacts on the physiology of reef builders and how acidification interacts with warming. Here, we report on an 8-week study that compared bleaching, productivity, and calcification responses of crustose coralline algae (CCA) and branching (*Acropora*) and massive (*Porites*) coral species in response to acidification and warming. Using a 30-tank experimental system, we manipulated CO2 levels to simulate doubling and three- to fourfold increases

[Intergovernmental Panel on Climate Change (IPCC) projection categories IV and VI] relative to present-day levels under cool and warm scenarios. Results indicated that high CO2 is a bleaching agent for corals and CCA under high irradiance, acting synergistically with warming to lower thermal bleaching thresholds. We propose that CO2 induces bleaching via its impact on photoprotective mechanisms of the photosystems. Overall, acidification impacted more strongly on bleaching and productivity than on calcification. Interestingly, the intermediate, warm CO2 scenario led to a 30% increase in productivity in *Acropora*, whereas high CO2 lead to zero productivity in both corals. CCA were most sensitive to acidification, with high CO2 leading to negative productivity and high rates of net dissolution. Our findings suggest that sensitive reef-building species such as CCA may be pushed beyond their thresholds for growth and survival within the next few decades whereas corals will show delayed and mixed responses.

Questions this article answers: How does acidification impacts the physiology of reef builders and how acidification interacts with warming?

Methodology: 8-week study; compared bleaching productivity, and calcification responses of crustose coralline algae (CCA) and branching (*Acropora*) and massive (*Porites*) coral species in response to acidification and warming. Manipulated Co2 levels to simulate doubling, three, and fourfold increases.

Findings:

- High-CO2 dosing led to 40_50% bleaching for the CCA and *Acropora* after 8 weeks of experimentation
- For the CCA and *Acropora*, the effect of CO2 dosing on bleaching was stronger than the effect of temperature: high-CO2 dosing led to a two- to threefold increase in bleaching relative to the control, whereas high temperature led to only 20% increase in bleaching for these species.
- Our results indicated that prolonged CO2 dosing (representative of CO2 stabilization categories IV and VI by the IPCC) (19) causes bleaching (loss of pigmentation) in two key groups of reef-building organisms
- The bleaching results indicate that future predictions of bleaching in response to global warming must also take account of the additional effect of acidification and suggests that any potential adaptation and acclimatization by coral reef organisms to thermal stress (20, 21) may be offset or overridden by CO2 effects

Quotes: Previous studies of CO2 enrichment and warming in corals and algae have not observed a bleaching response (22, 23). One explanation is that this study used a higher natural irradiance (average of _1000 _mol photons m_2 s_1), which is a key bleaching agent in corals (24), thereby bringing organisms closer to their bleaching thresholds.

Ateweberhan, M., McClanahan, T. R., Graham, N. A. J., & Sheppard, C. R. C. (2011). Episodic heterogeneous decline and recovery of coral cover in the indian ocean. *Coral Reefs, 30*, 739-752.

Abstract: Long-term changes in coral cover for the Caribbean and the Pacific/Southeast Asia regions (PSEA) have proven extremely useful in assessing the main drivers, magnitude and timescales of change. The one major coral reef region where such assessments have not been made is the Indian Ocean (IO). Here, we compiled coral cover survey data from across the IO into a database of *2,000 surveys from 366 coral reef sites collected between 1977 and 2005. The compilation shows that the 1998 mass coral bleaching event was the single most important and widespread factor influencing the change in coral cover across the region. The trend in coral cover followed a step-type function driven by the 1998 period, which differs from findings in the Caribbean and the PSEA regions where declines have been more continuous and mostly began in the 1980s. Significant regional variation was observed, with most heterogeneity occurring during and after 1998. There was a significant relationship between cover and longitude for all periods, but the relationship became stronger in the period immediately after 1998. Before 1998, highest coral cover was observed in the central IO region, while this changed to the eastern region after 1998. Coral cover and latitude displayed a significant U-shaped relationship immediately after 1998, due to a large decrease in cover in the northern-central regions. Post-1998 coral cover was directly correlated to the impact of the disturbance; areas with the lowest mortality having the highest cover with India–Sri Lanka being an outlier due to its exceptionally high recovery. In 1998, reefs within Marine Protected Areas (MPAs) were more heavily impacted than unmanaged reefs, losing significantly greater total cover. MPA recovery was greater such that no differences were observed by 2001–2005. This study indicates that the regional patterns in coral cover distribution in the IO are driven mainly by episodic and acute environmental stress.

Questions this article answers: what are the long-term changes in coral cover in the Indian Ocean?

Methodology: literature review: compiled coral cover survey data from 1977-2005

Findings:

- The Indian Ocean region (IO) remains the one major global coral reef region where little is known about the timing, rate, or spatial variability in coral cover change over the past few decades
- Temporal variation in region-wide coral cover
    - Regional cover was lowest in 1998and highest in 1995-1997
- The distribution properties of the coral cover reflect the change in cover before and after 1998 (El Nino)
- Reefs in central western Indian Ocean Islands (CIOI), the Arabian/Persian Gulf (GULF), and IND–SRI had the highest absolute decline in mean cover across 1998 (32–35%) followed by East Africa
- EIO (eastern region), RS–GA (Red Sea and Gulf of Aden), and SWIOI

(southwestern Indian Ocean) had lower declines (4.0–8.7%), while MOZ–SAF had a marginal increase in cover (1%).

- 1998 temperature anomaly was the single most important factor influencing regional change in coral cover in the Indian Ocean
- The main decline in the 1980s was either due to white band disease and subsequent bleaching impacts or due to high hurricane activity
- High initial coral cover and the fast post-1998 recovery-
    - Suggest that IO reefs under less pressure from other stress factors that caused major declines and no recovery in cover in the Caribbean and the rest of the Indo-Pacific (coral diseases and mass predation by crown of thorns starfish)
- Temporal change in relationship between coral cover and lat/long- spatial gradient of environmental variables affecting coral cover change (ex. Negative relationship between thermal stress and latitude)
- The 2001–2005 coral cover was directly correlated with the cover immediately after 1998-
    - Indicates that coral cover on most of the reefs has not recovered to the level of pre-1998 and the impact was still visible at the end of the study.

Quotes:
"It is highly likely that the 1998 disturbance will continue to shape future responses. For example, Maynard et al. (2008) found a greater thermal tolerance of Great Barrier Reef corals to a strong bleaching event in 2002 compared with an earlier, weaker one in 1998. Similarly, comparison of bleaching events in the eastern Pacific indicated higher thermal tolerance to the stronger 1998 bleaching event compared with a slightly weaker 1982/1983 event." 749

"The general trend in coral cover differs from observations in the wider Caribbean and the Pacific/SE Asia regions where decline in coral cover has been more uniform, started much earlier in the 1980s, and was linked with other anthropogenic factors. In contrast, the broad IO-wide change was mainly linked with the 1998 bleaching disturbance and there has been a steady regionwide recovery." 751

Baker, A. C., Glynn, P. W., & Riegl, B. (2008). Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, *80*(4), 435-471.

Abstract: Since the early 1980s, episodes of coral reef bleaching and mortality, due primarily to climate-induced ocean warming, have occurred almost annually in one or more of the world's tropical or subtropical seas. Bleaching is episodic, with the most severe events typically accompanying coupled ocean–atmosphere phenomena, such as the El Niño-Southern Oscillation (ENSO), which result in sustained regional elevations of ocean temperature. Using this extended dataset (25+ years), we review the short- and

long-term ecological impacts of coral bleaching on reef ecosystems, and quantitatively synthesize recovery data worldwide. Bleaching episodes have resulted in catastrophic loss of coral cover in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics. Bleaching has also set the stage for other declines in reef health, such as increases in coral diseases, the breakdown of reef framework by bioeroders, and the loss of critical habitat for associated reef fishes and other biota. Secondary ecological effects, such as the concentration of predators on remnant surviving coral populations, have also accelerated the pace of decline in some areas.

Questions this article answers: What are the short term and long-term impacts of coral bleaching on reef ecosystems? Can affected reefs continue to function as they had prior to bleaching episodes?

Methodology: quantitatively synthesized recovery data worldwide, looking at 25-year span of bleaching episodes

Findings:

- Although bleaching severity and recovery have been variable across all spatial scales, some reefs have experienced relatively rapid recovery from severe bleaching impacts. There has been a significant overall recovery of coral cover in the Indian Ocean, where many reefs were devastated by a single large bleaching event in 1998.
- In contrast, coral cover on western Atlantic reefs has generally continued to decline in response to multiple smaller bleaching events and a diverse set of chronic secondary stressors. No clear trends are apparent in the eastern Pacific, the central-southern-western Pacific or the Arabian Gulf, where some reefs are recovering and others are not.
- Whether or not affected reefs can continue to function as before will depend on:
    - How much coral cover is lost, and which species are locally extirpated
    - The ability of remnant and recovering coral communities to adapt or acclimatize to higher temperatures and other climatic factors such as reductions in aragonite saturation state
    - The changing balance between reef accumulation and bioerosion
    - Our ability to maintain ecosystem resilience by restoring healthy levels of herbivory, macroalgal cover, and coral recruitment

Quotes:

- “Since human populations inhabiting tropical coastal areas derive great value from coral reefs, the degradation of these ecosystems as a result of coral bleaching and its associated impacts is of considerable societal, as well as biological concern.”
- “If significant reductions in greenhouse gas emissions can be achieved within the next two to three decades, maximizing coral survivorship during this time may be critical to ensuring healthy reefs can recover in the long term.”

Barshis, D. J., Stillman, J. H., Gates, R. D., & et al. (2010). Protein expression and genetic structure of the coral porites lobata in an environmentally extreme samoan back reef: Does host genotype limit phototypic plasticity? *Molecular Ecology, 19*(8), 1705-1720.

Abstract: The degree to which coral reef ecosystems will be impacted by global climate change depends on regional and local differences in corals' susceptibility and resilience to environmental stressors. Here, we present data from a reciprocal transplant experiment using the common reef building coral Porites lobata between a highly fluctuating back reef environment that reaches stressful daily extremes, and a more stable, neighbouring forereef. Protein biomarker analyses assessing physiological contributions to stress resistance showed evidence for both fixed and environmental influence on biomarker response. Fixed influences were strongest for ubiquitin-conjugated proteins with consistently higher levels found in back reef source colonies both pre and posttransplant when compared with their forereef conspecifics. Additionally, genetic comparisons of back reef and forereef populations revealed significant population structure of both the nuclear ribosomal and mitochondrial genomes of the coral host (FST = 0.146 $P < 0.0001$, FST = 0.335 $P < 0.0001$ for rDNA and mtDNA, respectively), whereas algal endosymbiont populations were genetically indistinguishable between the two sites. We propose that the genotype of the coral host may drive limitations to the physiological responses of these corals when faced with new environmental conditions. This result is important in understanding genotypic and environmental interactions in the coral algal symbiosis and how corals may respond to future environmental changes.

Questions this article answers: What are the regional and local differences in coral's susceptibility and resilience to environmental stressors (climate change)?

Methodology: reciprocal transplant experiment using the common reef building coral Porites lobata between a highly fluctuating back reef environment that reaches stressful daily extremes, and a more stable, neighbouring forereef.

Findings:

- Host genetic background can alter such physiological responses as upper thermal tolerance limits across taxonomic and latitudinal gradients
- Coral response is a function of genotype and environmental influence: 3 of the 4 colonies showed substantial variation in response to the different characteristics of fore and back reef enviros
- The influence of source colony origin on the ubiquitin response appears stronger than that of transplant destination
- Genotypes of corals drive limitations to physiological responses of corals when they're in new environmental conditions
- Beneficial aspects of exposure to fluctuating temperatures such as increases in

growth and thermal tolerance limits

Baskett, M. L., Gaines, S. D., & Nisbet, R. M. (2009). Symbiont diversity may help coral reefs survive moderate climate change. *Ecological Applications*, *19*(1), 3-17.

Source Type: journal article

Abstract: Given climate change, thermal stress-related mass coral-bleaching events present one of the greatest anthropogenic threats to coral reefs. While corals and their symbiotic algae may respond to future temperatures through genetic adaptation and shifts in community compositions, the climate may change too rapidly for coral response. To test this potential for response, here we develop a model of coral and symbiont ecological dynamics and symbiont evolutionary dynamics. Model results without variation in symbiont thermal tolerance predict coral reef collapse within decades under multiple future climate scenarios, consistent with previous threshold-based predictions. However, model results with genetic or community-level variation in symbiont thermal tolerance can predict coral reef persistence into the next century, provided low enough greenhouse gas emissions occur. Therefore, the level of greenhouse gas emissions will have a significant effect on the future of coral reefs, and accounting for biodiversity and biological dynamics is vital to estimating the size of this effect.

Questions this article answers: Will the climate change too rapidly for genetic adaptation and shifts in coral reef community composition? How quickly can symbiont evolutionary dynamics adapt?

Methodology: Quantitative genetic model of coral and symbiont ecological dynamics/symbiont evolutionary dynamics: This model provides an example approach to exploring the interaction between ecological and evolutionary dynamics in a changing climate

Findings:

- The model presented here explores the community and genetic dynamics of corals and their symbiotic algae given variation in thermal tolerance and different climate scenarios.
- The persistence of coral reefs depends on the potential for coral communities to respond to climate change. In coral reefs, local adaptation and acclimatization to high average temperatures and recurrent thermal stress have occurred
- The climate may change too rapidly for coral communities to respond in reality
- Given past temperature data (ISST). all three simulations predict coral persistence with declines in coral cover during previously observed major bleaching events
- Given future temperature data from the more severe (SRES A1b) climate scenario, all three simulations predict coral collapse within the next century, with the earliest collapse in simulations without symbiont diversity and the latest collapse in simulations with symbiont community diversity

- Given future temperature data from the less severe (SRES B1) climate scenario, simulations without symbiont diversity predict coral collapse, while simulations with symbiont diversity predict coral persistence, with greater coral cover in simulations with community diversity compared to genetic diversity
- Assuming limited thermal tolerance (as suggested by the bleaching mortality in the relatively stress-tolerant massive Porites first reported during the 1998 bleaching event [Mumby et al. 2001]), substantial declines in the slow-growing species may, within decades, follow the collapse of the fast-growing species.
- Our model results suggest that a shift in the dominant corals to slowergrowing, thermal-stress-tolerant species may be a transient indicator of overall coral reef decline provided continued climate change.

Quotes:

- "In summary, symbiont diversity, on both the genetic and community levels, has the potential to allow coral reef persistence over some scenarios for the next 100 years of climate change" – pg 14
- "Some corals may harbor only one symbiont type and thus lack the capacity to respond to future climate change through symbiont community shifts"-pg 14
- "Therefore, provided a conservation goal of protecting coral reefs more likely to be resistant and resilient to future climate change (West and Salm 2003), empirically measuring symbiont genetic variation and community composition may be vital to identifying coral reefs to target for protection from additional anthropogenic impacts."14

Bauman, A. G., Baird, A. H., & Cavalcante, G. H. (2011). Coral reproduction in the world's warmest reefs: Southern persian gulf (dubai, united arab emirates). *Coral Reefs, 30*(2), 405-413

Abstract: Despite extensive research on coral reproduction from numerous geographic locations, there remains limited knowledge within the Persian Gulf. Given that corals in the Persian Gulf exist in one of the most stressful environments for reef corals, with annual variations in sea surface temperature (SST) of 12_C and maximum summer mean SSTs of 36_C, understanding coral reproductive biology in the Gulf may provide clues as to how corals may cope with global warming. In this study, we examined six locally common coral species on two shallow reef sites in Dubai, United Arab Emirates (UAE), in 2008 and 2009 to investigate the patterns of reproduction, in particular the timing and synchrony of spawning. In total, 71% colonies in April 2008 and 63% colonies in April 2009 contained mature oocytes. However, the presence of mature gametes in May indicated that spawning was potentially split between April and May in all species. These results demonstrate that coral reproduction patterns within this region are highly seasonal and that multi-species spawning synchrony is highly probable. Acropora downingi, Cyphastrea microphthalma and Platygyra daedalea were all hermaphroditic broadcast spawners with a single annual gametogenic cycle. Furthermore, fecundity and mature oocyte sizes were comparable to those in other regions. We conclude that the reproductive biology of corals in the southern Persian Gulf is similar to other regions, indicating that these species have adapted to the extreme environmental conditions in the southern Persian Gulf.

Questions this article answers: Are corals in the southern Persian Gulf reproductively active? What are the months of spawning (of the six common coral species within the region)? What is the reproductive biology of three abundant species: *Acropora downingi, Cyphastrea*
microphthalma and Platygyra daedalea.

Methodology: The reproductive conditions of six locally common coral species from the southern Persian Gulf were examined monthly from January 2008 to August 2009. Surveys were conducted at two shallow (\5.0 m) near-shore reef sites in Dubai, UAE

Findings:

- Coral assemblages in the Persian Gulf (24–30_N) experience the highest annual variability in water temperatures of any coral reefs
- Considering that corals in the Persian Gulf survive in one of the most stressful physical environments encountered by any reef corals, understanding the process of coral reproduction under such extreme physical conditions may be crucial as similar conditions may eventually become commonplace on a broad range of coral reefs due to climate change
- Spawning months: all species contained the highest proportion of mature colonies prior to the full moon in April (2008 and 2009)
- April 2008- 71% of colonies contained mature colonies; April 2009- 635 contained mature colonies
- Reproductive biology of *Acropora downingi, Cyphastrea microphthalma and Platygyra daedalea:*
    - All three species are simultaneous hermaphrodites that broadcast spawn their gametes.
    - C. microphthalma and P. daedalea are broadcast spawners; All three species have a single annual gametogenic cycles
- Coral reproduction was seasonal, with peak reproductive activity in April, corresponding to rising mean SST above 26.5_C.
- The reproductive biology of these species appears to be well adapted to extreme annual environmental fluctuations in the Gulf
- The rapid recovery of Acropora assemblages in the Gulf following recurrent bleaching events in the Gulf suggests that sexual reproduction remains the dominant reproductive strategy

Quotes:
"The adaptive capacity of corals in the Persian Gulf is likely facilitated by a combination of short-term acclimation in individuals during acute environmental conditions (e.g., recurrent bleaching events) and long-term adaptation among coral populations to chronic

environmental conditions (e.g., extreme temperatures).” 410

“Whether future coral populations in the southern Persian Gulf are capable of reproductive activities under more extreme environmental conditions as a result of climate change will likely depend on how quickly they are able to adapt.” 411

“Overall, this work provides the first information on the timing of reproduction and spawning of a range of corals within the southern Persian Gulf and confirms that corals are capable of reproductive activities under extreme environmental conditions. Importantly, such findings provide circumstantial evidence that coral can adapt to extreme environments; the question remains how quickly this capacity can evolve.” 411

Bauman, A. G., Burt, J. A., Feary, D. A., & et al. (2010). Tropical harmful algal blooms: An emerging threat to coral reef communities? *Marine Pollution Bulletin, 60*(11), 2117-2122.

Abstract: Tropical harmful algal blooms (HABs) are increasing in frequency and intensity and are substantially affecting marine communities. In October/November 2008 a large-scale HAB event (> 500 km2, dinoflagellate Cochlodinium polykrikoides) in the Gulf of Oman caused the complete loss of the branching corals, Pocillopora and Acropora spp., and substantial reductions in the abundance, richness and trophic diversity of the associated coral reef fish communities. Although the causative agents of this C. polykrikoides bloom are unknown, increased coastal enrichment, natural oceanographic mechanisms, and the recent expansion of this species within ballast water discharge are expected to be the main agents. With rapid changes in oceanic climate, enhanced coastal eutrophication and increased global distribution of HAB species within ballast water, large-scale HAB events are predicted to increase dramatically in both intensity and distribution and can be expected to have increasingly negative effects on coral reef communities globally.

Questions this article answers: what was the role of the large-scale HAB event in the Gulf of Oman? Did it alter the benthic coral reef community and the associated fish community? What is the importance of such disturbance events in structuring the composition, abundance, and diversity of coral communities?

Methodology: The study was conducted at two locations in the Gulf of Oman; Dibba (25_360N, 56_210E) and East Musandam (25_460N, 56_200E). Each location was initially surveyed in November 2008; following these surveys, a large-scale 500 km2) dinoflagellate bloom occurred throughout the Gulf of Oman. The bloom was first reported in September 2008 elsewhere in Oman (Richlen et al., 2010), although the peak of the bloom occurred in November 2008 at our locations. Corals and fish were again surveyed at each location in December 2008.

Findings:

- There was exceptionally high biomass of phytoplankton at the surface (1 m depth) within the inshore sites, which was substantially reduced at 6 m
- Benthic community- changes in coral cover at both locations may have been due to substantial reductions in oxygen during the HAB event
    - Low dissolved oxygen levels during algal blooms have been identified as one of the primary causes of benthic mortality, and the combination of reduced surface light penetration and anoxia are likely to have rapidly decreased coral photosynthetic efficiency and increasing respiratory rates
- The HAB event resulted in significant declines in fish abundance at both locations
- Both species composition and functional composition changed significantly at both locations in association with the HAB event
    - Change in species composition- mainly due to the reduction and/or complete elimination of the majority species
    - The change in functional composition at both locations was mainly due to reductions in the majority of functional groups, with the majority of change at both locations associated with substantial reductions in the abundance of both invertivores and planktivores
- The changes in fish community structure associated with the HAB event are most likely to have resulted from increased mortality of individuals because:
    - Fish move between reefs in response to disturbance and seasonal migrations occur in this region; however suggeststhat movement of individual away from the bloom would be negligible, except at the margins. In concurrence, dead fishes were observed during the HAB and fish die-offs were reported elsewhere in the region during this period
    - Similar mass mortalities of fish communities have been associated with HAB events in both temperate and tropical environments, suggesting that large-scale changes in fish community structure may be a common result of HAB.
- The effects of HAB are very similar to the changes in coral community structure as observed during severe bleaching events.

Quotes:

"In combination with other stressors predicted to increase in the coming decades (i.e., temperature, acidification, eutrophication, etc.), HAB may contribute to the permanent alteration of the structure and function of coral reef communities. Further research is required to understand the synergistic effects of anthropogenic eutrophication and climate change on increasing HAB events and their potential impacts on coral reef ecosystems." 2121

Bennett, S., Verges, A., & Bellwood, D. R. (2010). Branching coral as a macroalgal

refuge in a marginal coral reef system. ***Coral Reefs, 29*****(2), 471-480.**

Abstract: Marginal coral reef systems may provide valuable insights into the nature of ecosystem processes in systems on the trajectory towards a phase shift to an alternate ecosystem state. This study investigates the process of herbivory in a marginal coral reef system in the Keppel Islands at the southern end of the Great Barrier Reef. Branching Acropora coral and the brown macroalga
Lobophora variegata occupied up to 95% of the reef crest substratum at the three surveyed reefs. Feeding rates of herbivorous fishes and removal rates of Lobophora were directly quantified within areas of branching Acropora and on planar surfaces. Feeding rates by herbivorous fishes were habitat dependent with the highest bite rates being found in planar habitats for both Lobophora and the epilithic algal matrix (EAM) by 1–2 orders of magnitude, respectively. Feeding rates on Lobophora were, however, much lower than rates on the EAM. The low rates of
Lobophora removal and significantly lower rates of herbivory in branching habitats were consistent with the high biomass of this brown alga throughout the Keppel Islands and with its distribution on reef crests, where Lobophora biomass was 20 times greater in branching than in planar habitats. This lack of feeding by herbivorous fishes within branching coral habitats in the Keppel Islands contrasts with the typical role of coral and topographic complexity on herbivores on coral reefs and highlights the potential for complex interactions between algae, corals and fishes on coral reefs. On marginal systems, herbivory may modify algal distributions but may be unable to contain the proliferation of algae such as Lobophora.

Questions this article answers: what is the process of herbivory in a marginal coral reef system (in the Keppel Islands, southern end of GBR)?

Methodology: December 2008 at three inshore fringing reefs within Keppel Island; each reef, benthic cover was quantified along 8 9 20 m transects along the reef crest using a diver-operated underwater video

Findings:

- The erosion of ecological resilience on coral reefs has been demonstrated across the globe with a decrease in coral cover
- 14 species of roving herbivores from the families Acanthuridae, Kyphosidae, Labridae and Siganidae were recorded on UVC's, within Middle Island, Olive Point and Halfway Island
- Feeding rates by herbivorous fishes were significantly higher in planar than branching habitats for both Lobophora and the EAM.
- Bite rates on Lobophora were relatively low, with both habitats displaying less than 10% consumption of Lobophora assays
- Herbivorous fish feeding rates on EAM were much higher with feeding rates on planar habitats (two orders of magnitude higher than in areas of branching corals)
    - -Consistent with high biomass of brown alga in the 3 study sites
- Using the RUV's allowed for the study to provide independent evidence of low removal rates (of control assays with herbivore exclusion)
- The state of the southern inshore reefs documented in the current study is

dynamic
    - Monospecific stands of branching Acropora in the Keppel Islands have been dominant on the reef crest for at least 20 years until 2006 bleaching event
    - After bleaching event- vegetative growth of branching Acropora has been rapid, resulting in the reduced proportional cover of Lobophora (current state of system)
- Herbivores respond to change, not drive it- probably unable to control the increase in algal biomass on reef crests throughout these benthic dynamics
- In contrast to the understood role of herbivores throughout the rest of the GBR and presents interesting questions about the resilience and future trajectory of marginal systems such as the Keppel Islands

Quotes: "The findings of the current study, therefore, provide an indication of the potential role of some corals in limiting the key role played by herbivores in controlling macroalgae on coral reefs, a coral-mediated limitation that may apply to reefs elsewhere on the GBR and around the world."

Biggs, D. (2011). Understanding resilience in a vulnerable industry: The case of reef tourism in Australia. *Ecology and Society, 16*(1)

Abstract: Understanding the resilience of vulnerable sectors of social-ecological systems is critical in an era of escalating global change. The coral reef tourism sector is highly vulnerable not only to ecological effects of climate change and other anthropogenic disturbances on reefs, but also to shocks such as economic recession and energy price escalation. Commercial tourism enterprises are key players in reef tourism in Australia and elsewhere. However, the factors that confer resilience to reef-based tourism enterprises, or the reef tourism sector more broadly, in the face of large disturbances have not been investigated to date. This paper empirically examines the perceived resilience of reef tourism enterprises on Australia's Great Barrier Reef to large disturbances or shocks. Binary logistic regression analysis of two measures of enterprise resilience demonstrates the importance of human capital in strengthening enterprise resilience. Lifestyle identity, measured as the extent to which owners and senior managers are active in reef tourism as a lifestyle choice, is positively related to enterprise resilience. Finally, reef tourism enterprises indicate that financial and marketing support are the most important actions that government can take to support enterprises in the face of a large shock.

Questions this article answers: what is the resilience of the coral-reef tourism sector (given both the ecological and economic factors involved)?

Methodology: This study collected data in the Cairns and the Whitsundays regions; Surveys (interviews) focused on enterprises whose dominant source of income is taking visitors to reef attractions to dive and snorkel. The author compiled a complete list of reef tourism enterprises that met this criterion in the study area

Findings:

- Enterprises surveyed had an average age of 13.2 years (Table 5), with considerable variation in enterprise size.
- Enterprises had an average of 32.7 employees and a median of 9.5.
- Enterprises indicated that the coral reefs that are the focus of their tourist activities were on average in good condition; Human capital was considered to be good on average (average score 3.8), while social capital, financial condition in a shock scenario, and access to finance in a shock scenario scored lower
- Elevated lifestyle identity among staff and a high level of human capital are the two strongest determinants of perceived resilience of reef tourism enterprises on the Great Barrier Reef.

- Lifestyle choices are often a strong factor in decisions made by owners of small tourism firms, particularly in rural areas
- Human capital is a vital component of enterprise resilience. In specialist markets such as reef tourism, human capital is considered essential in providing a quality product
  - A tourism enterprise whose owners and staff have the capacity to be flexible and adaptive is able to anticipate and respond to crises
- Times of stability and growth in the reef tourism sector may be the best times to conduct training and skills development programs aimed at strengthening the resilience of enterprises to future shocks.

Bonin, M. C., Almany, G. R., & Jones, G. P. (2011). Contrasting effects of habitat loss and fragmentation on coral-associated reef fishes. *Ecology, 92*(7), 1503-1512.

Abstract: Disturbance can result in the fragmentation and/or loss of suitable habitat, both of which can have important consequences for survival, species interactions, and resulting patterns of local diversity. However, effects of habitat loss and fragmentation are typically confounded during disturbance events, and previous attempts to determine their relative significance have proved ineffective. Here we experimentally manipulated live coral habitats to examine the potential independent and interactive effects of habitat loss and fragmentation on survival, abundance, and species richness of recruitment-stage, coral associated reef fishes. Loss of 75% of live coral from experimental reefs resulted in low survival of a coral-associated damselfish and low abundance and richness of other recruits 16 weeks after habitat manipulations. In contrast, fragmentation had positive effects on damselfish survival and resulted in greater abundance and species richness of other recruits. We hypothesize that spacing of habitat through fragmentation weakens competition within and among species. Comparison of effect sizes over the course of the study period revealed that, in the first six weeks following habitat manipulations, the positive effects of fragmentation were at least four times stronger than the effects of habitat loss. This initial positive effect of fragmentation attenuated considerably after 16

weeks, whereas the negative effects of habitat loss increased in strength over time. There was little indication that the amount of habitat influenced the magnitude of the habitat fragmentation effect. Numerous studies have reported dramatic declines in coral reef fish abundance and diversity in response to disturbances that cause the loss and fragmentation of coral habitats. Our results suggest that these declines occur as a result of habitat loss, not habitat fragmentation. Positive fragmentation effects may actually buffer against the negative effects of habitat loss and contribute to the resistance of reef fish populations to declines in coral cover.

Questions this article answers: What is the potential independent and interactive effects of habitat loss and fragmentation on survival, abundance, and species richness of coral reef fishes?

Methodology: (manipulative field experiment) experimentally manipulated live coral habitats to examine the potential independent and interactive effects of habitat loss and fragmentation on survival, abundance, and species richness of recruitment-stage, coral associated reef fishes

Findings:

- Two weeks after habitat manipulations, experimental reefs had similar abundance and species richness, but at 6 weeks, abundance and richness were four times and three times greater, respectively, on fragmented reefs relative to control reefs
- Abundance and richness declined on fragmented reefs between 6 and 16 weeks, the positive effect of fragmentation persisted
- Contrary to expectations, and similar to the results for C. parasema, the positive effects of fragmentation were much stronger than the negative effects of habitat loss 6 weeks following habitat manipulations
- Many potential predators of recruits were associated with experimental reefs, although the abundance of these predators did not differ significantly among treatments
- Although habitat loss and fragmentation are likely to influence species in different ways, disentangling the effects of these two processes has proven difficult.
    - Our results provide evidence for a positive effect of fragmentation and a negative effect of habitat loss
- Sixteen weeks after an experimental disturbance, habitat loss alone had a strong negative effect on survival of transplanted damselfish (C. parasema) recruits, whereas fragmentation alone had little effect on survival
    - Fragmentation had a positive effect on survival when 75% of the habitat was removed
- What could have caused this positive effect of fragmentation on survival in this study? We hypothesize that reduced interference competition for shelter in fragmented habitats led to greater C. parasema survival.
- An alternative explanation for the effects on survival and recruitment could be differences in predator distributions between fragmented and non-fragmented reefs.

Bouma, J. A., Kuik, O., & Dekker, A. G. (2011). Assessing the value of earth observation for managing coral reefs: An example from the great barrier reef. *Science of the Total Environment, 409*, 4497-4503.

Abstract: The Integrated Global Observing Strategy (IGOS, 2003) argues that further investments in Earth Observation information are required to improve coral reef protection worldwide. The IGOS Strategy does not specify what levels of investments are needed nor does it quantify the benefits associated with better-protected reefs. Evaluating costs and benefits is important for determining optimal investment levels and for convincing policy-makers that investments are required indeed. Few studies have quantitatively assessed the economic benefits of Earth Observation information or evaluated the economic value of information for environmental management. This paper uses an expert elicitation approach based on Bayesian Decision Theory to estimate the possible contribution of global Earth Observation to the management of the Great Barrier Reef. The Great Barrier Reef including its lagoon is a World Heritage Area affected by anthropogenic changes in land-use as well as climate change resulting in increased flows of sediments, nutrients and carbon to the GBR lagoon. Since European settlement, nutrient and sediment loads having increased 5-10 times and the change in water quality is causing damages to the reef. Earth Observation information from ocean and coastal color satellite sensors can provide spatially and temporally dense information on sediment flows. We hypothesize that Earth Observation improves decision-making by enabling better-targeted run-off reduction measures and we assess the benefits (cost savings) of this improved targeting by optimizing run-off reductions under different states of the world. The analysis suggests that the benefits of Earth Observation can indeed be substantial, depending on the perceived accuracy of the information and on the prior beliefs of decision-makers. The results indicate that increasing informational accuracy is the most effective way for developers of Earth Observation information to increase the added value of Earth Observation for managing coral reefs.

Buddemeier, R.W., Lane, Diana R., Martinich., J.A. (2011). Modeling regional coral reef responses to global warming and changes in ocean chemistry. *Climatic Change, 109*, 375-397.

Abstract: Climatic change threatens the future of coral reefs in the Caribbean and the important ecosystem services they provide. We used a simulation model [Combo ("Coral Mortality and Bleaching Output")] to estimate future coral cover in the part of the eastern Caribbean impacted by a massive coral bleaching event in 2005. Combo calculates impacts of future climate change on coral reefs by combining impacts from long-term changes in average sea surface temperature (SST) and ocean acidification with impacts from episodic high temperature mortality (bleaching) events.We used mortality and heat dose data from the 2005 bleaching event to select historic temperature datasets, to use as a baseline for running Combo under different future climate scenarios and sets of assumptions. Results suggest a bleak future for coral reefs in the eastern Caribbean. For three different emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC; B1, A1B, and A1FI), coral cover on most Caribbean reefs is projected to drop below 5% by the year 2035, if future mortality rates are equivalent to some of those observed in the 2005 event (50%). For a scenario where corals gain an additional 1–1.5◦C of heat tolerance through a shift in the algae that live in the coral tissue, coral cover above 5% is prolonged until 2065. Additional impacts such as storms or anthropogenic damage could result in declines in coral cover even faster than those projected here. These results suggest the need to identify and preserve the locations that are likely to have a higher resiliency to bleaching to save as many remnant populations of corals aspossible in the face of projected wide-spread coral loss.

Questions this article answers: What might the future coral cover of the eastern Caribbean that was impacted by a massive coral bleaching event in 2005 look like?

Methodology: simulation model to estimate future coral cover in the part of the eastern Caribbean impacted by a massive coral bleaching even in 2005; model gives a 'probabilistic assessment of the effects of different future global climate scenarios on individual corals and on coral reef communities that have the extensive calcium carbonate structures typically associated with reefs."

Findings:

- The Combo model focuses on changes in live coral cover as the key metric for defining the health of coral communities
- Eastern Caribbean may not fully recover from 2005 bleaching event:
    - Coral cover expected to drop 5% by 2035 (if mortality rates are the same as some in 2005)
- Coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035, given the current low cover values following the 2005 event
- We suggest there is strong evidence that the modeling results can be reasonably extrapolated to the Southeast Caribbean (from the data gathered in the Virgin Islands)
    - The Virgin Islands area was used to calibrate doseresponse relationships, both because it is a particularly well-documented area and because the heat doses were generally similar to most of the islands
- Decreasing coral cover is often accompanied by increases in the cover of macroalgae, suggesting that a qualitative shift in the coral community occurs with decreasing coral cover
- It is suggested that future actions to reduce GHG emissions may have little influence on coral bleaching mortality in the Caribbean, which has already been identified as an area especially vulnerable relative to the Indo-Pacific because of its setting and evolutionary history and its failure to demonstrate recovery from

previous coral cover losses

Quotes:
"Given the value of coral reefs as ecosystems with high biodiversity (Knowlton 2001b), the loss of this diversity is itself an important consequence of bleaching. It is certainly possible that a few percent of corals will show successful adaptation or survive in particularly favorable microhabitats. Thus, we are not predicting the complete loss of corals when considered at the organism or taxon level, but highly diverse, viable reef communities in the Eastern Caribbean seem likely to disappear within the lifetime of a single human generation." 394

"Given the modeling results presented here, urgent efforts are needed to identify and protect what appear to be the most resilient coral reefs in the Caribbean.Although the extent to which these efforts could reduce wide-spread bleaching impacts is unknown, any actions that could increase the cover or extent of remnant populations will benefit science and posterity." 394

Cantin, N. E., Cohen, A. L., Karnauskas, K. B., & et al. (2010). Ocean warming slows coral growth in the central red sea. *Science, 329*(5989), 322-325.

Abstract: Sea surface temperature (SST) across much of the tropics has increased by 0.4° to 1°C since the mid-1970s. A parallel increase in the frequency and extent of coral bleaching and mortality has fueled concern that climate change poses a major threat to the survival of coral reef ecosystems worldwide. Here we show that steadily rising SSTs, not ocean acidification, are already driving dramatic changes in the growth of an important reef-building coral in the central Red Sea. Three-dimensional computed tomography analyses of the massive coral Diploastrea heliopora reveal that skeletal growth of apparently healthy colonies has declined by 30% since 1998. The same corals responded to a short-lived warm event in 1941/1942, but recovered within 3 years as the ocean cooled. Combining our data with climate model simulations by the Intergovernmental Panel on Climate Change, we predict that should the current warming trend continue, this coral could cease growing altogether by 2070.

Questions this article answers: How is rising SST changing the growth of reef-building corals in the central Red Sea?

Methodology: experimental and field observations three-dimensional computed tomography analyses of the massive coral Diploastrea heliopora

Findings:
- The combined effects of rising temperatures and ocean acidification could increase the frequency of bleaching events and reduce coral calcification by 80%

of modern values when atmospheric CO2 concentrations reach 560 ppm (around 2055)

- Elevated temperatures suppress the calcification rates of reef-building corals by affecting the relationship between the coral host and its algal symbionts (zooxanthellae).
- Elevated temperatures can negatively affect calcification long before bleaching is evident
- Red Sea corals might be naturally adapted for extreme temps and high salinity (but lack of empirical data about it)
- Decline in coral growth rates is probably a consequence of the impact of thermal stress on the coral host–symbiont relationship

- Increase in duration and intensity of heat stress over the past decade- corresponds directly with decline in skeletal growth and calcification measured in coral cores
- The skeletal growth response to historical SST variability shows that these corals can recover from major warming anomalies if the episodes are short-lived
- It's expected that D. heliopora will cease calcifying altogether by 2070, when summer SSTs will exceed current summer values by 1.85°C (a conservative estimate)
- Data do not suggest that D. heliopora has acquired enhanced resistance, despite a decade of exposure to persistent thermal stress

Cao, L., & Caldeira, K. (2008). Atmospheric CO2 stabilization and ocean acidification. *Geophysical Research Letters*, *35*(19), L19609.

Abstract: We use a coupled climate/carbon-cycle model to examine the consequences of stabilizing atmospheric CO2 at different levels for ocean chemistry. Our simulations show the potential for major damage to at least some ocean ecosystems at atmospheric CO2 stabilization levels as low as 450 ppm. Before the industrial revolution, more than 98% of corals reefs were surrounded by waters that were >3.5 times saturated with respect to their skeleton materials (aragonite). If atmospheric CO2 is stabilized at 450 ppm only 8% of existing coral reefs will be surrounded by water with this saturation level. Also at this CO2 level 7% of the ocean South of 60_S will become undersaturated with respect to aragonite, and parts of the high latitude ocean will experience a decrease in pH by more than 0.2 units. Results presented here provide an independent and additional basis for choosing targets of atmospheric CO2 stabilization levels.

Questions this article answers: What are the consequences of stabilizing atmospheric CO2 at different levels for ocean chemistry? How chemical conditions of seawater surrounding existing coral reefs will change under various CO2 concentrations? What CO2 stabilization levels are required to avoid calcite and/or aragonite undersaturation in different parts of the ocean? How will pH change at different CO2 stabilization levels?

Methodology: Used the Earth System Climate Model version 2.8 to simulate CO2 concentrations: quantitatively studied composition of simulated ocean chemistry. (To relate open water chemistry to that of coral reefs, we obtain the longitude and latitude location of each coral reef from the Reefbase dataset (www.reefbase.org) and then interpolate model-predicted nearby open-water values to each reef location. Non-reef building coral communities are excluded in our analysis.)

Findings:

- In preindustrial times, aragonite saturation ranged from 1.4 in cold polar waters to 4.7 in warm tropical waters; calcite saturation ranged between 2.2 and 7.0
    - With increasing atmospheric CO2 concentrations, high latitude ocean would be the first to become undersaturated with respect to calcium carbonate
- Even with low CO2 stablization levels- (450 ppm) parts of the Southern Ocean will become undersaturated regarding aragonite
- At 550 ppm half of ocean south is undersaturated with respect to aragonite
- 750 ppm- 95% of this area is undersaturated w aragonite
- Little is known about the potential adaptation and acclimation of coral reefs to lower aragonite saturation states, but no adaptation has yet been observed. Corals polyps may continue to persist under low aragonite saturation conditions in soft-body forms lacking calcifiedskeletons [Fine and Tchernov, 2007], but organisms in this state would not be reef builders.
- Increasing atmospheric CO2 concentrations over the past two centuries caused 0.1 units decrease in avg pH for global surface ocean
- Calcification rate of coral reefs may increase with temperature increase, but this increase is unlikely to continue after a temperature rise of 2_C to 3_C
- For example, the effect of climate change on ocean chemistry is to somewhat diminish the CO2-induced decrease in aragonite saturation state around coral reefs

Quotes:

- "At the CO2 stabilization level of 450 ppm, more than 10% of the surface ocean, including a large portion of the Southern, North Pacific, and Arctic oceans, experiences a pH decrease of more than 0.2 units, in violation of the criteria set forth by the U.S. Environmental Protection Agency [1976] that ''for open ocean waters. . .the pH should not be changed more than 0.2 units from the naturally occurring variation''- L19609

Carilli, J. E., Norris, R. D., Black, B., & et al. (Global Change Biology). Century-scale records of coral growth rates indicate that local stressors reduce coral thermal tolerance threshold. *2010, 16*(4), 1247-1257.

Abstract: Coral bleaching, during which corals lose their symbiotic dinoflagellates, appears to be increasing in frequency and geographic extent, and is typically associated with abnormally high water temperatures and solar irradiance. A key question in coral

reef ecology is whether local stressors reduce the coral thermal tolerance threshold, leading to increased bleaching incidence. Using tree-ring techniques, we produced master chronologies of growth rates in the dominant reef builder, massive Montastraea faveolata corals, over the past 75–150 years from the Mesoamerican Reef. Our records indicate that the 1998 mass bleaching event was unprecedented in the past century, despite evidence that water temperatures and solar irradiance in the region were as high or higher mid-century than in more recent decades. We tested the influence on coral extension rate from the interactive effects of human populations and thermal stress, calculated here with degree-heating-months (DHM). We find that when the effects of chronic local stressors, represented by human population, are taken into account, recent reductions in extension rate are better explained than when DHM is used as the sole predictor. Therefore, the occurrence of mass bleaching on the Mesoamerican reef in 1998 appears to stem from reduced thermal tolerance due to the synergistic impacts of chronic local stressors.

Questions this article answers: Do local stressor reduce coral thermal tolerance thresholds (resulting in greater bleaching incidents)? What is the effect of increasing general himan impacts on the thermal tolerance threshold of Montastraea faveolata?

Methodology: tree-ring techniques: produced master chronologies of growth rates in the dominant reef builder, massive Montastraea faveolata corals, over the past 75–150 years from the Mesoamerican Reef

Findings:

- Thermal tolerance decreased with increased dissolved inorganic nitrogen sourced from land
- Scleractinian corals contain annual growth bands in their skeleton, which are revealed by X-rays: preserved records of growth can be used to investigate how environmental change has affected coral health

- Collected a total of 92 coral cores of which 87 (95%) have a stress band associated with the 1998 bleaching event
- Only three individual years in different cores contained a high-density stress band before the year 1998
- The four chronologies underscore an observed increase in bleaching frequency over recent years as well as the severity of the 1998 bleaching event
- On the Mesoamerican reef, the 1998 bleaching event was almost certainly unprecedented over the last century as evidenced by a lack of prior stress banding in our cores
- Corals on the Mesoamerican Reef did not bleach mid-century despite high thermal stress- this is consistent with patterns of thermal stress and bleaching in Jamaica
- The concept that local stress interacts with thermal stress is also consistent with differences in the resistance and resilience of corals among the four sites

Quotes:

"Our data suggest that chronic local stressors depress the thermal tolerance threshold, increasing the likelihood of coral bleaching under only moderate thermal stress. Although our study addresses M. faveolata, the dominant reef framework builder in most of the Mesoamerican reef region, this finding may be common to other coral species and regions."

"Local management strategies that reduce local stressors, such as creating effective `s to protect from overfishing, or reducing runoff impact by watershed management and protecting or replanting coastal mangroves, may increase coral thermal tolerance and thus the associated likelihood of surviving future warming."

Castillo, K. D., & Lima, F. P. (2010). Comparison of in situ and satellite-derived (MODIS-Aqua/Terra) methods for assessing temperatures on coral reefs. *Limnology and Oceanography, 8*, 107-117.

Abstract: Thermal stress has been regarded as one of the most important parameters monitored on reefs to assess coral health, and therefore, it is important to have accurate temperature data for reef environments. Whereas most studies of thermal stress on reefs have relied on sea surface temperature (SST) data, recent findings have suggested that subsurface temperatures may differ considerably from those at the surface. We compared concomitant in situ and satellite-derived SST measurements on two different coral reefs off southern Belize. Seawater temperatures adjacent to corals at 3 to 5 m depth were measured every 10 to 30 min, from June 2002 to
December 2007. An accompanying data set of seawater temperatures was collected every 10 min at 1, 3, 6, 9 and 15 m depth, from October 2006 to December 2007. Concurrent nighttime and daytime SST measurements from MODIS Aqua and Terra platforms with a spatial resolution of 4 km were obtained for comparative purposes. Results indicate a negative (cool) bias for remotely sensed SSTs when compared with in situ measurements for both satellites across these two locations. Compared with daytime values, nighttime satellite-derived SST measurements yielded larger negative biases and were less correlated with in situ measurements. Understanding these biases will not only provide a better evaluation of the thermal regime on individual reefs, but will also create opportunities for more precise temperature comparisons among coral reef environments. We stress the importance of "sea-truthing" and complementing satellite-derived SST readings with in situ data when measuring temperatures on coral reefs.

Questions this article answers: How do subsea surface temperatures differ from those at the surface? (And their impact on coral reef health?)

Methodology: compared concomitant in situ and satellite-derived SST measurements on two different coral reefs off southern Belize. Seawater temperatures adjacent to corals at 3 to 5 m depth were measured every 10 to 30 min, from June 2002 to December 2007. An accompanying data set of seawater temperatures was collected every 10 min at 1, 3, 6, 9 and 15 m depth, from October 2006 to December 2007.

Findings:

- There is a negative (cool) bias for remotely sensed SSTs when compared with in situ measurements for both satellites across these two locations
- The only exception was data derived from Aqua daytime readings which consistently showed a small positive bias
- Some of satellite studies may have effectively ignored thermal processes at scales and frequencies not detectable by the analysis of remotely sensed SST alone
- In fact, daytime sea surface temperature derived from both MODIS Terra and Aqua satellites closely reflected in situ measurements between 3 and 5 m
- The fact that very small differences were observed between daytime satellite readings and in situ data were surprising

Castillo, K. D., Ries, J. B., & Weiss, J. M. (2011). Declining coral skeleton extension for forereef colonies of siderastrea siderea on the MesoAmerican reef system, southern belize. *PLoS One, 6*(2)

Abstract:
Background: Natural and anthropogenic stressors are predicted to have increasingly negative impacts on coral reefs. Understanding how these environmental stressors have impacted coral skeletal growth should improve our ability to predict how they may affect coral reefs in the future. We investigated century-scale variations in skeletal extension for the slow-growing massive scleractinian coral Siderastrea siderea inhabiting the forereef, backreef, and nearshore reefs of the Mesoamerican Barrier Reef System (MBRS) in the western Caribbean Sea.
Methodology/Principal Findings: Thirteen S. siderea cores were extracted, slabbed, and X-rayed. Annual skeletal extension was estimated from adjacent low- and high-density growth bands. Since the early 1900s, forereef S. siderea colonies have shifted from exhibiting the fastest to the slowest average annual skeletal extension, while values for backreef and nearshore colonies have remained relatively constant. The rates of change in annual skeletal extension were 20.02060.005, 0.01160.006, and 20.00860.006 mm yr21 per year [mean6SE] for forereef, backreef, and nearshore colonies respectively. These values for forereef and nearshore S. siderea were significantly lower by 0.03160.008 and by 0.01960.009 mm yr21 per year, respectively, than for backreef colonies. However, only forereef S. siderea exhibited a statistically significant decline in annual skeletal extension over the last century.
Conclusions/Significance: Our results suggest that forereef S. siderea colonies are more susceptible to environmental stress than backreef and nearshore counterparts, which may have historically been exposed to higher natural baseline stressors. Alternatively, sediment plumes, nutrients, and pollution originating from watersheds of Guatemala and Honduras may disproportionately impact the forereef environment of the MBRS. We are presently reconstructing the history of environmental stressors that have impacted the MBRS to constrain the cause(s) of the observed reductions in coral skeletal growth. This should improve our ability to predict and potentially mitigate the effects of future environmental stressors on coral reef ecosystems.

Questions this article answers: how do environmental (natural and anthropogenic) stressors impact coral skeletal growth? Can this help improve our ability to predict how they may affect coral reefs in the future?

Methodology: extracted coral cores: Cores were extracted from colonies of S. siderea from the forereef, backreef, and nearshore reef zones of the MBRS in southern Belize. Forereef and backreef coral cores were obtained from the Sapodilla Cayes Marine Reserve, on the seaward and shoreward side of the reef crest, respectively.

Findings:

- Since the mid-1930's forereef colonies have shifted from exhibiting the fastest to the slowest average annual skeletal extension while values for backreef and nearshore S. siderea colonies have remained relatively consistent over this interval
- The decline in skeletal extension for forereef S. siderea and the relative stability of skeletal extension for backreef and nearshore colonies over the past century suggest that forereef S. sidereal colonies may be more susceptible to natural and/or anthropogenic stress than backreef and nearshore conspecifics
    - Differences in susceptibility to natural and/or anthropogenic stress may arise, in part, from differences in the coral colonies' history of exposure to baseline environmental stress amongst the reef zones
- Increasing seawater temperature and thermal stress:
- Several recent studies have examined the effects of rising seawater temperature and associated thermal stress on coral skeletal extension
    - However, not all studies have revealed that coral skeletal extension is negatively impacted by rising seawater temperatures.
- In addition to rising baseline seawater temperatures within the three reef zones, short-lived fluctuations in temperature may also influence annual skeletal extension amongst the three reef zones of the MBRS
- Hydraulic regime has also been shown to affect coral skeletal extension
    - Rates of change in skeletal extension were also lower in the generally higher energy shallow forereef environment than in the generally lower energy nearshore and backreef environments
    - We cannot exclude water motion and wave activity as a factor influencing differences in skeletal extension amongst these three reef zones.
- Sedimentation: the southern portions of the MBRS receive sediment from two general directions: eastwardflowing run-off from the sparsely populated watersheds of Belize, and northward-flowing run-off from the larger and more densely populated watersheds of Honduras and Guatemala
- Pollution: forereef S. siderea colonies, which are more proximal to the larger and more densely populated watersheds of the Honduran and Guatemalan coast—the primary source of the pollution to this region [63]— was more negatively impacted than colonies on the nearshore and backreef environments that are more proximal to the sparsely populated coast of southern Belize
- The effects of multiple stressors: more important than once single stressor; the

results indicated that local stressors on the MBRS have increased steadily over time and that these stressors were higher in the southern part of the reef system than in the northern part.

- Model outputs suggest that anthropogenic alteration of landscapes bordering the Gulf of Honduras has caused the increased erosion, runoff, and nutrient delivery evident in the southern portion of the MBRS

Quotes:
"The observation that skeletal extension remained unchanged over approximately the last century for S. siderea within the historically high-stress nearshore reef environment (subject to increased sedimentation, pollution, and freshwater input) and within the more thermally variable and heat-stressed backreef environment (where restricted circulation supports elevated seawater temperatures), yet decreased for corals from the cooler and more thermally stable forereef environment, suggests that acclimatization [28] and/or adaptation [30,31] may be important processes influencing the response of these corals to global climate change and increasing anthropogenic stress

Ceccarelli, D. M., Jones, G. P., & McCook, L. J. (2011). Interactions between herbivorous fish guilds and their influence on algal succession on a coastal coral reef. *Journal of Experimental Marine Biology and Ecology, 399*(1), 60-67.

Abstract: Herbivory is an important mechanism affecting algal succession, particularly on coral reefs where the relationship between algae and corals is largely controlled by herbivores. However, different functional groups of herbivores may have contrasting effects on succession, which may explain different trajectories of coral reef recovery after disturbance. Here, the effects of different herbivore groups (roving herbivores= foragers and territorial damselfish=farmers) were isolated by a multi-factorial experiment carried out on a coastal coral reef with high macroalgal cover, high farmer densities and relatively low forager abundance. The effects of foragers and farmers were distinguished by monitoring algal succession on settlement tiles placed inside and outside exclusion cages, with orthogonal treatments established inside and outside damselfish territories (with appropriate cage controls). Within 12 months, algal assemblages on ungrazed tiles inside exclusion cages proceeded rapidly from fine filamentous turfs, to corticated algae, to tough erect (e.g. Amphiroa spp.) and foliose (e.g. Peyssonnellidae) calcified algae. Farmers had a dramatic impact on succession, essentially arresting the development of the algal community at a point where it was dominated by palatable filamentous algae of the genus Polysiphonia. Fleshy macroalgae such as Sargassum spp. were excluded from farmer territories. In contrast, foragers did not suppress fleshy macroalgae, but rather, appeared to decelerate succession and promote a relatively diverse assemblage. In

contrast to forager-dominated reefs, farmer territories did not appear to function solely as forager exclusion areas or promote algal diversity as a result of intermediate grazing pressure. The relatively strong effects of farmers observed here may represent a future scenario for coral reefs that are increasingly subject to overfishing of large grazing fishes.

Questions this article answers: how do different functional groups of herbivores affect succession? (This may help explain different trajectories of coral reef recovery after disturbance)

Methodology: This experiment was conducted in Nelly Bay, on Magnetic Island, Great Barrier Reef- monitored algal succession on settlement tiles placed inside and outside exclusion cages, with orthogonal treatments established inside and outside damselfish territories (with appropriate cage controls) for 12 months.

Findings:

- Understanding algal succession and the influence of herbivory is central to the development of knowledge about how coral reef ecosystems may respond to and recover from increasing anthropogenic pressures
- Foragers had a major impact on the development of algal communities outside farmer territories, affecting all major benthic a5nd algal groups- grazing foragers can significantly modify succession (even in low densities)
- The benthic community on the tiles was significantly altered by farmer activities within territories, supporting the hypothesis that direct management (weeding and selective feeding) by farmers affects algal succession- significantly affected the trajectories of most benthic groups
- The cage artifacts were found to have minimal effects on the development of benthic communities on the tiles.
- The results of this study highlight the pronounced and different effects farmers and foragers can have on coral reef benthic succession
    - The numerically dominant farmers had more dramatic effects than foragers on algal succession in this system. However, foragers also directly impacted succession, effectively decelerating the rate of succession to a diverse community that included macroalgae
- It appears that succession was dramatically decelerated under the influence of farmers, remaining at an 'early' stage where it was dominated by filamentous algae of the genus Polysiphonia
- **Foragers:** the activities of foragers on the reef crest decelerated succession to result in a diverse 'mid-successional' assemblage that included corticated red algae and fleshy macroalgae, but not a 'late-successional' assemblage of fleshy macroalgae and erect calcified algae.
    - Foragers had a moderate impact on algal succession, but their grazing regime on open tiles did not lead to an algal assemblage that differed dramatically from ungrazed tiles
- Farmers: completely different and much more dramatic than the effects of foragers; different species of damselfishes (farmers) manipulate the development of algal communities in their territories based on a combination of their

preferences and the availability of food algae in their immediate environment
- The significance of farmer and forager effects for mediating coral– algal interactions depends strongly on the resulting algal community. Thick turfs and fleshy macroalgae have been found to be the most damaging to coral survival and regeneration, but crustose coralline algae can enhance recruitment.
- Most research suggests that foragers are crucial to coral resilience but there is still not enough information to determine whether farmer effects are beneficial or detrimental to coral communities.

Quotes:
"The relative importance of foragers and farmers may change along environmental and geographic gradients, with farmers becoming more effective at controlling or changing algal communities as forager influence decreases."

Cheal, A. J., MacNeil, M. A., Cripps, E., & et al. (2010). Coral-macroalgal phase shifts or reef resilience: Links with diversity and funcitonal roles of herbivorous fishes on the great barrier reef. *Coral Reefs, 29*(4), 1005-1015.

Abstract: Changes from coral to macroalgal dominance following disturbances to corals symbolize the global degradation of coral reefs. The development of effective conservation measures depends on understanding the causes of such phase shifts. The prevailing view that coral– macroalgal phase shifts commonly occur due to insufficient grazing by fishes is based on correlation with overfishing and inferences from models and small-scale experiments rather than on long-term quantitative field studies of fish communities at affected and resilient sites. Consequently, the specific characteristics of herbivorous fish communities that most promote reef resilience under natural conditions are not known, though this information is critical for identifying vulnerable ecosystems. In this study, 11 years of field surveys recorded the development of the most persistent coral–macroalgal phase shift ([7 years) years observed on Australia's Great Barrier Reef (GBR). This shift followed extensive coral mortality caused by thermal stress (coral bleaching) and damaging storms. Comparisons with two similar reefs that suffered similar disturbances but recovered relatively rapidly demonstrated that the phase shift occurred despite high abundances of one herbivore functional group (scraping/excavating parrotfishes: Labridae). However, the shift was strongly associated with low fish herbivore diversity and low abundances of algal browsers (predominantly Siganidae) and

grazers/detritivores (Acanthuridae), suggesting that one or more of these factors underpin reef resilience and so deserve particular protection. Herbivorous fishes are not harvested on the GBR, and the phase shift was not enhanced by unusually high nutrient levels. This shows that unexploited populations of herbivorous fishes cannot ensure reef resilience even under benign conditions and suggests that reefs could lose resilience under relatively low fishing pressure. Predictions of more severe and widespread coral mortality due to global climate change emphasize the need for more effective identification and protection of ecosystem components that are critical for the prevention of coral reef phase shifts.

Questions this article answers: so characteristics of herbivorous fish communities promote reef resilience in natural conditions?

Methodology: 11 years of field surveys the Great Barrier Reef (Reef fish and coral communities were surveyed annually on three inshore reefs of the GBR (Havannah Is., Fitzroy Is. and Low Isles) between 1997 and 2007, with the exception of 2006 when data were not collected.

Findings:
Incidences of coral bleaching, tropical storms and A. planci outbreaks contributed to high coral mortality at our three study reefs and precipitated the degradation of one of these reefs through a shift from coral to macroalgal dominance

Specific characteristics of herbivory (diversity and the functional roles of surgeonfishes and rabbitfishes) could be particularly important for reef resilience and hence be of high conservation value

Disclaimer: the phase shift reported here is the most persistent yet to be quantified on the GBR, but even so, our results probably underestimated the full ecological influence of L. variegata because Havannah Is. was always surveyed between February and July; the season when cover of this alga is lowest on the GBR

As only one reef experienced a phase shift, relationships between herbivorous fishes and shifts to macroalgal dominance must be interpreted cautiously

Fish communities with low herbivore diversity and low abundances of algal browsers and grazers/detritivores were strongly associated with a coral–macroalgal phase shift.

Insufficient herbivore diversity as well as low abundances of algal browsers and grazers/detritivores may all have contributed to the phase shift at Havannah Is., but the relative contribution of each cannot be distinguished

The phase shift at Havannah Is. occurred despite relatively low levels of anthropogenic stress on the GBR and in the absence of fishing pressure on herbivorous fishes.

Quotes:
"Our observations support the space availability model of Williams et al. (2001), who showed experimentally that if enough space is opened up for colonization, macroalgal

growth can exceed the grazing capacity of herbivore populations. The predictions of more severe and widespread coral mortality associated with global climate change (Hoegh-Guldberg et al. 2007) imply that herbivore populations that are currently capable of preventing phase shifts could in the future be overwhelmed by higher macroalgal abundances."

Cinner, J. E., McClanahan, T. R., Graham, N. A., Pratchett, M. S., Wilson, S. K., & Raina, J. B. (2009). Gear‐based fisheries management as a potential adaptive response to climate change and coral mortality. *Journal of Applied Ecology*, *46*(3), 724-732.

Abstract: Fisheries managers will require a range of tools to meet the novel challenges posed by climate change. This study presents a way to help reduce the negative impacts of climate change and potentially increase resilience of marine ecosystems by managing fishing gear. Specific gears used by artisanal fishers differentially target fish functional groups. In the coral reefs that we studied, traps and spear guns targeted a high proportion of species highly susceptible to coral mortality and critical to coral reef resilience through their top-down control. Given that full fisheries closures are not always practical, selectively banning or restricting fishing gears is a potentially powerful tool for reducing the detrimental ecosystem effects of climate change disturbances.

Questions this article answers: What species depend on coral reefs for feeding or habitat are likely to be susceptible to the loss of coral? What is the relationship between gear types and fish catch though to be critical to the recovery of corals and those species susceptible to coral mortality? Can gear selectivity be used as a basis for managing coral reef fisheries?

Methodology: Literature review of fisheries landing data from 15 sites in Papua New Guinea and Kenya: We used data on species composition of fisheries catches from small-scale artisanal fishers in five sites in PNG (Cinner & McClanahan 2006; 2008). These study sites encompass a wide range of social, economic, and demographic conditions, but in both countries, fishing was generally undertaken in shallow-water (<20 m depth) coral reef and seagrass ecosystems. PNG data were collected over 2–3 weeks in each village during a period between October 2001 and June 2002 (Cinner & McClanahan 2006a). Kenyan data were collected between October 2004 and May 2008 with a lesser amount collected in 1998.

Findings:

- Climate-induced coral bleaching and the associated degradation of reef habitats have the potential to affect coral reef fishes targeted by artisanal reef and reef-related fisheries through several key mechanisms
- Fishes have varying levels of susceptibility to bleaching and coral mortality, with those species directly dependent on live coral for food, settlement, and shelter experiencing the most negative effects
- Species associated with reef structure will experience declines associated with the gradual erosion of dead coral skeletons
- Many coral reefs are located in poor, developing countries (Donner & Portere 2007) where fishing restrictions can undermine local livelihoods and are, therefore, difficult to justify and enforce
- Fishers are generally more supportive of restrictions on specific types of fishing gear compared to outright closure of fishing grounds
- Catch data was comprised of 223 different species in PNG, and 127 species in Kenya
- The predominant fishing methods used in PNG were: (i) line fishing, where fishers used a single baited hook attached to nylon line; (ii) gill nets, where fishers used monofilament nets in shallow coral reef or seagrass habitats; and (iii) spear guns, where fishers dove with homemade spears (generally fashioned from bicycle spokes, wood, and an inner tube for propulsion).
- Only 6% of the fishes targeted by fishers were susceptible to the immediate effects of coral mortality; however, loss of habitat structure following coral mortality is expected to affect 56% of targeted species.
- Importantly, 25% of target species had feeding characteristics (i.e. reef scrapers/excavators and grazers) that contribute to the recovery of coral reef ecosystems, and gears differed considerably in catches of these species.
- Spear guns and traps target a high proportion of species likely to be affected by bleaching and key for the recovery of corals. These gears are strong candidates for management restrictions in reefs with high coral mortality. In contrast, line fishing catches the lowest proportion of susceptible and recovery-enabling species and is preferential for increasing recovery rates on coral reefs.

Quotes:

- "A principal finding is that fishes with strong coral associations currently represent only a small proportion (<6% by number) of artisanal fisheries catches in both PNG and Kenya. Species within this category are often small bodied, and feed, dwell, or settle into live coral"-pg 729

- "Fisheries-landing studies in Seychelles and Kenya before and after coral mortality have indicated that these species are not immediately affected by bleaching events (Grandcourt & Cesar 2003); however, the longer-term erosion of reef structures and subsequent loss of structural complexity can have detrimental effects on their abundance and size structure (Graham *et al* . 2007). Thus, fishes with medium levels of coral association are expected to be vulnerable to longer-term combined effects of coral mortality and fishing."- pg 729
- "Adaptively managing resources in a changing climate is going to depend on the use of pragmatic management tools that can be rapidly implemented. Relatively short windows of opportunity are available for effectively responding to events such as bleaching."- 729
- Consequently, regularly collected site-specific information on fishing pressure, gear use and selectivity will help mangers to make informed decisions about adaptively managing gear.

Cinner, J. E., McClanahan, T. R., Daw, T. M., Graham, N. A., Maina, J., Wilson, S. K., & Hughes, T. P. (2009). Linking social and ecological systems to sustain coral reef fisheries. *Current Biology*, *19*(3), 206-212.

Source type: journal article

Abstract: The ecosystem goods and services provided by coral reefs are critical to the social and economic welfare of hundreds of millions of people, overwhelmingly in developing countries. Widespread reef degradation is severely eroding these goods and services, but the socioeconomic factors shaping the ways that societies use coral reefs are poorly understood. We examine relationships between human population density, a multidimensional index of socioeconomic development, reef complexity, and the condition of coral reef fish populations in five countries across the Indian Ocean. Sustaining coral reef fisheries requires an integrated approach that uses tools such as protected areas to quickly build reef resources while also building capacities and capital in societies over longer time frames to address the complex underlying causes of reef degradation.

Questions this article answers: What are the relationships between human population density, socioeconomic development, reef complexity, and the condition of coral reef fish populations in five countries across the Indian Ocean?

Methodology: We studied 19 coastal communities and adjacent coral reef sites in the western Indian Ocean spanning five countries: Kenya, Tanzania, Seychelles, Mauritius, and Madagascar. At each site, we investigated the following socioeconomic indicators: community-level infrastructure (as a measure of economic development); human population density; the proportion of the community involved in fishing (and that ranked it as their primary livelihood strategy); the proportion engaged in salaried employment; the proportion of fishers that use gillnets, reef handlines, spearguns, small seine nets, and pelagic gear; the proportion of fishers that own boats and engines; and the presence of customary sociocultural institutions such as taboos that may restrict fishing.

Findings:

- In fished sites, fish biomass was negatively related to human population density, but it was best explained by reef complexity and a U-shaped relationship with socioeconomic development.
- The biomass of reef fishes was four times lower at locations with intermediate levels of economic development than at locations with both low and high development.
- In contrast, average biomass inside fishery closures was three times higher than in fished sites and was not associated with socioeconomic development.

Quotes:

- “To minimize the potential negative effects of economic growth on reef systems, socioeconomic development needs to be coupled with effective legislation, institutional strengthening, and regional agreements.”
- “These economic and policy approaches for sustaining coral reefs and associated fisheries operate on different, but complimentary, spatial and temporal scales.”

Correa, A. M. S., & Baker, A. C. (2011). Disaster taxa in microbially mediated metazoans: How endosymbionts and environmental catastrophes influence the adaptive capacity of reef corals. *Global Change Biology, 17*(1), 68-75.

Abstract: Reef corals are examples of metazoans that engage in mutualisms with a variety of microorganisms, including dinoflagellates, Bacteria, Archaea, and viruses. The high adaptive capacity of these microbial symbionts can be coopted by their coral hosts, and various emergent traits of these associations, such as thermotolerance, are undergoing strong selection due to climate change. This selection may spur the rise of microbial ‘disaster taxa’: opportunistic, cosmopolitan generalists that can proliferate and increase host survivorship following disturbances. Coral bleaching (a stress-induced loss

of dinoflagellates) constitutes one type of catastrophic disturbance for resident symbiont communities, and opens novel patches of host for colonization by microbial disaster taxa. Moreover, the compartmentalization of microbial symbionts within coral polyps reduces their effective population size and thus facilitates the spread of disaster taxa during times of environmental change. These phenomena suggest that, despite widespread loss of coral cover as a result of climate disturbances, the potential spread of resilient microbial disaster taxa in surviving colonies can have important implications for coral reef persistence over the coming decades.

Questions this article answers; What is the role of mutualistic relationships of corals in times of climate disturbances? How might microbial disaster taxa in surviving colonies affect coral reef persistence?

Methodology: literature review

Findings:

- Thesis: compartmentalization, bleaching, associational drift, and selective sweeps all play a role in the diversification and/or divergence of Symbiodinium (and potentially other endosymbiotic microorganisms) over evolutionary time
- Given their extremely large population sizes, primarily asexual nature and short generation times, symbiotic microbes are likely to respond rapidly to, and may even keep pace with, the directional influence of human activitie
    - Metazoans that associate with these microbes may have a higher adaptive capacity than has previously been recognized
- Bleaching events:
    - Represent catastrophic disturbances to the resident symbionts of reef corals, and are a potential mechanism for purging accumulated variation within microbial ecotypes over large geographic scales
    - Favor mutualistic disaster taxa
    - Create opportunities for symbiont variants to form the basal nodes of novel lineages, and for previously uncommon adaptive ecotypes to rise to dominance
- Despite the gain in adaptive capacity that is acquired through mutualisms with microbes, the evolutionary trajectory of coral animals is likely to be more constrained than that of Bacteria, Archaea, viruses, or Symbiodinium in isolation

Cote, I. M., & Darling, E. S. (2010). Rethinking ecosystem resilience in the face of climate change. *PLoS Biology, 8*(7)

Abstract: Resilience is usually defined as the capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services. The concept therefore encompasses two separate processes: resistance—the magnitude of disturbance that causes a change in structure—and recovery—the speed of return to the original structure which are fundamentally different but rarely distinguished. Yet, resilience has become a central concept in the management of natural ecosystems Measuring resilience is fraught with difficulties. Nevertheless, assessing changes in resilience as a result of management action is critical because there is general agreement for the existence of a strong link between resilience and sustainability. Successfully

increasing the resilience of natural systems may therefore have important implications for human welfare in the face of global climate change. In this Perspective, we will argue that the expectation of increased resilience of natural communities to climate change through the reduction of local stressors may be fundamentally incorrect, and that resilience-focused management may, in fact, result in greater vulnerability to climate impacts. We illustrate our argument using coral reefs as a model. Coral reefs are in an ecological crisis due to climate change and the ever-increasing magnitude of human impacts on these biodiverse habitats. These impacts stem from a multiplicity of local stressors, such as fishing, eutrophication, and sedimentation It is therefore not surprising that the concept of resilience—to climate change in particular—is perhaps more strongly advocated as an underpinning of management for coral reefs than for any other ecosystem. Marine reserves or no-take areas, the most popular form of spatial management for coral reef conservation, are widely thought to have the potential to increase coral reef resilience. But do they really?
Questions this article answers: Do marine reserves have the potential to increase coral reef resilience?

Methodology: literature review

Findings:
- High species diversity within marine reserves is expected to provide protected reefs with ecological insurance and increased functional redundancy, which is commonly assumed to increase resilience to disturbance events
    - marine reserves do not reduce the frequency or intensity of thermally induced coral bleaching OR bleaching-induced mortality compared to unprotected areas
- Thermal stress- can cause proportionally greater coral mortality in protected (rather than unprotected corals)
- There is no evidence that marine reserves are currently located in areas that are less likely to get hot
- Despite all this- many reserves show higher coral recruitment [53] or coral species diversity [32], maintain coral cover, and increase rates of coral recovery, with concomitant declines in macroalgal cover
- Intact reef communities do not appear to be more resilient to climate disturbance: If a species' tolerance to a non-climatic disturbance is correlated with its tolerance to climatic impacts then degradation can actually increase the abundance of disturbance-tolerant species within a community (and an ecosystem to resist impacts of climate change)
- The assumption that reducing local stressors will mitigate climate change impacts is flawed
    - The alleviation of local stressors can potentially enhance reef recovery from climate change impacts
- On severely degraded reefs, managing for resistance may be unsuccessful and removing local stressors could offer the only hope for recovery in between disturbances.
- Climate change- likely to be the dominant driver of ecological change in the 21st

century- removing local stressors- not enough to maintain biological diversity

Crabbe, M. J. C. (2008). Climate change, global warming and coral reefs: Modelling the effects of temperature. *Computational Biology and Chemistry*, *32*(5), 311.

Source type: journal type

Abstract: Climate change and global warming have severe consequences for the survival of scleractinian (reefbuilding) corals and their associated ecosystems. This review summarizes recent literature on the influence of temperature on coral growth, coral bleaching, and modeling the effects of high temperature on corals. Satellite-based sea surface temperature (SST) and coral bleaching information available on the internet is an important tool in monitoring and modeling coral responses to temperature. Within the narrow temperature range for coral growth, corals can respond to rate of temperature change as well as to temperature *per se*. We need to continue to develop models of how non-steady-state processes such as global warming and climate change will affect coral reefs.

Questions this article answers: What is the recent literature on the influence of temperature on coral growth, coral bleaching, and modeling the effects of high temperature on corals

Methodology: Literature review

Findings:

- Coral reefs, found predominantly between the tropics of Capricorn and Cancer, provide an environment in which one third of all marine fish species and many thousands of other species are found, and from which 6 million tons of fish are caught annually
- The growth and subsistence of corals depend on many variables, including temperature, irradiance, calcium carbonate saturation, turbidity, sedimentation, salinity, pH, and nutrients. These variables influence the physiological processes of photosynthesis and calcification as well as coral survival, and as a result coral reefs occur only in select areas of the world's oceans.
- Coral reefs under severe threat from climate change and anthropogenic factors (overfishing and pollution)
- A 1 ◦C rise in temperature would lead to an increase in the density rate of about 10.5% and an increase in the calcification rate of about 4.5%.
- Coral calcification rates and extension rates have been highly correlated with sea surface temperatures (SSTs) and to a lesser extent with incoming solar radiation
- Most of the pigmentation within corals is within the symbiotic algal cells—the zooxanthellae. Coral bleaching is caused by corals losing their zooxanthellae.
    - Thermal bleaching occurs when the coral is exposed to prolonged above-normal (or below-normal) temperatures, resulting in additional energy demands on the coral, depleted reserves, and reduced biomass
    - The effect of high temperatures can be aggravated by high levels of irradiance (Gleason andWellington, 1993), although high UV radiation is not a primary factor in causing mass bleaching (Hoegh-Guldberg, 1999).

- Corals can die as a result of bleaching, though they may partially or fully recover from bleaching events (Lough, 2000).
- Bleaching causes a decrease in the growth rate of corals, and the time taken for a coral to recover from a bleaching event may be several years or decades. If the frequency of bleaching increases, then the capacity for coral reefs to recover is diminished (Done, 1999).

The frequency that corals will be bleached in the future has been estimated by using projections of future sea surface temperatures from four different general circulation models (GCMs) forced by the IPCC IS92a emission scenario (Hoegh-Guldberg, 1999).

Cripps, I. L., Munday, P. L., & McCormick, M. I. (2011). Ocean acidification affects prey detection by a predatory reef fish. *PLoS One, 6*(7)

Abstract: Changes in olfactory-mediated behaviour caused by elevated CO2 levels in the ocean could affect recruitment to reef fish populations because larval fish become more vulnerable to predation. However, it is currently unclear how elevated CO2 will impact the other key part of the predator-prey interaction – the predators. We investigated the effects of elevated CO2 and reduced pH on olfactory preferences, activity levels and feeding behaviour of a common coral reef meso-predator, the brown dottyback (Pseudochromis fuscus). Predators were exposed to either current-day CO2 levels or one of two elevated CO2 levels (,600 matm or ,950 matm) that may occur by 2100 according to climate change predictions. Exposure to elevated CO2 and reduced pH caused a shift from preference to avoidance of the smell of injured prey, with CO2 treated predators spending approximately 20% less time in a water stream containing prey odour compared with controls. Furthermore, activity levels of fish was higher in the high CO2 treatment and feeding activity was lower for fish in the mid CO2 treatment; indicating that future conditions may potentially reduce the ability of the fish to respond rapidly to fluctuations in food availability. Elevated activity levels of predators in the high CO2 treatment, however, may compensate for reduced olfactory ability, as greater movement facilitated visual detection of food. Our findings show that, at least for the species tested to date, both parties in the predator-prey relationship may be affected by ocean acidification. Although impairment of olfactory-mediated behaviour of predators might reduce the risk of predation for larval fishes, the magnitude of the observed effects of elevated CO2 acidification appear to be more dramatic for prey compared to predators. Thus, it is unlikely that the altered behaviour of predators is sufficient to fully compensate for the effects of ocean acidification on prey mortality.

Questions this article answers: how will elevated CO2 impact predatory reef fish, specifically P. fuscus, a common meso-predator on the GBR.

Methodology: This study was conducted at Lizard Island Research Station: GBR; March and April 2010. Case study of P. fuscus

Findings:

- The ability of a common meso-predator to detect chemical cues produced by it's prey is hindered and activity levels are elevated by exposure to elevated CO_2
- P. fuscus naturally exhibited a preference for the olfactory cues of injured prey, however, following exposure to dissolved CO_2 concentrations that could be widespread in the ocean by the end of the century, they displayed a slight avoidance to these cues
- A change in reaction to olfactory cues is consistent with previous studies that have found that larval fish exposed to elevated CO_2 were unable to discriminate between ecologically important cues
- P. fuscus inhabit topographically complex reef habitats, potentially limiting the effectiveness of locating prey via visual information over long distances
    - A shift from attraction to repulsion of favourable prey cues due to ocean acidification could result in a decrease in the predatory activity of meso-predators and a reduced ability to respond to fluctuations in food availability.
- Following CO_2 treatment, predators spent 20% less time in a water stream containing the smell of injured prey
- Avoidance of the beneficial olfactory cue of injured prey may be attributed to an alteration of neuro-sensory functioning following exposure to elevated CO_2
- Predatory fish use a variety of sensory cues to detect and locate prey, and although olfaction is often important [31], vision can also play an important role in prey detection and capture
    - Increased activity in the high CO_2 treatment could have resulted in the fish relying more on vision than olfaction to detect food

Quotes:

"This study is the first to demonstrate the potential impacts of ocean acidification on a predatory fish, beyond the early life history stages. Combined effects of elevated CO_2 on attraction to prey odour and changes in general activity levels suggest that even moderate increases in atmospheric CO_2 affect the behaviour of meso-predators and the outcome of interactions between P. fuscus and their prey."

Davis, K. A., Lentz, S. J., Pineda, J., & et al. (2011). Observations of the thermal environment on red sea platforms reefs: A heat budget analysis. *Coral Reefs, 30*(SI), 25-36.

Abstract: Hydrographic measurements were collected on nine offshore reef platforms in the eastern Red Sea shelf region, north of Jeddah, Saudi Arabia. The data were analyzed for spatial and temporal patterns of temperature variation, and a simple heat budget analysis was performed with the goal of advancing our understanding of the physical processes that control temperature variability on the reef. In 2009 and 2010, temperature variability on Red Sea reef platforms was dominated by diurnal variability. The daily temperature range on the reefs, at times, exceeded 5_C—as large as the annual range of water temperature on the shelf. Additionally, our observations reveal the proximity of distinct thermal microclimates within the bounds of one reef platform. Circulation on the reef flat is largely wave driven. The greatest diurnal variation in water temperature occurs in the center of larger reef flats and on reefs protected from direct wave forcing, while smaller knolls or sites on the edges of the reef flat tend to experience less diurnal temperature variability. We found that both the temporal and spatial variability in water temperature on the reef platforms is well predicted by a heat budget model that includes the transfer of heat at the air–water interface and the advection of heat by currents flowing over the reef. Using this simple model, we predicted the temperature across three different reefs to within 0.4_C on the outer shelf using only information about bathymetry, surface heat flux, and offshore wave conditions.

Questions this article answers: What is happening with the thermal environment on the Red Sea Platform reefs?

Methodology: Hydrographic measurements were collected on offshore reef platforms in the eastern Red Sea shelf region, north of Jeddah, Saudi Arabia; the observations presented here are part of a larger, multiyear study of coral ecology, shelf-scale circulation, and air–sea dynamics in the Red Sea. We restrict our focus to measurements of meteorological conditions, currents, and water temperatures on nine offshore reef platforms

Findings:

- Water temperature on the Red Sea reef platforms is spatially and temporally variable

- In 2009 and 2010, temperature variability on Red Sea reef platforms was dominated by diurnal variability
    - The daily temperature range on the reefs, at times, exceeded 5_C—as large as the annual range of water temperature on the shelf
    - Shallow topography of reef platforms- enhances diurnal temp cycle: concentrates the effect of surface heat flux into a small volume of water, exposes reef to wind and wave
- Topographic complexity of the reefs also leads to a high degree of temperature variability at small spatial scales, with cooler temperatures on the forereef or wave-exposed side of the reef and warmer temperatures in the reef interior and on the wave-protected side of the reef

- We predicted the temperature difference across three reefs to within 0.4_C on the outer shelf and 0.9_C on the inner shelf (95% confidence) using only information about bathymetry, surface heat flux, and offshore wave conditions, the last two of which were measured at the meteorological buoy for this study, but could be obtained from remote sensing products or coastal weather stations

Dawson, J. L., & Smithers, S. G. (2010). Shoreline and beach volume change between 1967 and 2007 at raine island, great barrier reef, australia. ***Global and Planetary Change, 163*****(2), 497-507**

Abstract: Raine Island is a vegetated coral cay located on the far northern outer Great Barrier Reef (GBR), recognised as a globally significant turtle rookery. Cay geomorphology, specifically the morphology of the beach and swale, dictate the availability of nesting sites and influence nesting success. Understanding short and long-term shoreline change is critical for managers charged with protecting the nesting habitat, particularly as climate change progresses. Historical topographic surveys, a simple numerical model and geographic information system (GIS) techniques were used to reconstruct a 40-year (1967–2007) shoreline history of Raine Island.
Results show that significant shoreline change has occurred on 78% of the island's shoreline between 1967 and 2007; 34% experienced net retreat and 44% net progradation during the study interval. Shoreline retreat is mainly concentrated on the east–southeast section of the shoreline (average annual rate of−0.3±0.3 m/yr), while the shore on the western side of the island prograded at a similar rate (0.4±0.2 m/yr). A seasonal signal was detected relating to oscillations in wind direction and intensity, with the southeast and west–southwest shorelines migrating an average of ~17 m from season to season. The volume of sediment deposited on Raine Island between 1967 and 2007 increased by ~68,000 m3 net, but accretion rates varied significantly seasonally and from year to year. The largest volumetric changes have typically occurred over the last 23 years (1984–2007). Despite the recent concern that Raine Island is rapidly eroding, our data demonstrate net island growth (6% area, 4% volume) between 1967 and 2007. Perceptions of erosion probably reflect large morphological changes arising from seasonal, inter-annual and inter-decadal patterns of sediment redistribution rather than net loss from the island's sediment budget.

Questions this article answers: What is the importance of understanding short-term and long-term shoreline change for coral reef managers, particularly as climate change progresses?

Methodology: historical topographic surveys, a simple numerical model and geographic information system (GIS) techniques were used to reconstruct a 40-year (1967–2007) shoreline history of Raine Island

Findings:

- Coral cays are low-lying reef islands formed from sediments derived from the reef on which they sit and swept by refracted waves to a focal point on the reef flat where they are deposited
- Raine Island is a low reef island located on the outer edge of the far northern GBR, Australia. It is one of the world's most important nesting sites for marine turtles, also geographically unique- has geomorphic figures rarely found in combination on reef islands (e.g. a phosphate rock cap and intertidal beachrock pavements
    - Accretion did not occur at a steady rate, but was characterised by significant variability from year to year. Large changes in total island volume have occurred since about 1984 while volume changes as large as 4% of the total island volume can occur in a single year
- Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007: Raine Island did not erode but instead modestly accreted during the 40-year study period
- Changes are most pronounced at the southeast and western ends of the cay, where large shoreline changes probably reflect seasonal shifts in dominant wind direction
- The large accretion in 2007 may reflect the rapid return of this sediment back onto the beach during cyclone Guba
- The opposing ends of the island are very dynamic and exhibit some of the greatest variability in lateral shoreline movement
- The significantly wider reef-flat to the east–southeast (2010 m versus 46 m for the reef flat to the west– southwest) will dissipate most wave energy, thus reducing the potential for waves to geomorphically influence the shore

- A major environmental driving force on the morphological change of reef islands on the Great Barrier Reef (GBR) is elevated storm surge/ waves associated with tropical cyclones
- A longer-term trend in which the beach rotates in a clockwise direction was identified, with east–southeast shoreline retreating by an average of 0.3 m per year whereas the north– northwest shore prograded at an average rate of 0.4 m per year over the 40-year period.

De'ath, G., Lough, J. M., & Fabricius, K. E. (2009). Declining coral calcification on the Great Barrier Reef. *Science*, *323*(5910), 116-119.

Source type: journal article

Abstract: Reef-building corals are under increasing physiological stress from a changing climate and ocean absorption of increasing atmospheric carbon dioxide. We investigated 328 colonies of massive Porites corals from 69 reefs of the Great Barrier Reef (GBR) in Australia. Their skeletal records show that throughout the GBR, calcification has declined by 14.2% since 1990, predominantly because extension (linear growth) has declined by 13.3%. The data suggest that such a severe and sudden decline in calcification is unprecedented in at least the past 400 years. Calcification increases linearly with increasing large-scale sea surface temperature but responds nonlinearly to annual temperature anomalies. The causes of the decline remain unknown; however, this study suggests that increasing temperature stress and a declining saturation state of seawater aragonite may be diminishing the ability of GBR corals to deposit calcium carbonate.

Questions this article answers: What do the skeletal records of GBR corals tell about calcification? Are reef-building corals under increasing physiological stress from a changing climate and ocean absorption of carbon dioxide?

Methodology: Investigated 328 colonies of massive Porites corals from 69 reefs of the Great Barrier Reef (GBR) in Australia- investigated annual calcification rates- annual data for three growth parameters (skeletal density, annual extension rate (linear growth), and calcification rate). Mean annual sea surface temperature (SST) records were obtained from the HadISST1 global SST compilation (1°-square resolution) for the period 1900–2006

Findings:

- Preliminary exploratory analysis of the data showed strong declines in calcification for the period 1990–2005, based on growth records of 189 colonies from 13 reefs.

- Despite high variation of calcification between both reefs and colonies, the linear component of the decline was consistent across both reefs and colonies for 1990–2005.
- The 1990–2005 decline in calcification was specific to that period, rather than reflecting ontogenetic properties of the outermost annual growth bands in coral skeletons.
- The causes for the GBR-wide decline in coral calcification of massive Porites remain unknown, but this study shows that the causes are probably large-scale in extent and that the observed changes are unprecedented within the past 400 years.
- Factors known to determine coral growth and calcification include competition for space, water quality, salinity, diseases, irradiance, currents, large-scale and longterm oceanographic oscillations, SST, temperature stress, and carbonate saturation state
- SST is an important environmental driver of coral growth. Our data confirmed previous studies that coral calcification increases linearly with large-scale mean annual SST

Quotes:
"Competition with neighboring corals is unlikely to have intensified during a period when coral cover has either remained similar or declined on most GBR reefs (7). Terrestrial runoff and salinity, although potentially affecting inshore reefs, are also unlikely causes because calcification declines at similar rates on offshore reefs away from flood plumes. Diseases can also be excluded because only visibly healthy colonies were sampled." -118

"Additionally, if temperature and carbonate saturation are responsible for the observed changes, then similar changes are likely to be detected in the growth records from other regions and from other calcifying organisms. These organisms are central to the formation and function of ecosystems and food webs, and precipitous changes in the biodiversity and productivity of the world's oceans may be imminent"- 118

Donelson, J. M., Munday, P. L., McCormick, M. I., & et al. (2011). Acclimation to predicted ocean warming through developmental plasticity in tropical reef fish. *Global Change Biology, 17*(4), 1712-1719.

Abstract: Determining the capacity of organisms to acclimate and adapt to increased temperatures is key to understand how populations and communities will respond to global warming. Although there is evidence that elevated water temperature affects metabolism, growth and condition of tropical marine fish, it is unknown whether they have the potential to acclimate, given adequate time. We reared the tropical reef fish Acanthochromis polyacanthus through its entire life cycle at present day and elevated (11.5 and13.0 1C) water temperatures to test its ability to thermally acclimate to ocean temperatures predicted to occur over the next 50–100 years. Fish reared at 3.0 1C greater than the present day average reduced their resting oxygen consumption (RMR) during summer compared with fish reared at present day temperatures and tested at the elevated temperature. The reduction in RMR of up to 69mgO2 kg_1 h_1 in acclimated fish could represent a significant benefit to daily energy expenditure. In contrast, there was no acclimation to summer temperatures exhibited by fish reared at 1.5 1C above present day temperatures. Fish acclimated to 13.0 1C were smaller and in poorer condition than fish reared at present day temperatures, suggesting that even with acclimation there will be significant consequences for future populations of tropical fishes caused by global warming.

Questions this article answers: Do tropical fish have the potential to acclimate, given adequate time? (Key to understanding how populations will respond to global warming.)

Methodology: We reared the tropical reef fish Acanthochromis polyacanthus through its entire life cycle at present day and elevated (11.5 and13.0 1C) water temperatures to test its ability to thermally acclimate to ocean temperatures predicted to occur over the next 50–100 years.

Findings:

- Acclimation is an important mechanism for coping with a changing or fluctuating

environment.
    - At least some tropical reef fishes can undertake developmental plasticity to acclimate their RMRs as water temperatures increase due to global warming
- Fish acclimated to a higher than normal temperature were on average smaller than fish kept at present day temperatures, suggesting that increased temperature, or acclimation per se, incurred some physiological cost.
    - It is also likely that physiological processes involved in growth, like protein synthesis and cell proliferation, influence RMR
- Fish at both elevated temperatures were in poorer condition than fish reared at present day temperatures
    - Even with acclimation, warmer sea temps will likely impact reef fish significantly
- The RMR of11.5 and13.0 1C fish in their respective temperatures was higher than that of fish reared at present day temperatures, and both these groups had lower body condition than fish reared in the present day temperature treatment
- Despite acclimation of RMR to the summer average in fish reared at 3.0 1C above present day averages, there was no evidence for acclimation in fish reared at 1.5 1C above
    - The absence of acclimation to 30.0 1C in the 11.5 1C fish is likely to be related to the costs and benefits of acclimation
- Reduced physical condition at elevated temperatures is likely to have important ramifications for reef fish populations in a natural setting.
    - It is well documented that survival rates are positively that survival rates are positively associated with body condition in juvenile reef fishes
    - Fewer fish will potentially survive to maturity at elevated temperatures, because they will be in poorer condition. Reduced condition will also affect reproductive output, with fewer and smaller offspring being produced compared with good condition counterparts
- Fish from the13.0 1C treatment group were shorter on average, which also has ramifications for individual fitness, including reduced size at maturity, which in turn may reduce reproductive output
- Acclimation to one temperature extreme often does not coincide with poor performance at the opposite temperature extreme

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: the other CO2 problem. ***Marine Science*****,** ***1*****.**

Abstract: Rising atmospheric carbon dioxide (CO2), primarily from human fossil fuel combustion, reduces ocean pH and causes wholesale shifts in seawater carbonate chemistry. The process of ocean acidification is well documented in field data, and the rate will accelerate over this century unless future CO2 emissions are curbed dramatically. Acidification alters seawater chemical speciation and biogeochemical cycles of many elements and compounds. One well-known effect is the lowering of calcium carbonate saturation states, which impacts shell-forming marine organisms from plankton to benthic molluscs, echinoderms, and corals. Many calcifying species exhibit reduced calcification and growth rates in laboratory experiments under high-CO2 conditions. Ocean acidification also causes an increase in carbon fixation rates in some photosynthetic organisms (both calcifying and noncalcifying). The potential for marine organisms to adapt to increasing CO2 and broader implications for ocean ecosystems are not well known; both are high priorities for future research. Although ocean pH has varied in the geological past, paleo-events may be only imperfect analogs to current conditions.

Questions this article answers: What are the impacts of ocean acidification on oceans? How does it alter seawater chemical speciation and how does it affect shell-forming marine organisms? Can species adapt?

Methodology: literature review

Findings:

- Over the past 250 years, atmospheric carbon dioxide (CO2) levels increased by nearly 40%, from preindustrial levels of approximately 280 ppmv (parts per million volume) to nearly 384 ppmv in 2007 (Solomon et al. 2007). This rate of increase, driven by human fossil fuel combustion and deforestation, is at least an order of magnitude faster than has occurred for millions of years
- Ocean CO2 uptake causes pH reductions and alterations in fundamental chemical

balances- creates f

- The surface ocean currently absorbs approximately one-third of the excess carbon dioxide
- (CO_2) injected into the atmosphere from human fossil fuel use and deforestation, which
- leads to a reduction in pH and wholesale shifts in seawater carbonate chemistry.
- The resulting lowering of seawater carbonate ion concentrations and the saturation state for calcium carbonate are well documented in field data, and the rate of change is projected to increase over the 21st century unless predicted future CO_2 emissions are curbed dramatically.
- Acidification will directly impact a wide range of marine organisms that build shells from calcium carbonate, from planktonic coccolithophores and pteropods and other molluscs, to echinoderms, corals, and coralline algae. Many calcifying species exhibit reduced calcification and growth rates in laboratory experiments under high-CO_2 conditions, whereas some photosynthetic organisms (both calcifying and noncalcifying) have higher carbon fixation rates under high CO_2.
- Our present understanding of potential ocean acidification impacts on marine organisms stems largely from short-term laboratory and mesocosm experiments; consequently, the response of individual organisms, populations, and communities to more realistic gradual changes is largely unknown (Boyd et al. 2008).
- The potential for marine organisms to adapt to increasing CO_2 and the broader implications for ocean ecosystems are not well known; an emerging body of evidence suggests that the impact of risingCO_2 on marine biota will be more varied than previously thought, with both ecological winners and losers.
- Ocean acidification likely will affect the biogeochemical dynamics of calcium carbonate, organic carbon, nitrogen, and phosphorus in the ocean as well as the seawater chemical speciation of trace metals, trace elements, and dissolved organic matter.
- Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.
- Geo-engineering solutions that attempt to slow global warming without reducing atmospheric CO_2 concentration, such as injection of stratospheric aerosols (Crutzen 2006), will not reduce ocean acidification.

Quotes: "A fully integrated program of laboratory, mesocosm, field monitoring, and modeling approaches is required to provide policymakers with informed management strategies that address how humans might best mitigate or adapt to these long-term changes." -17

Donner, S. D. (2011). An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. ***Ecological Applications, 21*****(5), 1718-1730.**

Abstract: Over the past 30 years, warm thermal disturbances have become commonplace on coral reefs worldwide. These periods of anomalous sea surface temperature (SST) can lead to coral bleaching, a breakdown of the symbiosis between the host coral and symbiotic dinoflagellates which reside in coral tissue. The onset of bleaching is typically predicted to occur when the SST exceeds a local climatological maximum by 18C for a month or more.
However, recent evidence suggests that the threshold at which bleaching occurs may depend on thermal history. This study uses global SST data sets (HadISST and NOAA AVHRR) and mass coral bleaching reports (from Reefbase) to examine the effect of historical SST variability on the accuracy of bleaching prediction. Two variability-based bleaching prediction methods are developed from global analysis of seasonal and interannual SST variability. The first method employs a local bleaching threshold derived from the historical variability in maximum annual SST to account for spatial variability in past thermal disturbance frequency. The second method uses a different formula to estimate the local climatological maximum to account for the low seasonality of SST in the tropics. The new prediction methods are tested against the common globally fixed threshold method using the observed bleaching reports.The results find that estimating the bleaching threshold from local historical SST variability delivers the highest predictive power, but also a higher rate of Type I errors. The second method has the lowest predictive power globally, though regional analysis suggests that it may be applicable in equatorial regions. The historical data analysis suggests that the bleaching threshold may have appeared to be constant globally because the magnitude of interannual variability in maximum SST is similar for many of the world's coral reef ecosystems. For example, the results show that a SST anomaly of 18C is equivalent to 1.73–2.94 standard deviations of the maximum monthly SST for two-thirds of the world's coral reefs. Coral reefs in the few regions that experience anomalously high interannual SST variability like the equatorial Pacific could prove critical to understanding how coral communities acclimate or adapt to frequent and/or severe thermal disturbances.

Questions this article answers: Does the threshold at which coral bleaching occurs depend on thermal history? What is the effect of historical SST variability on the accuracy of bleaching prediction?

Methodology: Two variability-based bleaching prediction methods are developed from global analysis of seasonal and interannual SST variability. The first method employs a local bleaching threshold derived from the historical variability in maximum annual SST to account for spatial variability in past thermal disturbance frequency. The second method uses a different formula to estimate the local climatological maximum to account for the low seasonality of SST in the tropics.

Findings:

- Estimating the bleaching threshold from local historical SST variability delivers the highest predictive power, but also a higher rate of Type I errors
- The second method has the lowest predictive power globally, though regional analysis suggests that it may be applicable in equatorial regions.
- The historical data analysis suggests that the bleaching threshold may have appeared to be constant globally because the magnitude of interannual variability in maximum SST is similar for many of the world's coral reef ecosystems
- This analysis finds that the seasonal and interannual SST variability for the majority of the world's coral reefs lies within a small range
- The second method has the lowest predictive power globally, though regional analysis suggests that it may be applicable in equatorial regions
- The bleaching threshold may have appeared to be constant globally because the magnitude of interannual variability in maximum SST is similar for many of the world's coral reef ecosystems
- The results show that a SST anomaly of 18C is equivalent to 1.73–2.94 standard deviations of the maximum monthly SST for two-thirds of the world's coral reefs
- Coral reefs in the few regions that experience anomalously high interannual SST variability like the equatorial Pacific could prove critical to understanding how coral communities acclimate or adapt to frequent and/or severe thermal disturbances.

Eakin, C. M., Morgan, J. A., Heron, S. F., & et al. (2010). Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLoS One, 5*(11)

Abstract: Background: The rising temperature of the world's oceans has become a major threat to coral reefs globally as the severity and frequency of mass coral bleaching and mortality events increase. In 2005, high ocean temperatures in the tropical Atlantic and Caribbean resulted in the most severe bleaching event ever recorded in the basin.
Methodology/Principal Findings: Satellite-based tools provided warnings for coral reef managers and scientists, guiding both the timing and location of researchers' field observations as anomalously warm conditions developed and spread across the greater Caribbean region from June to October 2005. Field surveys of bleaching and mortality exceeded prior efforts in detail and extent, and provided a new standard for documenting the effects of bleaching and for testing nowcast and forecast products. Collaborators from 22 countries undertook the most comprehensive documentation of basin-scale bleaching to date and found that over 80% of corals bleached and over 40% died at many sites. The most severe bleaching coincided with waters nearest a western Atlantic warm pool that was centered off the northern end of the Lesser Antilles.
Conclusions/Significance: Thermal stress during the 2005 event exceeded any observed from the Caribbean in the prior 20 years, and regionally-averaged temperatures were the warmest in over 150 years. Comparison of satellite data against field surveys demonstrated a significant predictive relationship between accumulated heat stress (measured using NOAA Coral Reef Watch's Degree Heating Weeks) and bleaching intensity. This severe, widespread bleaching and mortality will undoubtedly have long-term consequences for reef ecosystems and suggests a troubled future for tropical marine ecosystems under a warming climate.

Questions this article answers: What is the effect of rising temperature to coral reefs? How did the high ocean temperatures in 2005 affect the tropical Atlantic and Caribbean region?

Methodology: Field surveys of bleaching and mortality: collaboration in 22 countries for field observations from June-October 2005; NOAA's Coral Reef Watch (CRW) developed and maintains a suite of operational satellite sea surface temperature (SST)-based products that provide coral bleaching nowcasts and alerts

Findings:

- Unlike many past Caribbean bleaching years, strong tropical climate forcing was only a minor driver of Caribbean SSTs in 2005
- NOAA measured sustained thermal stress in 2005 that exceeded 16 degrees C-weeks in some regions, far greater than the thresholds that have usually been associated with the onset of mass coral bleaching
- As the event developed, water temperatures rose across the basin to levels well above normal (i.e., long-term average condition, Figure 2A) and remained above normal for more than 7 months, resulting in especially severe thermal stress at the northern end of the Lesser Antilles
- Sustained thermal stress in the Caribbean during 2005 was more intense than any of the previous 20 years
- In the Florida Keys in 2005, bleaching was less severe than in the Caribbean proper but increased temperatures were quickly followed by a loss of resistance to pathogenic disease and an increased abundance of microbial pathogens in A. palmata
    - Might explain the high incidence of disease following the thermal stress by either contagious or opportunistic pathogens
- Frequent monitoring of A. palmate also revealed that bleached corals suffered greater diseaseassociated mortality than unbleached colonies, indicating that disease severity was dependent on host susceptibility
- Strong coherence between thermal stress and widespread bleaching
- Average ocean temperatures during the July-October period for the Caribbean exceeded temperatures seen at any time during the prior 150 years
- Hurricane season that damaged coral reefs in Jamaica, Cuba, the Yucatan, Flower Garden Banks, and the Florida Keys as well as causing major damage to communities and loss of human life.
- It is unlikely that natural climate variability was the cause of declines in Caribbean reefs during recent decades, as coral reef community composition had remained remarkably stable for the prior 220,000 years- probably is mainly from human disturbances
- BUT the repeated coral bleaching events since the 1980s have been strongly attributed to anthropogenic climate change

Quotes:

"Hurricanes have been observed to cause mechanical damage to coral reefs, including damaging coral tissue and dislodging colonies, weakening corals in ways than could slow recovery following bleaching, and contributing to long-term ecosystem decline. However, hurricanes that pass within several hundred kilometers of coral reefs have been shown to cool anomalously warm SSTs below bleaching thresholds, and were probably significant in reducing thermal stress and preventing more severe bleaching in the Florida Keys in 2005." Pg 5

"Bleaching and mortality such as that seen in the Caribbean in 2005 will undoubtedly have longterm consequences for Caribbean coral reefs, as these corals have shown very slow rates of recovery to mortality from mass bleaching. This means that any future bleaching is likely to add to the damage caused in 2005, just as the 2005 event continued the decline of reefs that have suffered past mortality from bleaching, disease, and local stressors." 6

"As this paper went to press in 2010, major bleaching was again striking reefs in the Caribbean, in some places worse than in 2005. Major bleaching events have returned to the Caribbean every five years or less, and with growing intensity." 6

Edgar, G. J., Davey, A., Kelly, G., & et al. (2010). Biogeographical and ecological context for managing threats to coral and rocky reef communities in the lord howe island marine park, south-western pacific. ***Aquatic Conservation: Marine and Freshwater Ecosystems, 20*****(4), 378-396.**

Abstract: 1. Quantitative subtidal surveys of fishes, macro-invertebrates and sessile organisms at 33 sites within the Lord Howe Island Marine Park revealed a rich fauna and flora, including 164 fishes, 40 mobile invertebrate taxa, 53 coral and other sessile invertebrate taxa, 32 algal taxa, and two seagrasses. The biota in this newly-zoned marine park was overwhelmingly tropical when species lists were tabulated; however, species with distributions centred on temperate coasts of eastern Australia and New Zealand occurred in disproportionately high densities compared with the tropical species.
2. Lord Howe Island reefs were generally in good condition. Virtually no bleached coral was observed (0.2% of the reef surface; 0.8% of total hard coral cover). Living scleractinian coral comprised the predominant group of organisms growing on reef surfaces, with 25.5% cover overall. Other major taxa observed were brown algae (18.8% cover) and red algae (16.9% cover).
3. Three distinctive community types were identified within the marine park—coral reefs, macroalgal beds and an offshore/open coast community. The distribution of these community types was strongly related to wave exposure, as indicated by an extremely high correlation with the first principal coordinates axis for biotic data (R250.80).
4. The close (o3 km) proximity of tropical coral and temperate macroalgal community types off Lord Howe Island is highly unusual, with localized patterns of nutrient enrichment suggested as the primary cause. The macroalgal community type is only known from a small area off the south-western coast that is not protected from fishing. This community is considered highly susceptible to threats because of potential impacts of global warming and the possibility of expansion of sea urchin barrens. Coral bleaching and ocean acidification associated with global climate change also threaten the coral reef community, which includes relatively high numbers of endemic and near endemic fish species.

Questions this article answers: What is the biogeographical and ecological context for managing threats to coral and rocky reef communities (in Lord Howe Island Marine Park)?

Methodology: quantitative subtidal surveys of fishes, macro-invertebrates and sessile organisms at 33 sites within Lord Howe Island Marine Park

Findings:

- Lord Howe Island possesses a rich fish fauna compared with other regions surveyed using the same transect technique- average of 16 taxa recognized during all fish transects
- The most abundant fish species sighted were the three planktivorous damselfishes Chromis hypsilepis, Chrysiptera notialis and Neoglyphidodon polyacanthus, followed by the carnivorous wrasse Pseudolabrus luculentus, planktivorous cardinalfish Ostorhinchus norfolcensis and three herbivorous damselfishes Parma polylepis, Stegastes gascoynei and Stegastes fasciolatus
- Four of the top seven biomass dominants were herbivores
- No introduced fish species or fish listed under the IUCN Red List were observed
- Almost half of all fish species sighted during transects were categorized trophically as benthic carnivores; however, this trophic category contributed only 17% of total abundance and 24% of total biomass
- A total of 40 macro-invertebrate taxa and seven cryptic fish taxa were recorded during 50m_1m transects
- The species richness, density and biomass of fishes at different trophic levels tended to be very stable between sites within a community type- low level of site-to-site variation
- Not surprisingly, coral communities possessed the highest percentage cover of hard corals, and also the highest amount of bare substratum in the form of dead coral rubble

Quotes:

"Lord Howe Island lies at a marine biogeographic crossroad with a biotic mix of different distributional elements, including endemic, insular, tropical, subtropical and warm temperate species. The contributions of these different biogeographic elements vary between taxonomic groups and location, and also depend on whether species richness or abundance is considered."

"Tropical fish species present at Lord Howe Island have lower conservation significance as a group than subtropical, warm, temperate or endemic taxa. Their low abundances indicate that population strongholds are largely elsewhere, and that few possess significant functional roles in local ecosystems."

Edwards, H. J., Elliott, I. A., Eakin, C. M., & et al. (2011). How much time can herbivore protection buy for coral reefs under realistic regimes of hurricanes and coral bleaching? ***Global Change Biology, 17*****(6), 2033-2048.**

Abstract: Coral reefs have been more severely impacted by recent climate instability than any other ecosystem on Earth. Corals tolerate a narrow range of physical environmental stress, and increases in sea temperature of just 1 1C over several weeks can result in mass coral mortality, often exceeding 95% of individuals over hundreds of square kilometres. Even conservative climate models predict that mass coral bleaching events could occur annually by 2050. Unfortunately, managers of coral-reef resources have few options available to meet this challenge. Here, we investigate the role that fisheries conservation tools, including the designation of marine reserves, can play in altering future trajectories of Caribbean coral reefs. We use an individual-based model of the ecological dynamics to test the influence of spatially realistic regimes of disturbance on coral populations. Two major sources of disturbance, hurricanes and coral bleaching, are simulated in contrasting regions of the Caribbean: Belize, Bonaire, and the Bahamas. Simulations are extended to 2099 using the HadGEM1 climate model. We find that coral populations can maintain themselves under all levels of hurricane disturbance providing that grazing levels are high. Regional differences in hurricane frequency are found to cause strikingly different spatial patterns of reef health with greater patchiness occurring in Belize, which has less frequent disturbance, than the Bahamas. The addition of coral bleaching led to a much more homogenous reef state over the seascape. Moreover, in the presence of bleaching, all reefs exhibited a decline in health over time, though with substantial variation among regions. Although the protection of herbivores does not prevent reef degradation it does delay rates of coral loss even under the most severe thermal and hurricane regimes. Thus, we can estimate the degree to which local conservation can help buy time for reefs with values ranging between 18 years in the Bahamas and over 50 years in Bonaire, compared with heavily fished systems. Ultimately, we demonstrate that local conservation measures can benefit reef ecosystem services but that their impact will vary spatially and temporally.
Recognizing where such management interventions will either help or fail is an important step towards both achieving sustainable use of coral-reef resources and maximizing resource management investments.

Questions that this article answers: What are the roles that fisheries conservations can have in altering future trajectories of Caribbean coral reefs?

Methodology: An individual-based model of the Montastraea annularis zone of a Caribbean coral reef was used to model the ecological dynamics and subject coral populations to spatially realistic regimes of disturbance.

Findings:

- Climate change impacts are detrimental throughout the Caribbean but that the rates of decline vary substantially with geographic location
- The frequency of predicted thermal stress events increased with time; more extreme events were observed in the later years (2070–2099)
- No severe bleaching expected in the Bahamas between 2010 and 2039- Bahamas site exposed to almost annual severe bleaching events by 2070
    - Sites in Belize experienced up to 25 severe bleaching events in the last 30 years of the time series
- Individual runs of the model show that coral cover fell as low as 30% immediately following extreme hurricane events and that recovery to predisturbance levels took up to 30 years
- Although simulated hurricane events could cause a rapid decline in coral cover, the frequency of severe events was low enough that net recovery was always observed.
- Reducing parrotfish grazing in models from 40% to 10%- different reef communities, even in hurricane-only scenarios
    - Well-grazed coral reefs were able to withstand the entire range of hurricane regimes observed in the three regions, whereas overfished reefs always resulted in coral decline with o5% cover within 20–30 years
- Coral-reef trajectories within each region were influenced by the size of the region and by the range of hurricane disturbance events that occurred
- Different hurricane disturbance regimes were also found to generate different emergent patterns in reef health

Quotes:

"Patterns of coral bleaching had little deterministic spatial structure and served to attenuate spatial patchiness of reef health. This does not imply that coral bleaching is entirely homogenous, but in this case, the overall impact on corals showed little consistent structure."

"Our analyses showed that Bonaire has the most benign disturbance environment of the three regions studied. It also predicted that reefs in Bonaire would remain healthier for longer than areas experiencing more intense hurricane disturbance. These simple predictions have some support empirically in that reefs in Bonaire are currently among the healthiest in the Caribbean."

Fabry, V. J., Seibel, B. A., Feely, R. A., & Orr, J. C. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science: Journal du Conseil*, *65*(3), 414-432.

Abstract: Oceanic uptake of anthropogenic carbon dioxide (CO2) is altering the seawater chemistry of the world's oceans with consequences for marine biota. Elevated partial pressure of CO2 (pCO2) is causing the calcium carbonate saturation horizon to shoal in many regions, particularly in high latitudes and regions that intersect with pronounced hypoxic zones. The ability of marine animals, most importantly pteropod molluscs, foraminifera, and some benthic invertebrates, to produce calcareous skeletal structures is directly affected by seawater CO2 chemistry. CO2 influences the physiology of marine organisms as well through acid-base imbalance and reduced oxygen transport capacity. The few studies at relevant pCO2 levels impede our ability to predict future impacts on foodweb dynamics and other ecosystem processes. Here we present new observations, review available data, and identify priorities for future research, based on regions, ecosystems, taxa, and physiological processes believed to be most vulnerable to ocean acidification. We conclude that ocean acidification and the synergistic impacts of other anthropogenic stressors provide great potential for widespread changes to marine ecosystems.

Questions this article answers: How does seawater CO2 chemistry affect marine organisms' ability to produce calcareous skeletal structures? What are the impacts of ocean uptake of anthropogenic carbon dioxide? What are new observations, available data, and priorities for future research?

Methodology: literature review

Findings:

- Approximately one-third of the anthropogenic CO2 produced in the past 200 years has been taken up by the oceans
- Elevated partial pressure of CO2 (pCO2) in seawater (also known as hypercapnia) can impact marine organisms both via decreased calcium carbonate (CaCO3) saturation, which affects calcification rates, and via disturbance to acid–base (metabolic) physiology.
- Oceanic uptake of anthropogenic CO2 and the concomitant changes in seawater

chemistry have adverse consequences for many calcifying organisms, and may result in changes to biodiversity, trophic interactions, and other ecosystem processes

- The inorganic carbon system is one of the most important chemical equilibria in the ocean and is largely responsible for controlling the pH of seawater.
- The reaction of CO2 with seawater reduces the availability of carbonate ions that are necessary for marine calcifying organisms, such as corals, molluscs, echinoderms, and crustaceans, to produce their CaCO3 shells and skeletons.
- The secretion of CaCO3 skeletal structures is widespread across animal phyla, and evolved independently and repeatedly over geologic time since the late Precambrian period
- The majority of work has tested warm-water corals and coccolithophorid algae (Royal Society, 2005; Kleypas et al., 2006). Evidence suggests that the calcification rate in corals is controlled by the CaCO3 saturation state, rather than pH or another parameter of the seawater CO2 system.
- Quantification of these complex ecosystem processes requires additional empirical data, as well as new modeling efforts, particularly on regional scales.

Quotes:
"In sensitive regions and for critical species, we need to track the abundances and depth distributions of calcareous and noncalcifying fauna, measure calcification and metabolic rates of these groups, and relate these data to changes in the CO2 chemistry of the water column. This requires commitment to long-term monitoring programmes at appropriate temporal and spatial scales to detect possible shifts, and distinguish between natural variability and anthropogenically induced changes."- 14

"Ocean acidification could also affect foodwebs and carbon cycling through bottom-up controls involving pH-dependent speciation of nutrients and metals (Huesemann et al., 2002), which, in turn, may alter species composition and rates of primary productivity"- 14

"The interactive effects and feedback of changing seawater CO2 chemistry with other stressors, such as warming, eutrophication, introduced species, and overfishing, may act to alter ecosystem responses that would otherwise result from only one of these stressors" – 14

Fabry, V. J. (2008). Marine calcifiers in a high-CO2 ocean. *Science*, *320*(5879), 1020-1022.

Abstract: The oceans have taken up about one third of the total carbon dioxide (CO2) released into the atmosphere by human activities over the past 200 years (*1*). This addition of CO2 to the surface ocean changes seawater chemistry, resulting in a decrease in pH and carbonate ion concentration, and an increase in the concentrations of bicarbonate ion and hydrogen ion. Ocean absorption of anthropogenic CO2 also reduces the saturation state of seawater with respect to calcite and aragonite, two common types of calcium carbonate secreted by marine biota. Experiments with calcareous organisms indicate that calcification is strongly dependent on the carbonate saturation state of seawater (*2–6*), which suggests that ocean acidification will adversely impact calcifying taxa. Evidence is now accumulating that the acidifying effects of CO2 on seawater may have diverse consequences for marine calcifiers.

Questions this article answers: Do marine organisms respond differently within and between species to ocean acdification?

Methodology: literature review

Findings:

- Ocean absorption of anthropogenic CO2 also reduces the saturation state of seawater with respect to calcite and aragonite, two common types of calcium carbonate secreted by marine biota
- Evidence is now accumulating that the acidifying effects of CO2 on seawater may have diverse consequences for marine calcifiers.
- Only six species of living, planktonic calcifying organisms have been investigated—four coccolithophore species and two foraminiferan species.
- Recently, Iglesias-Rodríguez *et al*. confirmed that the response of calcifying organisms to CO2-induced changes in seawater chemistry is not uniform and may be much more complex than previously thought
- The authors suggest that one reason their results differ from previous work with this species is that they manipulated the inorganic carbon system of seawater by bubbling with air containing different concentrations of CO2.
- Calcification mechanisms in calcium carbonate– secreting organisms are not sufficiently understood to explain the species-specific differences observed in

CO2-perturbation experiments

- Given the importance of coastal and high-latitude regions to fisheries and other ecosystem services, a comprehensive understanding of the impacts of ocean acidification is urgently needed.

Quotes:

"Future work should investigate additional species and life stages of calcifiers, examine the possible interactions of increasing CO2 with other environmental variables, and explore the capacity of organisms to adapt to projected changes. Equally important is the development of internationally agreed-upon, standardized protocols for the control of seawater composition in manipulative experiments, as well as for the measurement of calcification rates."

Feary, D. A., Burt, J. A., Bauman, A. G., & et al. (2010). Fish communities on the world's warmest reefs: What can they tell us about the effects of climate change in the future? *Journal of Fish Biology, 77*(8), 1931-1947.

Abstract: To examine the role of climatic extremes in structuring reef fish communities in the Arabian region, reef fish communities were visually surveyed at four sites within the southern Persian Gulf (also known as the Arabian Gulf and The Gulf), where sea-surface temperatures are extreme (range: 12–35◦ C annually), and these were compared with communities at four latitudinally similar sites in the biogeographically connected Gulf of Oman, where conditions are more moderate (range: 22–31◦ C annually). Although sites were relatively similar in the cover and composition of coral communities, substantial differences in the structure and composition of associated fish assemblages were apparent. Fish assemblages in the southern Persian Gulf held significantly lower estimates of abundance, richness and biomass, with significantly higher abundances of smaller sized individuals than Gulf of Oman assemblages. Functionally, southern Persian Gulf sites held significantly lower abundances of nearly all the common fish trophic guilds found on Gulf of Oman sites, although higher abundances of herbivorous grazers were apparent. These results suggest the potential for substantial changes in the structure of reef-associated fish communities, independent of changes in habitat within an environment of increasing fluctuations in oceanic climate.

Questions this article answers: What is the role of climatic extremes in structuring reef fish communities in the Arabian region?

Methodology: visual surveyes at four site within the southern Persian Gulf, compared to four latitudinally similar sites in the Gulf of Oman

Findings:

- The southern Persian Gulf is characterized by extreme environmental conditions, with physical extremes not observed in tropical reefs anywhere else in the world
- Diverse and abundant coral and coral-associated fish communities do develop in this area, indicating that a variety of reef fauna can survive at or above the elevated sea temperatures predicted for much of the world in the coming decades
    - While a number of species can tolerate these extreme conditions, the communities are generally lower in diversity and abundance, and function differently, than those in more benign environments
- Significantly lower fish species abundance and biomass (richness) in the southern Persian Gulf compared with the Gulf of Oman

    - -Also due to physical extremes in Persian Gulf
- Gulf of Oman communities held substantially higher species richness, when comparing the same number of individuals, to southern Persian Gulf communities
- Of the 28 species that contributed to community dissimilarity, over half were more abundant in the Gulf of Oman than the southern Persian Gulf
- The size structure of fish communities differed significantly between the southern
- Persian Gulf and the Gulf of Oman
    - Relatively higher abundance of fishes in the 50–100 mm *L*T class in the Persian Gulf, with abundance in all other *L*T classes higher in the Gulf of Oman
- Coral cover was comparable between the southern Persian Gulf and the Gulf of Oman but showed variation among sites within regions
- In terms of overall community structure, fish and coral communities were shown to be only weakly correlated with each other in RELATE in terms of both fish species and guild structure *v*. coral species and growth form structure
    - There was a significant relationship between fish abundance and total coral cover in transects across regions
    - There was no relationship between coral cover and fish biomass or fish species richness
- **Such low concordance between demographic variables and coral assemblage structure shows that assemblages within both regions may be less tightly associated with the live coral structure than the reef structure itself**
- There were broad differences in the abundance and biomass of fish communities between regions, which may be associated with either temperature or salinity effects

Quotes:
"There were substantial differences in the structure and composition of reef fish communities in the southern Persian Gulf and the Gulf of Oman, despite these being biogeographically connected, indicating the importance of environmental extremes in structuring fish assemblages."

Ferrari, M. C., Dixson, D. L., Munday, P. L., McCORMICK, M. A. R. K., Meekan, M. G., Sih, A., & Chivers, D. P. (2011). Intrageneric variation in antipredator responses of coral reef fishes affected by ocean acidification: implications for climate change projections on marine communities. *Global Change Biology*, *17*(9), 2980-2986.

Abstract: Our planet is experiencing an increase in the concentration of atmospheric carbon dioxide (CO2) unprecedented in the past 800 000 years. About 30% of excess atmospheric CO2 is absorbed by the oceans, thus increasing the concentration of carbonic acid and reducing the ocean's pH. Species able to survive the physiological stress imposed by ocean acidification may still suffer strong indirect negative consequences. Comparing the tolerance of different species to dissolved CO2 is a necessary first step towards predicting the ecological impacts of rising CO2 levels on marine communities. While it is intuitive that not all aquatic species will be affected the same way by CO2, one could predict that closely related species, sharing similar life histories and ecology, may show similar tolerance levels to CO2. Our ability to create functional groups of species according to their CO2 tolerance may be crucial in our ability to predict community change in the future. Here, we tested the effects of CO2 exposure on the antipredator responses of four damselfish species (Pomacentrus chrysurus, Pomacentrus moluccensis, Pomacentrus amboinensis and Pomacentrus nagasakiensis). Although being sympatric and sharing the same ecology and life history, the four congeneric species showed striking and unexpected variation in CO2 tolerance, with CO2-induced loss of response to predation risk ranging from 30% to 95%. Using P. chrysurus as a model species, we further tested if these behavioural differences translated into differential ability to survive predators under natural conditions. Our results indicate that P. chrysurus larvae raised under CO2 levels predicted by 2070 and 2100 showed decreased antipredator responses to risk, leading to a five- to sevenfold increase in predation-related mortality in the first few hours of settlement. Examining ocean acidification, along with other environmental variables, will be a critical step in further evaluating ecological responses to predicted climatic change.

Questions this article answers: What are the effects of CO2 exposure on the antipredator responses of four damselfish species? Does behavioral differences and varying response to CO2 translate into different abilities to survive predation under natural conditions? Do tolerances of different species to dissolved CO2 vary?

Methodology: Quantitatively observed how fish species responded to varying CO2 levels in laboratory setting:
Fish trapped and transferred into aquariums that were either aerated with 390ppm (current-day control), 728 or 1008 ppm CO2-enriched air (Munday et al., 2009a; Dixson

et al., 2010). Aeration with CO_2-enriched air produced dissolved CO_2 levels of approximately 700 and 850ppm (see Munday et al., 2010 for more details). Seawater for the system was pumped directly from the ocean into 70 L sumps, where it was aerated with the same concentration of CO_2-enriched air as the rearing aquariums. Rearing aquariums received a continuous flow of water from their respective sump at approximately 225– 250mLmin_1. Water temperature averaged 27.6 1C _ 1.3 [standard deviation).

Findings:

- When inspected in the laboratory, CO_2-exposed fish lack the adaptive antipredator responses to risk cues exhibited by control fish
- As CO_2 increased, individuals decreased the intensity of their antipredator response towards the risk cues- consistent with previous lab studies
- There was an increased variation in the responses of fish to risk in the 700 ppm treatment, compared with the control and 850 ppm treatments. A greater variability in the effect of CO_2 indicates that some individuals are much more affected than others under these conditions, and thus, 700 ppm might represent a threshold for which biological adaption may be possible
- When presented in a flume containing the odour of a predator in one arm and control water in the other, roughly half of the juvenile damselfish, Pomacentrus wardi, treated with 700 ppmCO_2 preferred the water side (nonaffected) while the other half preferred the predator side (affected).
- Even a slight difference in survival could lead to considerable opportunity for selection of those CO_2 tolerant phenotypes
- P. amboinensis appear as a very sensitive species, showing a _95% reduction in antipredator response at levels as low as 700 ppm, which suggests that they would likely show a maladaptive response at CO_2 levels even lower than those tested here
    - P. nagasakiensis was less affected – only showing 30% and 40% reduction in antipredator response at 700 and 850 ppm – and consequently should have the greatest opportunity to adapt and possibly even gain indirect benefits (e.g., via decreased competition) as CO_2 levels rise over the next decades
        -Differences unrelated to body size
- Phylogenetic distances between our four species does not seem to correlate with our results, given that P. moluccensis and P. amboinensis are more related than P. moluccensis and P. chrysurus
- Fish with altered behavioural responses in the lab showed a fivefold (700 ppm) to sevenfold (850 ppm) increase in mortality in the wild.
- Although fish may survive CO_2 exposures better than other marine species (Munday et al., 2009b), our results indicate that they may be as affected by ocean acidification through indirect lethal consequences of ocean acidification

Quotes:

"Our results indicate that increased levels of CO_2 may impact recruitment patterns for coral reef fishes, and possibly other marine species. Furthermore, interspecific variation in response to rising CO_2 may result in changes to community composition of prey species, which in turn, may affect biodiversity at higher trophic levels"- 2985

"The impact of ocean acidification on marine ecosystems will depend not only on the magnitude of species differences, but also how much and how fast these species can adapt to their novel environmental conditions, but this is currently unknown." -2985

Ferrari, M. C. O., McCormick, M. I., Munday, P. L., Meekan, M. G., Dixon, D. L., Lonnstedt, O., & Chivers, D. P. (2011). Putting prey and predator into the CO_2 equation – qualitative and quantitative effects of ocean acidification on predator–prey interactions. *Ecology Letters, 14*, 1143-1148.

Abstract: Little is known about the impact of ocean acidification on predator–prey dynamics. Herein, we examined the effect of carbon dioxide (CO_2) on both prey and predator by letting one predatory reef fish interact for 24 h with eight small or large juvenile damselfishes from four congeneric species. Both prey and predator were exposed to control or elevated levels of CO_2. Mortality rate and predator selectivity were compared across CO_2 treatments, prey size and species. Small juveniles of all species sustained greater mortality at high CO_2 levels, while large recruits were not affected. For large prey, the pattern of prey selectivity by predators was reversed under elevated CO_2. Our results demonstrate both quantitative and qualitative consumptive effects of CO_2 on small and larger damselfish recruits respectively, resulting from CO_2-induced behavioural changes likely mediated by impaired neurological function. This study highlights the complexity of predicting the effects of climate change on coral reef ecosystems.

Questions this article answers: What are the effects of elevated CO_2 levels on prey and predators in coral reef ecosystems? Does it affect the selectivity of a common predator for prey species?

Methodology: case study/ a mesocosm experiment: predatory reef fish (the dottyback Pseudochromis fuscus,) interact with 8 small or large juvenile damselfishes two from each of four species (Pomacentrus moluccensis, P. amboinensis, P. nagasakiensis and P. chrysurus) for 24 hours.

Findings:

- Predation rates and prey selectivity were impacted by exposure to elevated levels of dissolved CO_2, but the outcome of the interaction was dependent on the size of juvenile prey
- Elevated dissolved CO_2 had a quantitative effect on the predator–prey interactions involving small juvenile damselfishes
  - Predation rates were higher under elevated CO_2 than under control conditions, predators didn't show a species-specific preference
- There was a qualitative effect of elevated CO_2 when the prey damselfishes were slightly larger.
  - CO_2 did not affect the number of prey consumed, but rather, elevated CO_2 affected the composition of the prey assemblage
  - P. fuscus preferentially consumed two species of damselfishes (P.

nagasakiensis and P. chrysurus) under present day CO_2 conditions, but this preference was reversed with elevated CO_2.

- Evidence suggests that the changes in predator–prey dynamics are due to CO_2-induced changes in behavior
- From a prey viewpoint, we know that CO_2 has a detrimental effect by influencing the way they respond to predator cues
- Recent research showed that exposure to elevated CO_2 affects both olfactory and auditory senses and a diverse range of behavioural activities in larval and adult fishes.
- The accumulating experimental evidence shows that impaired and altered behaviour following exposure to elevated CO_2 is caused by a systemic effect at the neurological level.

Figueira, W. F., & Booth, D. J. (2010). Increasing ocean temperatures allow tropical fishes to survive overwinter in temperate waters. ***Global Change Biology, 16*****(2), 506-516.**

Abstract: The southeast coast of Australia is a global hotspot for increasing ocean temperatures due to climate change. The temperate incursion of the East Australian Current (EAC) is increasing, affording increased connectivity with the Great Barrier Reef. The survival of tropically sourced juveniles over the winter is a significant stumbling block to poleward range shifts of marine organisms in this region. Here we examine the dependence of overwintering on winter severity and prewinter recruitment for eight species of juvenile coral reef fishes which are carried into temperate SE Australia (30–371S) by the EAC during the austral summer. The probability of persistence was most strongly influenced by average winter temperature and there was no effect of recruitment strength. Longterm (138 years) data indicate that winter water temperatures throughout this region are increasing at a rate above the global average and predictions indicate a further warming of 42 1C by the end of the century. Rising ocean temperatures are resulting in a higher frequency of winter temperatures above survival thresholds. Current warming trajectories predict 100% of winters will be survivable by at least five of the study species as far south as Sydney (341S) by 2080. The implications for range expansions of these and other species of coral reef fish are discussed.

Questions this article answers: what is the dependence of overwintering on winter severity and prewinter recruitment for eight species of juvenile coral reef fishes?

Methodology: data series collected by the authors (Lord Howe Island, Sydney, Jervis Bay and Merimbula) and others (Solitary Islands, data courtesy of H. Malcolm) as part of ongoing underwater visual censuses for tropical fish at each of the locations. These locations were areas in which tropical fish were known to recruit each summer based upon previous studies

Findings:

- Eight species of tropical coral reef fish were observed to commonly settle in at least half of the locations during the study period
  - Six of these species were damselfishes and two were butterflyfishes
- All of these species occur on the southern Great Barrier Reef and are generally found in rocky/rubble habitat among and peripheral to coral reefs
- The HadISST1 data set indicates significant global warming of about 0.5 1C between 1870 and 2000 and a winter (July–August) warming trend of between 0.7 and 1.5 1C for the locations explored in this study confirming previous observations that this area is a hotspot for increasing ocean temperatures
- As the average water temperature increased over the last 90 years, the type of

winter which a tropical fish can survive became increasingly more common

- The ability of four common species of tropical damselfishes to overwinter at temperate latitudes increases with average winter temperatures and seems to do so substantially between 16.5 and 17.5 1C,
    - This does not seemto be the case for one species, A. sexfasciatus which was never observed to overwinter at our study locations
    - That the two butterflyfish species observed require temperatures warmer than 19 1C to successfully overwinter
- Present warming trends will steadily increase the frequency of survivable winters, thus opening the door for potential range expansions of these species provided the biophysical requirements of the adult stage are also met (especially for reproduction).
- The higher threshold temperature for P. coelestis and S. gascoyni at Lord Howe Island suggests these fish may be adapted to warmer waters
- The study suggests- in regions with long-distance connectivity afforded by dominant boundary currents, climate-induced range shifts have the capacity to be rapid and dramatic.

Quotes:
"Thus for any range shift to occur for the species discussed in this study, the biophysical environment would have to be appropriate for the adult stages as well. In fact for all of the species described, juvenile and adult habitat and food requirements do not differ substantially."

Fisher, R., Radford, B. T., Knowlton, N., & et al. (2011). Global mismatch between research effort and conservation needs of tropical coral reefs. *Conservation Letters, 4*(1), 64-72.

Abstract: Tropical coral reefs are highly diverse and globally threatened. Management to ensure their persistence requires sound biological knowledge in regions where coral reef biodiversity and/or the threats to it are greatest. This paper uses a novel text analysis approach and Google Maps™ to examine the spatial coverage of scientific papers on coral reefs listed in *Web of Science*®. Results show that research is highly clumped spatially, positively related to per capita gross domestic product, negatively related to coral species richness, and unrelated to threats to coral reefs globally; indicating a serious mismatch between conservation needs and the knowledge required for effective management. Greater research effort alone cannot guarantee better conservation outcomes, but given some regions of the world (e.g., Central Indo-Pacific) remain severely understudied, priority allocation of resources to fill such knowledge gaps should support greater adaptive management capacity through the development of an improved knowledge base for reef managers.

Gagliano, M., McCormick, M. I., Moore, J. A., & et al. (2010). The basics of acidification: Baseline variability of pH on australian coral reefs. *Marine Biology, 157*(8), 1849-1856.

Abstract: Ocean acidification is one of the key threats facing coral reef ecosystems, but there are few estimates of spatial and temporal variability in pH among reef habitats. The present study documents levels of spatial variability in pH among coral reef habitats (9 to 10), among locations separated by 100's km of latitude and between east (Great Barrier Reef, GBR) and west (Ningaloo Reef) coasts of Australia. Differences were found in pH between inshore and offshore waters along Ningaloo Reef (means 8.45, 8.53, respectively). Replicate assessments here ranged from 8.22 to 8.64. On the GBR, the range of values over all habitats and replicates was 0.39 pH units (7.98 to 8.37). There were minor but significant differences of 0.05 pH units between 5 consecutive days for habitats on average. Highest pH was recorded in flamentous algal beds maintained by the damselfish *Dischistodus perspicillatus*. Lowest pH was found in water extracted from sand-dwelling goby holes. While there were marked changes in pH over a 48-h sampling period among 4 habitats at Lizard Island (GBR), there was little evidence of a diel trend. Understanding how pH varies at scales that are relevant to organisms that live on shallow coral reefs is crucial for the design and interpretation of experiments that test the effects on organisms of the changes in water chemistry predicted to affect oceans in the future.

Questions this article answers: What is the spatial and temporal variability in pH among reef habitats? What is the spatial variability in pH among coral reef habitats among locations separated by 100km of latitude and between the east and west coasts of Australia?

Methodology: samples were collected at three sampling scales from December 2007 to July 2008: (a) locations along the northern and central Great Barrier Reef spanning approximately 510 km of latitude; (b) within reef and beyond reef locations along Ningaloo Reef in Western Australia spanning 95 km of latitude; and (c) from 10 microhabitats within 2 sites 50 m apart on the leeward side of Lizard Island on the northern Great Barrier Reef

Findings:

- There were significant differences in the pH among the 10 habitats sampled within the Lizard Island lagoon
- There was a significant difference in pH among the 9 microhabitats between Magnetic Island and Bay Rock back-reefs
- There were also trends in the variability among replicate observations that were consistent among habitats, with high variability shown at 9 pm of day 1, 5 pm of day 2 and 9 pm of day 2.
    - o Consistent trends among habitats through time may be due to the tidal cycle bringing water of different pH into the sampling site

- That there are consistent differences at small spatial and temporal scales and that these differences can be of the order of 0.4 pH units.
- Locations sampled 0.2–1 km oV the reef exhibited higher pH values (i.e. lower acidity) than those sampled over the reef matrix

Quotes:
"The few studies that have quantified differences in pH among reef habitats have shown levels of variability that span 0.4 to 1 unit. These are high given that the oceans are predicted to display a 0.5 unit decrease in pH by 2100 (Raven 2005). Understanding the levels of spatial variability in pH and the extent and magnitude of fluctuations through time is crucial for the design of controlled experiments that mimic Weld conditions. Much effort has been directed at understanding how changes in pH will affect the physiological capacity and survival of marine organisms under predicted climate change scenarios." 1855

Gardiner, N. M., Munday, P. L., & Nilsson, G. E. (2010). Counter-gradient variation in respiratory performance of coral reef fishes at elevated temperatures. *PLoS One, 5*(10)

Abstract: The response of species to global warming depends on how different populations are affected by increasing temperature throughout the species' geographic range. Local adaptation to thermal gradients could cause populations in different parts of the range to respond differently. In aquatic systems, keeping pace with increased oxygen demand is the key parameter affecting species' response to higher temperatures. Therefore, respiratory performance is expected to vary between populations at different latitudes because they experience different thermal environments. We tested for geographical variation in respiratory performance of tropical marine fishes by comparing thermal effects on resting and maximum rates of oxygen uptake for six species of coral reef fish at two locations on the Great Barrier Reef (GBR), Australia. The two locations, Heron Island and Lizard Island, are separated by approximately 1200 km along a latitudinal gradient. We found strong counter-gradient variation in aerobic scope between locations in four species from two families (Pomacentridae and Apogonidae). High-latitude populations (Heron Island, southern GBR) performed significantly better than low-latitude populations (Lizard Island, northern GBR) at temperatures up to 5uC above average summer surface-water temperature. The other two species showed no difference in aerobic scope between locations. Latitudinal variation in aerobic scope was primarily driven by up to 80% higher maximum rates of oxygen uptake in the higher latitude populations. Our findings suggest that compensatory mechanisms in high-latitude populations enhance their performance at extreme temperatures, and consequently, that high-latitude populations of reef fishes will be less impacted by ocean warming than will low-latitude populations.

Questions this article answers: Could local adaptation to thermal gradients cause populations in different parts of a range to respond differently? How does the increased oxygen demand affect species' response to higher temperatures?

Methodology: Thermal effects on respiratory performance were estimated for populations of six common coral reef fishes at Lizard Island and Heron Island reef on the Great Barrier Reef, Australia. Northern populations were sampled between December and January in 2008 and 2009 (max summer sea surface temps)

Findings:

- At common treatment temperatures, four out of the six species showed significantly higher MO2Rest and MO2Max at the high latitude location
- Significant differences in respiratory performance of reef fish populations at two widely separated locations on the Great Barrier Reef, but generally not as predicted by optimality models of thermal adaptation

- Strong counter-gradient variation in aerobic scope between locations in four species from two families (Pomacentridae and Apogonidae)
- High-latitude populations (Heron Island, southern GBR) performed significantly better than low-latitude populations (Lizard Island, northern GBR) at temperatures up to 5uC above average summer surface-water temperature
- The other two species showed no difference in aerobic scope between locations
- Reef fish in the warmer, northern Great Barrier Reef location did not cope better with higher temperatures than their conspecifics in the cooler, southern region
- Results suggest that Heron Island fish may perform better under warmer water conditions likely to occur in the future
    - Increases in average summer temperatures of $2uC at Lizard Island are likely to affect community structure
- Latitudinal variation in aerobic scope was primarily driven by up to 80% higher maximum rates of oxygen uptake in the higher latitude populations
- There is evidence for some level of genetic differentiation between Heron Island and Lizard Island populations consistent with a hypothesis of local adaptation in respiratory performance

Quotes:
"Whether warming oceans will shift the distributions of tropical marine species polewards depends strongly on the metabolic capacity of populations to keep pace with increased oxygen demand. If the strong counter-gradient patterns seen here are prevalent among reef fish, and other tropical marine ectotherms, then lower latitude populations inhabiting warmer waters will be more sensitive to global warming than populations of the same species at higher latitudes."

Gledhill, D. K., Wanninkhof, R., Millero, F. J., & Eakin, M. (2008). Ocean acidification of the greater Caribbean region 1996–2006. *Journal of Geophysical Research*, *113*(C10), C10031

Source type: journal article

Abstract: The global oceans serve as the largest sustained natural sink for increasing atmospheric carbon dioxide (CO2) concentrations. As this CO2 is absorbed by seawater, it not only reacts causing a reduction in seawater pH (or acidification) but also decreases the carbonate mineral saturation state (W), which plays an important role in calcification for many marine organisms. Ocean acidification could affect some of the most fundamental biological and geochemical processes of the sea in coming decades. Observations obtained in situ from Volunteer Observing Ships and multiple geochemical surveys have been extended using satellite remote sensing and modeled environmental parameters to derive estimates of sea-surface alkalinity (AT) and carbon dioxide partial pressure (pCO2,sw). Pairing estimates of AT and pCO2, sw have permitted characterization of the changes in sea-surface W, which have transpired over the past decade throughout the Greater Caribbean Region as a consequence of ocean acidification. The results reveal considerable spatial and temporal variability throughout the region. Despite this variability, we observed a strong secular decrease in aragonite saturation state (Warg) at a rate of approximately _0.012 ± 0.001 Warg yr_1 (r2 = 0.97, P < 0.001).

Questions this article answers: How might ocean acidification affect some of the most fundamental biological and geochemical processes of the sea in the near future? What are estimates of sea surface alkalinity and carbon dioxide partial pressure?

Methodology: Observations taken from Volunteer Observing ships and geochemical surveys + satellite remote sensing and modeled environmental parameters (for alkalinity and carbon dioxide partial pressure)

Findings:

- While the ocean's uptake of CO2 has alleviated some of the atmospheric burden, the subsequent impact on surface ocean chemistry may represent the most dramatic change in over 20 million years
- When CO2 reacts with seawater, a series of equilibrium reactions occur including the production of carbonic acid causing a reduction in seawater pH.
    - While seawater is naturally ''buffered'' against such changes, it does so at the expense of carbonate ions, which play an important role in the creation of calcium carbonate shells and skeletons produced by a large number of marine organisms
- The effects of ocean acidification on corals, which produce the calcium carbonate mineral aragonite, appears not to be directly related to changes in pH per se, but instead related to corresponding changes in carbonate mineral saturation state

- At least 2/3 of Caribbean reefs are threatened by numerous local threats with some of the greatest threats coming from human population growth, overfishing, coastal development, sediments, land-based pollution, nutrient runoff, boat damage and coral disease
- Variations in temperature, alkalinity (primarily driven by salinity changes), and pCO2,sw impart important controls on aragonite saturation state
- Some models have suggested that the secular decline in saturation state for atolls and other semi-enclosed carbonate systems may strongly depend on mineral buffering reactions and water mass residence time
- The highest and most stable aragonite saturation state values persist throughout the central GCR where the carbonate platforms of the Bahamas and Greater Antilles occur
- Summertime maximums in aragonite saturation state values occur in August and September when despite higher pCO2,sw values, the thermodynamic effect on carbonate equilibria drives up aragonite saturation state

Quotes:
"As numerous studies have now demonstrated a functional relationship between Warg and coral community calcification, mapping its distribution seasonally can offer an important tool to the ocean acidification and coral reef research and management communities"

Graham, N. A., McClanahan, T. R., MacNeil, M. A., Wilson, S. K., Polunin, N. V., Jennings, S., ... & Sheppard, C. R. (2008). Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS One*, *3*(8), e3039.

Source type: journal article

Abstract: Coral reefs have emerged as one of the ecosystems most vulnerable to climate variation and change. While the contribution of a warming climate to the loss of live coral cover has been well documented across large spatial and temporal scales, the associated effects on fish have not. Here, we respond to recent and repeated calls to assess the importance of local management in conserving coral reefs in the context of global climate change. Such information is important, as coral reef fish assemblages are the most species dense vertebrate communities on earth, contributing critical ecosystem functions and providing crucial ecosystem services to human societies in tropical countries. Our assessment of the impacts of the 1998 mass bleaching event on coral cover, reef structural complexity, and reef associated fishes spans 7 countries, 66 sites and 26 degrees of latitude in the Indian Ocean. Using Bayesian meta-analysis we show that changes in the size structure, diversity and trophic composition of the reef fish community have followed coral declines. Although the ocean scale integrity of these coral reef ecosystems has been lost, it is positive to see the effects are spatially variable at multiple scales, with impacts and vulnerability affected by geography but not management regime. Existing no-take marine protected areas still support high biomass of fish, however they had no positive affect on the ecosystem response to large-scale disturbance. This suggests a need for future conservation and management efforts to identify and protect regional refugia, which should be integrated into existing management frameworks and combined with policies to improve system-wide resilience to climate variation and change.

Questions this article answers: What is the importance of assessing local management in conserving coral reefs in the context of climate change? Do herbivorous reef fish increase in abundance following large-scale coral loss?

Methodology:

- Conducted a targeted research program whereby the original investigators who collected comprehensive benthic and fish assemblage data from Maldives, Chagos, Seychelles, Kenya, Tanzania, Mauritius, and Re´union in the mid- 1990s repeated their surveys post-bleaching, in 2005
- Used continuous model Bayesian meta-analysis to quantify effects of changes in live coral cover and physical complexity of reefs on the diversity, size structure, trophic structure and abundance of reef fish.

Findings:

- Grazing by herbivores, by creating space for invertebrate larval settlement, is thought to be key to maintaining reefs in a coral dominated state

- The majority of herbivorous fish in the Indo-Pacific will crop turf algae, but feed less on or avoid erect macroalgae once it has developed
  - Herbivores may become swamped by the biomass of the new algal resource and reefs can progress on a trajectory to macroalgal dominance after mass coral bleachings
- Herbivorous fish can prevent reefs from becoming dominated by erect microalgae
- Change in hard coral cover across the region between the mid 1990s and 2005 varied geographically
- The greatest declines were through the low latitude island states of Maldives, Chagos, and Seychelles.
- Kenyan and Tanzanian nationally protected sites experienced moderate declines, while Mauritius and Re´union sustained the smallest declines, and coral cover increased in Kenyan and Tanzanian fished sites
- 10 of 19 study locations exhibit declines that depart significantly from zero
- A greater proportion of No Take Areas (71%) than fished (42%) locations showed significant declines in coral cover over the study period.
- There was a strong correlation between loss in coral cover and loss in structural complexity across the region
  - The effects of changing coral cover on fish identified in the Bayesian meta-analyses are likely to result from a combination of loss in coral cover and structural complexity.
- Coral loss predicted declines in reef-fish species richness, and abundance of obligate corallivores, planktivores and fishes ,20 cm throughout the western Indian Ocean
- Given any future 50% decline in coral cover, there is a 76% probability of equivalent declines in obligate corallivores at any given site in the western Indian Ocean

- There was little difference in the decline of coral cover between NTAs and fished areas across the Indian Ocean, with some evidence for greater declines within NTAs
- We detected declines in fish species richness across the western Indian Ocean in response to loss of live coral cover.

Quotes:
"Geography seems to be a key determinant in the ability of reefs to absorb and recover from such large-scale disturbances and this should be considered for other regions likely to suffer similar large-scale disturbances in the future."- 7

Graham, N. A. J., Nash, K. L., & Kool, J. T. (2011). Coral reef recovery dynamics in a changing world. ***Coral Reefs, 30*****(2), 283-294.**

Abstract: Coral reef ecosystems are degrading through multiple disturbances that are becoming more frequent and severe. The complexities of this degradation have been studied in detail, but little work has assessed characteristics that allow reefs to bounce back and recover between pulse disturbance events. We quantitatively review recovery rates of coral cover from pulse disturbance events among 48 different reef locations, testing the relative roles of disturbance characteristics, reef characteristics, connectivity and anthropogenic influences. Reefs in the western Pacific Ocean had the fastest recovery, whereas reefs in the geographically isolated eastern Pacific Ocean were slowest to recover, reflecting regional differences in coral composition, fish functional diversity and geographic isolation. Disturbances that opened up large areas of benthic space recovered quickly, potentially because of nonlinear recovery where recruitment rates were high. The type of disturbance had a limited effect on subsequent rates of reef recovery, although recovery was faster following crown of- thorns starfish outbreaks. This inconsequential role of disturbance type may be in part due to the role of unaltered structural complexity in maintaining key reef processes, such as recruitment and herbivory. Few studies explicitly recorded potential ecological determinants of recovery, such as recruitment rates, structural complexity of habitat and the functional composition of reef-associated fish. There was some evidence of slower recovery rates within protected areas compared with other management systems and fished areas, which may reflect the higher initial coral cover in protected areas rather than reflecting a management effect. A better understanding of the driving role of processes, structural complexity and diversity on recovery may enable more appropriate management actions that support coral-dominated ecosystems in our changing climate.

Questions this article answers: What are the characteristics of reefs that allow them to recover between pulse disturbance events?

Methodology: literature review

Findings:

- The greatest predictors of rate of recovery were geographic region, management status and severity of disturbance.
- Many of the potential predictors of reef recovery, such as herbivore biomass, fish functional diversity and habitat structural complexity were not documented in the majority of studies and thus could not be evaluated in this review
- Recovery was greater after disturbances that reduced coral cover to\10% of benthic cover (but not\5%) and was slowest after disturbances that only reduced coral cover to [20%.
    - **Two reasons why this might happen:**
        - Recovery processes, such as ample coral recruits to occupy free space, are likely to be present. In this situation, occupation of new space may be rapid, and disturbances that have opened up more benthic space have greater recovery potential
        - Recovery dynamics of coral cover are likely to be nonlinear;

recovery from extreme coral loss and small losses may be slower, with most rapid recovery at medium to high levels of coral loss

- There was no evidence of dissimilar recovery rates among different reef types or reef zones
- Coral recovery was slowest in the eastern Pacific and fastest in the western Pacific, with the Indian Ocean also showing faster recovery than the eastern Pacific
    - There are substantial differences in functional diversity of corals and fish among these regions, which is highest in the western Pacific, intermediate in the Indian Ocean and lowest in the Caribbean and eastern Pacific
    - A further impediment to the eastern Pacific reefs is geographical isolation
- There was a weak, non-significant increase in recovery rates with increasing human population densities

Quotes:
"The focus on coral cover used here reflects that the majority of studies assessing recovery of reefs from disturbance use this metric. However, coral cover as a metric can miss the complexities of recovery in some instances. For example, a different assemblage of coral taxa may dominate a reef following disturbance and recovery. In other cases, a similar composition of dominant reef inhabitants may return Such complexities of reef recovery can have huge implications for the future resilience of the system or the diversity of other components of the ecosystem and should not be overlooked." Pg 292

Green, A. L., & Bellwood, D. R. (2009). Monitoring functional groups of herbivorous reef fishes as indicators of coral reef resilience: A practical guide for coral reef managers in the Asia Pacific Region.

Abstract: Coral reefs are the most structurally complex and taxonomically diverse marine ecosystems on earth, providing ecosystem goods and services for millions of people worldwide. These reefs are seriously threatened by a variety of anthropogenic threats, particularly overexploitation of marine resources, destructive fishing practices and runoff from poor land use practices. Resilience is the ability of an ecosystem to absorb shocks, resist phase shifts and regenerate after natural and human-induced disturbances. Herbivores play a critical role in coral reef resilience by limiting the establishment and growth of algal communities that impede coral recruitment. On coral reefs in the Indo-Pacific Region, fishes are the dominant group of herbivores, while both echinoids and fishes are both important in the Caribbean. Major families include surgeonfishes, parrotfishes, rabbitfishes and rudderfishes. Developing new metrics for monitoring coral reef resilience that are process oriented is an urgent priority for the improved management of coral reefs. Methods for assessing and monitoring coral reef resilience have been developed by the International Union for Conservation and Nature (IUCN) Working Group on Climate Change and Coral Reefs. This document provides practical advice to field practitioners based on an example from the Asia Pacific Region.

Questions this article answers: How can coral reef managers best manage reefs in the Asia Pacific Region? What are key functional groups of herbivores, and what methods are best for monitoring their abundance, biomass, size, and structure?

Methodology: literature review and practical advice

Findings:

- Climate change represents a new and increasing threat to coral reefs and associated ecosystems
- worldwide
  - Major threats include rising sea temperatures leading to mass coral bleaching, rising sea levels that threaten coastal ecosystems (e.g. mangrove forests), and changes in ocean chemistry that affect the ability of calcifying organisms (including corals) to deposit their calcium carbonate skeletons
  - Another concern: the degree to which global climate change may influence the frequency and intensity of tropical storms (IPCC 2007), leading to shorter recovery times between recurrences
  - Climate change has also been linked to the recent proliferation of other threats, particularly coral diseases
- A core component of resilience= the ability of an ecosystem to maintain its key ecological functions and processes after disturbance by either resisting or adapting to change
- Herbivory plays an important role in controlling algal communities- the primary driver
- Several studies have demonstrated the critical role herbivorous reef fishes play in influencing competitive interactions between corals and macroalgae and therefore coral reef resilience
- Bioerosion plays a critical role in coral reef resilience by removing dead coral and

cleaning areas of substratum for colonization by benthic organisms, facilitating the settlement, growth and survival of coralline algae and corals

- To reduce threats to coral reef resilience: need to identify key ecological processes:
  - -Establish no-take marine reserves, ecosystem approach to fisheries management, improved management of land-based threats (sedimentation, pollution)
- Four functional groups of herbivorous reef fishes were identified that play a critical role in coral reef resilience: scrapers/small excavators, large excavators/bioeroders, grazers/detritivores and browsers.
  - Roles differ in terms of how they feed, what they consume, and their impact on the underlying substratum
- Long term monitoring programs must be designed to provide useful information for coral reef conservation and management
      - If fishing pressure is low and the density and biomass of herbivorous reef fishes is high relative to that recorded in similar areas, adaptive management to protect these species may not be required

Guinotte, J. M., & Fabry, V. J. (2008). Ocean acidification and its potential effects on marine ecosystems. ***Annals of the New York Academy of Sciences*****,** ***1134*****(1), 320-342.**

Abstract: Ocean acidification is rapidly changing the carbonate system of the world oceans.

Past mass extinction events have been linked to ocean acidification, and the current rate of change in seawater chemistry is unprecedented. Evidence suggests that these changes will have significant consequences for marine taxa, particularly those that build skeletons, shells, and tests of biogenic calcium carbonate. Potential changes in species distributions and abundances could propagate through multiple trophic levels of marine food webs, though research into the long-term ecosystem impacts of ocean acidification is in its infancy. This review attempts to provide a general synthesis of known and/or hypothesized biological and ecosystem responses to increasing ocean acidification. Marine taxa covered in this review include tropical reef-building corals, cold-water corals, crustose coralline algae, *Halimeda*, benthic mollusks, echinoderms, coccolithophores, foraminifera, pteropods, seagrasses, jellyfishes, and fishes. The risk of irreversible ecosystem changes due to ocean acidification should enlighten the ongoing CO2 emissions debate and make it clear that the human dependence on fossil fuels must end quickly. Political will and significant large-scale investment in clean-energy technologies are essential if we are to avoid the most damaging effects of human-induced climate change, including ocean acidification.

Questions this article answers: What is known and/or hypothesized about biological and ecosystem responses to increasing ocean acidification?

Methodology: literature review

Findings:

- Ocean acidification may be defined as the change in ocean chemistry driven by the oceanic uptake of chemical inputs to the atmosphere, including carbon, nitrogen, and sulfur compounds.
- The current rate at which ocean acidification is occurring will likely have profound biological consequences for ocean ecosystems within the coming decades and centuries.
- Presently, atmospheric CO2 concentration is ~ 383 parts per million by volume (ppmv), a level not seen in at least 650,000 years, and is projected to increase by 0.5% per year
- The rate of this change is cause for serious concern, as many marine organisms, particularly those that calcify, may not be able to adapt quickly enough to survive these changes.
- Decreasing pH is not the only effect on the inorganic carbon system in seawater that results from the ocean's uptake of anthropogenic CO2.
- Calcite and aragonite are the major biogenically formed carbonate minerals produced by marine calcifiers, and the stability of both minerals is affected by the amount of CO2 in seawater, which is partially determined by temperature
- Colder waters naturally hold more CO2 and are more acidic than warmer waters.
- It is clear that human-induced changes in atmospheric CO2 concentrations are fundamentally altering ocean chemistry from the shallowest waters to the darkest depths of the deep sea.
- Assessing whether ocean acidification is the primary driver of a species' population decline will be difficult due to the multitude of ongoing physical and

chemical changes currently occurring in the ocean.
    - Ocean acidification is occurring in synergy with significant ongoing environmental changes
- Ocean acidification could have significant indirect effects on fishes and other deepsea organisms that rely on cold-water coral ecosystems for protection and nutritional requirements

Quotes:
"Ecosystem responses will also depend on the ability of biota to adapt to seawater chemistry changes that are occurring at rates they have not encountered in their recent evolutionary history"- 336

Haas, A., el-Zibdah, M., & Wild, C. (2010). Seasonal monitoring of coral-algae interactions in fringing reefs of the gulf of aqaba, northern red sea. *Coral Reefs, 29*(1), 93-103.

Abstract: This paper presents seasonal in situ monitoring data on benthic coverage and coral–algae interactions in high-latitude fringing reefs of the Northern Red Sea over a period of 19 months. More than 30% of all hermatypic corals were involved in interaction with benthic reef algae during winter compared to 17% during summer, but significant correlation between the occurrence of coral–algae interactions and monitored environmental factors such as temperature and inorganic nutrient availability was not detected. Between 5 and 10-m water depth, the macroalgae Caulerpa serrulata, Peyssonnelia capensis and filamentous turf algae represented almost 100% of the benthic algae involved in interaction with corals. Turf algae were most frequently (between 77 and 90% of all interactions) involved in interactions with hermatypic corals and caused most tissue damage to them. Maximum coral tissue loss of 0.75% day-1 was observed for Acropora-turf algae interaction during fall, while an equilibrium between both groups of organisms appeared during summer. Slowgrowing massive corals were more resistant against negative algal influence than fast-growing branching corals. Branching corals of the genus Acropora partly exhibited a newly observed phenotypic plasticity mechanism, by development of a bulge towards the competing organism, when in interaction with algae. These findings may contribute to understand the dynamics of phase shifts in coral reefs by providing seasonally resolved in situ monitoring data on the abundance and the competitive dynamic of coral–algae interactions.

Questions this article answers: what are the interactions between benthic coverage and coral-algae interactions in high-latitude fringing reef in the Northern Red Sea?

Methodology: Four different field expeditions were carried out to cover each season over a perdio of 19 months

Findings:

- The maximum coverage (55–65%) along the reef crest in Aqaba rapidly changed to less than 10% in the sand-dominated 5 m zone, but gradually increased from there with increasing water depth

- The dominant algae genera were the green algae Caulerpa serrulata, the red algae Peyssonnelia capensis, and different assemblages of turf algae
- Turf algae alone accounted for more than 90%of the total benthic algae coverage
    - The turf algae assemblages were predominantly composed of green algae of the genus Cladophora, red algae of the genus Gelidium and cyanobacteria, which are known to be often assembled with turf algae
- All three mentioned algae usually accounted for almost 100%of benthic reef algae found at the MSS study site, but benthic blooms of the green algae Enteromorpha flexuosa were observed during late winter and early spring
- Hermatypic corals and benthic algae as the two major kinds of benthic organisms in competition for space at the investigated fringing reefs in the Gulf of Aqaba
- Temporary blooming algae had negative influence on hermatypic corals

Quotes:

"The present study could not identify significant correlation between seasonal changes in availability of inorganic nutrients (bottom-up factor) and coral tissue loss in interaction with benthic reef algae. This indicates the possible simultaneous involvement of other factors."

"This study can thus not identify one single factor controlling the competitive dynamics in coral–algae interactions, but suggests that several factors act synergistically as described by other studies."

Hansen, L., Hoffman, J., Drews, C., & et al. (2010). Designing climate-smart conservation: Guidance and case studies. ***Conservation Biology, 24*****(1), 63-69.**

Abstract: To be successful, conservation practitioners and resource managers must fully integrate the effects of climate change into all planning projects. Some conservation practitioners are beginning to develop, test, and implement new approaches that are designed to deal with climate change. We devised four basic tenets that are essential in climate-change adaptation for conservation: protect adequate and appropriate space, reduce nonclimate stresses, use adaptive management to implement and test climate-change adaptation strategies, and work to reduce the rate and extent of climate change to reduce overall risk. To illustrate how this approach applies in the real world, we explored case studies of coral reefs in the Florida Keys; mangrove forests in Fiji, Tanzania, and Cameroon; sea-level rise and sea turtles in the Caribbean; tigers in the Sundarbans of India; and national planning in Madagascar. Through implementation of these tenets conservation efforts in each of these regions can be made more robust in the face of climate change. Although these approaches require reconsidering some traditional approaches to conservation, this new paradigm is technologically, economically, and intellectually feasible.

Questions this article answers: how can conservation practitioners and resource managers integrate the effects of climate change into all planning projects?

Methodology: case studies of coral reefs in the Florida Keys; mangrove forests in Fiji, Tanzania, and Cameroon; sea-level rise and sea turtles in the Caribbean; tigers in the Sundarbans of India; and national planning in Madagascar- applied four conservation tenets

Findings:

- Adaptive management is an "integration of design, management, and monitoring to systematically test assumptions in order to adapt and learn"
- The Florida Keys National Marine Sanctuary- established in 1990- helps protect and preserve nearly 1 million hectares of marine environment, and it encompasses seagrass meadows, mangrove islands, and the most extensive living coral reef in the United States
- 2006 the World Wildlife Fund (WWF) started to examine environmental and monitoring data in new ways to investigate the resilience of Florida's reefs to the combination of climate change and other stressors and to implement the conservation tenets
- Researchers are quantifying temporal and spatial relationships between key environmental parameters and coral-bleaching response that can reveal patterns in reef resilience
- Part of the larger Florida Reef Resilience Program, which brings scientists, reef managers, and people whose livelihoods and recreational pursuits depend on healthy coral reefs together to achieve a common goals
- WWF is investigating whether the effects of mangroves on water quality might lessen the susceptibility of fringing reefs to bleaching

Hearn, C. J. (2011). Perspectives in coral reef hydrodynamics. *Coral Reefs, 30*(Special Issue), 1-9.

Abstract: Some developments in coral reef hydrodynamics over the last decade are reviewed with an overview of papers in this special issue. Advances in hydrodynamics based on improved understanding of topographic complexity are illustrated for the reef at

Kilo Nalu Observatory and Kaneohe Bay (both in Hawaii). Models of the roughness layer are discussed as a background to numerical models of reef hydrodynamics for Molokai and Guam. Topographic complexity produces spatial temperature variability over reefs creating thermal microclimates, which are reported in this issue for the Red Sea. Uptake of ocean nutrients by reefs is controlled by hydrodynamics, and papers in this issue show its critical role in the ecology of a fringing reef at La Re´union Island; nutrient uptake rates are discussed here using new data for Hearn Roughness and Decadal Rugosity. The role of upwelled water by large amplitude internal waves on reefs is reported for the Similan Islands, providing major new evidence for the role of hydrodynamics in the ecology of reefs and its importance to climate change. The review suggests some important areas for new research including simulated corals used in flumes and the field. Major new modeling based on measured roughness maps combined with small scale lattice Boltzmann simulations should be possible in the next decade.

Questions this article answers: What are the developments in coral reef hydrodynamics over the last decade?

Methodology: literature review

Findings:

- Reefs are topographically complex entities and that complexity has a controlling influence on all physical and biogeochemical processes
- At low tide, many shallow reefs contain pools of water that are isolated for periods of hours
    - Other parts of a reef may be so shallow that friction greatly impedes currents leading to the idea of a coastal boundary layer that traps water
- The decade has seen increased emphasis on thermal conditions on reefs much of which is motivated by concerns over coral reef bleaching
- Coral reef roughness enhances friction and so increases the rate of energy dissipation
- The other role of roughness is to increase the surface area available for nutrient uptake while maintaining volume
- Roughness is sometimes used as a proxy for the space filling attributes of coral but it isn't an adequate measure
- Primary difference between the hydrodynamics of coral reefs and other coastal systems is the interface of water and coral.
- Corals can be simulated numerically
- Much more information is needed before nutrient uptake rates can be properly mapped and generalizations made about their role in reef ecology
- Two and three dimensional reef models are at present non-existent

Hendriks, I. E., Duarte, C. M., & Álvarez, M. (2010). Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. *Estuarine, Coastal and Shelf Science*, *86*(2), 157-164.

Abstract: The ocean captures a large part of the anthropogenic carbon dioxide emitted to the atmosphere. As a result of the increase in CO2 partial pressure the ocean pH is

lowered as compared to pre-industrial times and a further decline is expected. Ocean acidification has been proposed to pose a major threat for marine organisms, particularly shell-forming and calcifying organisms. Here we show, on the basis of meta-analysis of available experimental assessments, differences in organism responses to elevated pCO2 and propose that marine biota may be more resistant to ocean acidification than expected. Calcification is most sensitive to ocean acidification while it is questionable if marine functional diversity is impacted significantly along the ranges of acidification predicted for the 21st century. Active biological processes and small-scale temporal and spatial variability in ocean pH may render marine biota far more resistant to ocean acidification than hitherto believed.

Questions this article answers: Are marine biota more resistant to ocean acidification than expected?

Methodology: literature review: meta-analysis of available experimental assessments of the impacts of acidification on a range of functions across marine organisms.

Findings:
The ocean has captured between 28 and 34% of the anthropogenic carbon dioxide emitted to the atmosphere between 1980 and 1994
Warnings that ocean acidification is a major threat to marine biodiversity are largely based on the analysis of predicted changes in ocean chemical fields with limited experimental support

- Corals showed increases in metabolic rates, due to enhanced photosynthetic rates of autotrophic symbionts, while for the coral community as a whole the metabolic rate decreased
- Survival rates of the tested organisms showed an overall decrease by, on average, 31 _4.5%.
    - Only bivalves had a higher survival rate with acidification
- Reproduction rates also declined with increasing pCO2 by, on average, 34% for copepods to 40% for sea urchins, the only organisms tested for this trait
- Acidification effects differed considerably across taxonomic groups and functions, but that the magnitude of the changes were, overall, modest for acidification levels within ranges expected during this century
- Acidification does not occur in isolation, but in concert with other challenges such as warming, eutrophication, and increased UV radiation
- The data do suggest that calcification rate, the most sensitive process responding directly to ocean acidification (Gattuso et al., 1998; Gazeau et al., 2007; Leclercq et al., 2000; Riebesell et al., 2000), will decline by, on average, 25% at elevated pCO2 values of 731–759 ppmv.
- Short-term experimental results are likely to overestimate the impacts of acidification rates on marine organisms.

Quotes:

- "This analysis suggests that marine biota do not respond uniformly to ocean acidification. Some experiments report significant impacts for vulnerable taxa at pCO2 values expected within the 21st century, but there was no consistent evidence that suggests biological rates, apart from calcification for one functional group, the bivalves, might be significantly suppressed across the range of pCO2 anticipated for the 21st century."- 161

- "The ambition and sophistication of experimental approaches need be expanded, to assess complex communities, rather than single species, and to assess responses to enhanced CO2 over long terms. Such long-term experiments to observe community responses to long-term exposure to enhanced CO2 have been successfully conducted for terrestrial systems."- 161

Hobbs, J. P. A., & McDonald, C. A. (2010). Increased seawater temperature and decreased dissolved oxygen triggers fish kill at cocos (keeling) islands, indian ocean. *Journal of Fish Biology, 77*(6), 1219-1229.

Abstract: At the Cocos (Keeling) Islands in the north-eastern Indian Ocean >592 fishes from at least 11 species died in a series of events in December 2007, January and February 2008 and April 2009. The dead fishes were from a wide range of taxonomic

families, indicating that conditions exceeded the tolerances of a broad array of species. The 2007–2008 die-off events occurred on the warmest and calmest days of a significantly warmer and calmer summer. Fishes died in the southern inshore areas of the coral atoll lagoon at survey sites where seawater temperature was highest (33–35◦ C) and dissolved oxygen was lowest (1ÅE4–1ÅE8 mg l−1). The water temperature at these fish-kill survey sites (33–35◦ C) was significantly warmer than previous years (1997 to 2005, mean Å} s.e. = 28ÅE7 Å} 0ÅE1◦ C). Fishes probably died because they were unable to obtain the additional oxygen required for metabolism at higher temperatures. Repeated die-off events over the last 130 years indicate that some fishes have not yet adapted to rises in seawater temperature. This study provides empirical evidence to support suggestions that differences in physiological tolerances to increasing sea temperatures may be important in determining the structure of future coral-reef fish communities with respect to climate change.

Questions this article answers: What was the cause of the fish kill in Cocos Islands in the northeastern Indian Ocean?

Methodology: To quantify the spatial, temporal and taxonomic extent of the 2007–2008 summer dieoff events, observations during the February 25–26 die off were combined with information on earlier events gained from local people.

Findings:

- >592 fishes from at least 11 species, and several other taxa (*e.g.* octopus and crabs), died in the lagoon at the Cocos (Keeling) Islands during a series of die-off events in the summer of 2007–2008 and in April 2009
- The 2007–2008 die-off events occurred on the warmest and calmest days of a significantly warm and calm summer, with similar conditions triggering a dieoff event in April 2009.
- The short duration of the die-off events (2–5 days) was probably because the changes in the weather conditions that followed these events (reductions in air temperature and increases in wind speed) would have improved water conditions (decreased water temperature and increased dissolved oxygen).
- Cocos (Keeling) Islands has had a history of die-off events associated with warm calm weather
- Die-off events are from a culmination of factors-
    - Elevated water temperatures challenge the physiological capabilities of fishes because the concentration of oxygen required for basic metabolism increases with temperature
- Rise in water temperature from 29 to 33◦ C has been shown to kill some coral-reef fishes because they are unable to obtain sufficient oxygen to fuel their basic metabolic needs
- The increased consumption of oxygen by fishes (and other organisms) during elevated temperatures would have further reduced the amount of available dissolved oxygen
    - And the decomposition of decaying fish bodies may have stripped region of O2

- Increased sea temperature can also affect growth, reproduction and larval development of reef fishes- critical to long-term persistence

Quotes:
"The repeated occurrence of die-off events at the Cocos (Keeling) Islands for at least the last 130 years, and four times within the 2007–2008 summer and again in April 2009, indicates that many reef fishes have not yet acclimated or adapted sufficiently over short or long-time periods. These repeated die offs support suggestions that some fishes occupying low-latitude coral reefs may have limited scope for adaptation to rising sea temperatures."

Hobbs, J. A., Jones, G. P., & Munday, P. L. (2010). Rarity and extinction risk in coral reef angelfishes on isolated islands: Interrelationships among abundance, geographic range size and specialization. *Coral Reefs, 29*(1), 1-11.

Abstract: Determining the species most vulnerable to increasing degradation of coral reef habitats requires identification of the ecological traits that increase extinction risk. In the terrestrial environment, endemic species often face a high risk of extinction because

of an association among three traits that threaten species persistence: small geographic range size, low abundance and ecological specialisation. To test whether these traits are associated in coral reef fishes, this study compared abundance and specialization in endemic and widespread angelfishes at the remote Christmas and Cocos Islands in the Indian Ocean. The interrelationships among traits conferring high extinction risk in terrestrial communities did not apply to these fishes. Endemic angelfishes were 50–80 times more abundant than widespread species at these islands. Furthermore, there was no relationship between abundance and ecological specialisation. Endemic species were not more specialised than widespread congeners and endemics used similar resources to many widespread species. Three widespread species exhibited low abundance and some degree of specialisation, which may expose them to a greater risk of local extinction. For endemic species, high abundance and lack of specialisation on susceptible habitats may compensate for the global extinction risk posed by having extremely small geographic ranges. However, recent extinctions of small range reef fishes confirm that endemics are not immune to the increasing severity of large-scale disturbances that can affect species throughout their geographic range.

Questions this article answers: What ecological traits increase extinction risk in coral reef habitats?

Methodology: this study compared abundance and specialization in endemic and widespread angelfishes at the remote Christmas and Cocos Islands in the Indian Ocean

Findings:

- This study of coral reef angelfishes at two isolated islands did not find support for positive associations among small geographic range, low abundance or ecological specialization evident for many terrestrial organisms.
- With endemics being 50–80 times more abundant than widespread species, and being among the more generalist species in terms of depth range, diet and habitat use
- The highly abundant endemic angelfishes used the same resources as widespread relatives, and often coexisted with congeners in overlapping territories with no signs of competitive interactions
- Abundance is predicted to be positively correlated with niche breadth
- Abundance was not related to depth range, microhabitat use or diet. Support for this relationship is also generally lacking in the terrestrial environment and the reasons for the hypothesised relationship are not obvious
- Terrestrial macroecological patterns associated with extinction risk do not necessarily apply to reef fishes
- Endemic angelfishes at the remote Christmas and Cocos Islands were not specialists and did not have low abundance and therefore do not face an extreme risk of extinction

Hoegh-Guldberg, O. (2009). Climate change and coral reefs: Trojan horse or false prophecy?. *Coral Reefs*, *28*(3), 569-575.

Abstract: Maynard et al. (Coral Reefs 27:745–749, 2008a) claim that much of the concern about the impacts of climate change on coral reefs has been ‘‘based on essentially untested assumptions regarding reefs and their capacity to cope with future climate change’’. If correct, this claim has important implications for whether or not climate change represents the largest long-term threat to the sustainability of coral reefs,

especially given their ad hominem argument that many coral reef scientists are guilty of ‘‘popularising worst-case scenarios’’ at the expense of truth. This article looks critically at the claims made by Maynard et al. (Coral Reefs 27:745–749, 2008a) and comes to a very different conclusion, with the thrust and veracity of their argument being called into question. Contrary to the fears of Grigg (Coral Reefs 11:183–186, 1992), who originally made reference to the Cassandra syndrome due to his concern about the sensationalisation of science, the proposition that coral reefs face enormous challenges from climate change and ocean acidification has and is being established through ‘‘careful experimentation, long-term monitoring and objective interpretation’’. While this is reassuring, coral reef ecosystems continue to face major challenges from ocean warming and acidification. Given this, it is an imperative that scientists continue to maintain the rigour of their research and to communicate their conclusions as widely and clearly as possible. Given the shortage of time and the magnitude of the problem, there is little time to spare.

Questions this article answers: Is climate change a large, long-term threat to coral reefs? Is it sensationalized, as Maynard, et al. suggest?

Methodology: Response to Maynard et al. 2008 article- literature review

Findings:
- Maynard et al. (2008a) reviewed four key propositions, and claim that the available evidence does not support the notion that coral reefs face functional extinction from rapid climate change
- A broader examination of the literature strongly supports the notion that coral reefs are rapidly facing conditions, which may soon remove them as functional ecosystems within tropical oceans
- One of the key characteristics of reef-building corals is their sensitivity to small increases above the summer maximum temperature at any one location
    - The ‘Hotspot’ program at National Oceanic and Atmospheric Administration predicts coral bleaching when sea temperatures rises 1_C above the long-term summer sea surface temperature
- Maynard et al. (2008a) focused on the differences between species, presumably to show that some species of corals are not living close to their upper thermal thresholds
    - The variability of corals with respect to thermal stress has been reported numerous times (Hoegh Guldberg and Salvat 1995; Marshall and Baird 2000; Loya et al. 2001) and shows a consistent pattern whereby corals such as Acropora and Stylophora are among the first to bleach while other corals such as Porites are usually able to survive slightly higher sea temperature (usually another 1–2_C) before bleaching becomes visible
    - The key point here is that species extinction and the loss of biodiversity are not adaptive strategies per se
    - It is also important to note that while corals can survive acute short-term exposures over a few hours (Hoegh-Guldberg and Smith 1989; Takahashi et al. 2004) there are no examples of coral species or genotype that can

survive chronic exposures to 3–6_C increases above the summer sea temperature for more than a month at a particular site.

- Given that average sea temperatures surrounding coral reefs are projected increase by 3–6_C by the end of the century (IPCC 2007), this level of variability in thermal stress tolerance will not be enough for coral communities to survive current business- as-usual greenhouse scenarios
- Acclimatisation is a form of phenotypic plasticity whereby organisms such as corals and their symbionts can optimise their physiological performance in response to environmental changes within their tolerance range
    - There are a growing number of studies that have shown that corals will have slightly higher thermal tolerances if they are exposed to several weeks of higher temperatures prior to the temperature stress event
    - Acclimatisation does not give an organis a completely new set of capabilities, or improve its ability to deal with conditions outside its thermal tolerance range
- The projected changes in acidification will continue to affect growth, calcification and a range of other physiological processes as a result of changes in the carbonate ion chemistry and pH of seawater
- Recent evidence has demonstrated that ocean acidification is likely to increase the sensitivity of reef-building corals to elevated temperature, reducing the temperature thresholds quite dramatically
- Maynard et al. (2008a) state that only a few (10–12%) species of fish that are reliant on corals for food and shelter will be affected, and that none of these are important fishery species
    - Given that there are serious threats to coral abundance and a host of examples of where corals have, and are disappearing as reef calcifiers disappear and where reef rugosity is clearly under threat (see studies referenced by Bruno and Selig 2007), this conclusion seems out of step with most of the evidence
    - There are plenty of examples from the Eastern Pacific that illustrate the outcome for reef structures if calcifiers such as corals and red coralline algae are reduced in number

Hoegh-Guldberg, O. (2011). Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, *11*, 215-227.

Abstract: Coral reef ecosystems are among the most biologically diverse ecosystems on the planet. In addition to their value in terms of biodiversity, coral reefs provide food and resources for over 500 million people. Despite their importance, coral reefs are declining at a rapid rate (1–2% per year) as a result of a range of local (e.g., overexploitation of fisheries, declining water quality) and global (e.g., global warming and ocean acidification) drivers. Extensive experimental and field evidence suggests that

atmospheric carbon dioxide concentrations of 450 ppm will lead to the loss of coral dominated reef systems, with the prospect that dangerous levels of atmospheric carbon dioxide for coral reefs were exceeded in 1979 when mass coral bleaching was reported for the first time. The exact response of coral reefs remains uncertain although it is highly unlikely that coral-dominated reef systems will be present in future oceans at the current rate of warming and acidification of the world's tropical oceans. The loss of these important coastal ecosystems will diminish the resources available to hundreds of millions of people along tropical coastlines. Understanding the impacts on people and industry is an imperative if we are to devise effective systems by which tropical coastal communities are to adapt to rapidly changing tropical coastal environments. Our current understanding of these important issues, however, is in a relatively undeveloped state and must be a priority of future research.

Question this article answers: What are the impacts on people and industry from declining coral reefs? What are effective systems by which coastal communities can adapt to rapidly changing tropical coastal environments?

Methodology: literature review

Findings:

- The current global distribution of coral reefs provides important insight into the environmental conditions necessary for maintaining corals and the reefs that they build
    - Due to the need for abundant light for their photosynthetic symbionts, corals grow in shallow seas (depths not exceeding 100 m) in regions within 30 degrees north or south of the equator.
    - They also do not grow in regions inundated by sediment-laden rivers because of the turbidity
    - Coral reefs are also dependent on warm and thermally stable oceans, where temperature does not decrease below 18_C in the winter
    - The third major factor coinciding with the global distribution of corals is the concentration of carbonate ions, which is ultimately determined by ocean acidity and atmospheric carbon dioxide
- Many coral reefs having approximately 40–50% less coral cover than they had 30 years ago
- At a local level, many of these changes are coming about due to a range of human activities that result in poor water quality, overexploitation of key species, marine pollution, and destructive fishing practices
    - These changes are rapidly being exacerbated by the added influence of climate change
- Coral bleaching is a general response to stress. Corals will bleach in response to a range of conditions including sudden changes to light, temperature, and salinity, the presence of toxins and microbial infections
- Coral bleaching is not always fatal, and many corals will recover their dinoflagellate symbiotic populations following a bleaching event if the stress conditions are mild and short lived

- More than one-third of the carbon dioxide that has entered the atmosphere has entered the ocean where it combines with water to form the dilute acid, carbonic acid
    - Soon after it forms, carbonic acid dissociates to form a bicarbonate ion and a proton (Fig. 3a). The proton then combines with carbonate to produce a second bicarbonate ion and in doing so decreases the overall oceanic concentration of carbonate
- Other factors such as sea level rise, storm intensity, the incidence of drought, and impacts on sediment flux may play important though regional roles in their impact on coral reefs
- Current rates of coral growth and reef accretion appear to be able to keep up with the present rate of sea level rise. If sea level rise continues to accelerate, this situation may change, especially if coral growth and calcification has been compromised by the impacts of thermal stress and ocean acidification.

Hoegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, *328*(5985), 1523-1528.

Abstract: Marine ecosystems are centrally important to the biology of the planet, yet a comprehensive understanding of how anthropogenic climate change is affecting them has been poorly developed. Recent studies indicate that rapidly rising greenhouse gas concentrations are driving ocean systems toward conditions not seen for millions of years, with an associated risk of fundamental and irreversible ecological transformation. The impacts of anthropogenic climate change so far include decreased ocean

productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease. Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems. Further change will continue to create enormous challenges and costs for societies worldwide, particularly those in developing countries.

Questions this article answers: how is climate change altering ocean ecosystems?

Methodology: literature review
Findings:

- Ocean volume has increased with increased heat content of ocean: thermal expansion has lead to increased melt-water and ice from terrestrial glaciers and ice sheets
- There is growing paleological evidence that declining oxygen concentrations have played a major role in at least four or five mass extinction events, driving large amounts of hydrogen sulfide into the atmosphere as a result of deep-ocean anoxia
- The scale and pace of change in chemical and physical conditions have set in mode biological responses- impacts of anthropogenic climate change on general marine ecosystem services and processes-
- Temperature- influences molecular kinetic energy-determines rates of processes such as enzyme reactions, diffusion, and membrane transport
- Moderate increases in temperature increase metabolic rates: determine life history traits, population growth, and ecosystem processes
- Variation in temperature can also have impacts on key biological processes.
- Changes to ocean conditions also have direct influences on the life history characteristics of marine organisms as varied as invertebrates and sea birds
- Among the most clear and profound influences of climate change on the world's oceans are its impacts on habitat-forming species such as corals, sea grass, mangroves, salt marsh grasses, and oyster
- Areas with steep coastal inclines or coastal human infrastructure that limit landward migration are most at risk
- A rising number of species are expanding their ranges, often with large-scale impacts on ecosystems at the destination.

Quotes:
"Climate change has been implicated in recent variation in the prevalence and severity of disease outbreaks within marine ecosystems. These influences are likely to be a consequence of several factors, including the expansion of pathogen ranges in response to warming, changes to host susceptibility as a result of increasing environmental stress, and the expansion of potential vectors."

Hoeksema, B. W., van der Land, J., van der Meij, Sancia E. T., & et al. (2011). Unforeseen importance of historical collections as baselines to determine biotic change of coral reefs: The saba bank case. ***Marine Ecology- an Evolutionary Perspective, 32*****(2), 135-141.**

Abstract: Botanical and zoological collections may serve as archives for historical ecological research on the effects of global change and human impact on coral reef biota. Museum collections may harbour old specimens of reef-dwelling species that have become locally extinct. Such collections also help to determine whether early records of

invasive species can be obtained from times when they were not yet recognized as such. A case study (2006) involving Saba Bank,
Caribbean Netherlands (former Netherlands Antilles), suggests that the coral reef fauna here may have become impoverished when compared with data obtained during an earlier expedition in 1972. However, the 1972 sampling may have been incomplete, as it was performed by professional divers who were not trained taxonomists, whereas the collecting in 2006 was done by experienced marine biologists who knew the taxa they were sampling. As Saba Bank has been under stress due to the anchoring of large vessels, and invasive species have been a potential threat as well, future studies are needed to obtain more insights into the changing reef biota of Saba Bank. Using this Saba Bank example, we want to address the importance of natural history collections as reservoirs of valuable data relevant to coral reef biodiversity studies in a time of global change. As such, these collections are still underexplored and underexploited.

Questions this article answers: Do botanical and zoological collections suggest anything about the effects of global change and human impact on coral reef biota?

Methodology: Case study of Saba Bank, Caribbean Netherlands (2006) compared to data from 1972

Findings:

- Natural history museums and herbaria harbour samples of coral reef fauna and flora that have been stored there for over 100 years
- Documented cases include reefs that have completely disappeared due to sand mining or have become damaged by destructive fisheries, pollution or land-based activities, as in Jakarta Bay
- Museum specimens collected there before these reefs disappeared, may represent species that occurred there in the past
- Biological collections may also be important as reference material in relation to global change-related impacts on coral reefs, such as El Nin˜o Southern Oscillation (ENSO) events, ocean acidification, sedimentation and red tides, which may have long-lasting damaging effects on specific reef areas or particular species
- Museum specimens can be used to show that endangered species have survived or may even display much greater distribution ranges than previously assumed
- Five stony coral species collected from a total of 17 reef sites in 1972 were not found in 2006
    - Three of these five missing species were rare (each at one site), and the three other ones (at four and five sites, respectively) moderately rare in comparison with the most common species, Siderastrea radians
- 29 of 81 Saba Bank sponge species were sampled in 1972 but not in 2006
- Invasive species: The Indo-Pacific coral species Tubastraea coccinea Lesson, 1829, has been recorded in the Atlantic since 1943, in the Caribbean as well as in Brazil, and was probably introduced by ship traffic and imported oil platforms

Quotes:

"We need to ascertain if species represented in old collections are still present or if the species composition has changed due to habitat degradation and by invasive species. Furthermore, it would not be surprising if undescribed species from Saba Bank are still represented in natural history collections, such as two species of octocorals."

Hoey, A. S., Pratchett, M. S., & Cvitanovic, C. (2011). High macroalgal cover and low coral recruitment undermines the potential resilience of the World's southernmost coral reef assemblages. *PLoS One, 6*(10)

Abstract: Coral reefs are under increasing pressure from anthropogenic and climate-induced stressors. The ability of reefs to reassemble and regenerate after disturbances (i.e., resilience) is largely dependent on the capacity of herbivores to prevent macroalgal expansion, and the replenishment of coral populations through larval recruitment. Currently there is a paucity of this information for higher latitude, subtropical reefs. To assess the potential resilience of the benthic reef assemblages of Lord Howe Island

(31u329S, 159u049E), the worlds' southernmost coral reef, we quantified the benthic composition, densities of juvenile corals (as a proxy for coral recruitment), and herbivorous fish communities. Despite some variation among habitats and sites, benthic communities were dominated by live scleractinian corals (mean cover 37.4%) and fleshy macroalgae (20.9%). Live coral cover was higher than in most other subtropical reefs and directly comparable to lower latitude tropical reefs. Juvenile coral densities (0.8 ind.m22), however, were 5–200 times lower than those reported for tropical reefs. Overall, macroalgal cover was negatively related to the cover of live coral and the density of juvenile corals, but displayed no relationship with herbivorous fish biomass. The biomass of herbivorous fishes was relatively low (204 kg.ha21), and in marked contrast to tropical reefs was dominated by macroalgal browsing species (84.1%) with relatively few grazing species. Despite their extremely low biomass, grazing fishes were positively related to both the density of juvenile corals and the cover of bare substrata, suggesting that they may enhance the recruitment of corals through the provision of suitable settlement sites. Although Lord Howe Islands' reefs are currently coral-dominated, the high macroalgal cover, coupled with limited coral recruitment and low coral growth rates suggest these reefs may be extremely susceptible to future disturbances.

Questions this article answers: What is the potential resilience of the benthic (lowest level in the ocean including sediment surface and some sub-surface layers) reef assemblages of Lord Howe Island (world's most southern coral reef)? What is the amount of herbivorous fish in LHI? What are the rates of coral recruitment?

Methodology: visual consensus of fish and benthic community: surveys of herbivorous fish and benthic communities conducted at five sites; surveys were conducted in three different habitats (reef slope, reef crest, and shallow back reef)

Findings:

- Quantifying the relationships between benthic composition and herbivore community structure will improve our understanding of the processes that structure these high latitude reefs.
- Overall, mean coral cover was 37.4% (61.9 SE) at Lord Howe Island, but displayed significant variation among habitats and sites
    - Coral cover was mostly similar among habitats and sites, except on the reef crest of the southernmost site (i.e., site 5), where coral cover was ,2%
- The cover of macroalgae (overall mean=20.962.5%) was generally lower than that of coral, but displayed higher variability among habitats and sites
- The taxonomic composition of the benthic assemblages also varied among sites and habitats.
- The density of juvenile corals was generally lower on the back reef than on the reef crest, with the highest densities being recorded on the reef crest of sites 2 and 3
- Macroalgal browsing species dominated the herbivorous fish community on Lord Howe Island, accounting for 84.1% of the total herbivore biomass, as opposed to only 15.9% for grazing taxa

- The biomass of browsing fishes was greatest on the reef slope across all sites
- Subtropical reefs, located at the latitudinal limit of reef formation, are typically characterised by relatively low coral cover and high abundance of fleshy macroalgae
- This study revealed that the coral cover at Lord Howe Island, the worlds' southernmost coral reef, was higher (overall mean= 37.4%) than most other subtropical reefs (ca. 3.9–25.3%; [27,28,51,52]), and directly comparable to lower latitude reefs of the GBR, where mean coral cover typically ranges from 18.3–27.0% on inshore reefs to 30.7–33.6% on offshore reefs
- The apparent stability of Lord Howe Islands' coral communities may imply they are relatively resilient, however, these reefs have largely escaped the stressors (i.e. bleaching and disease) that have caused marked declines in coral cover
- The cover of live coral and the density of juvenile corals among locations were both negatively correlated with fleshy macroalgae in the present study.

Quotes
"The ability of coral communities to reassemble and regenerate after disturbances is critical to their long-term persistence, and is dependent on both the ongoing replenishment of coral populations through larval recruitment, as well as the maintenance of suitable substrates for coral settlement and growth. In this respect, herbivores that limit macroalgal expansion and overgrowth of reef substrata are critical to reef resilience."

"The results of this study suggest, that despite the benthic communities of Lord Howe Island being dominated by live scleractinian coral, the high macroalgal cover, coupled with the low level of coral recruitment (as proxied by juvenile coral density) and coral growth [68] may limit the capacity of this reef to reassemble following disturbances"

Hofmann, Gretchen, et al. (2011). High Frequency Dynamics of Ocean pH: A Multi-Ecosystem Comparison

Abstract: The effect of Ocean Acidification (OA) on marine biota is quasi-predictable at best. While perturbation studies, in the form of incubations under elevated pCO2, reveal sensitivities and responses of individual species, one missing link in the OA story results from a chronic lack of pH data specific to a given species' natural habitat. Here, we present a compilation of continuous, high-resolution time series of upper ocean pH, collected using autonomous sensors, over a variety of ecosystems ranging from polar to tropical, open-ocean to coastal, kelp forest to coral reef. These observations reveal a continuum of month-long pH variability with standard deviations from 0.004 to 0.277

and ranges spanning 0.024 to 1.430 pH units. The nature of the observed variability was also highly site-dependent, with characteristic diel, semi-diurnal, and stochastic patterns of varying amplitudes. These biome-specific pH signatures disclose current levels of exposure to both high and low dissolved CO2, often demonstrating that resident organisms are already experiencing pH regimes that are not predicted until 2100. Our data provide a first step toward crystallizing the biophysical link between environmental history of pH exposure and physiological resilience of marine organisms to fluctuations in seawater CO2. Knowledge of this spatial and temporal variation in seawater chemistry allows us to improve the design of OA experiments: we can test organisms with a priori expectations of their tolerance guardrails, based on their natural range of exposure. Such hypothesis-testing will provide a deeper understanding of the effects of OA. Both intuitively simple to understand and powerfully informative, these and similar comparative time series can help guide management efforts to identify areas of marine habitat that can serve as refugia to acidification as well as areas that are particularly vulnerable to future ocean change.

Questions this article answers: What are the effects of specific pH data on species' natural habitats? What are the impacts of high pH on polar, tropical, open-ocean, coastal, kelp forest, and coral reef ecosystems?

Methodology: Continuous, high-resolution time series of upper ocean pH (using autonomous sensors) for 30 days in varying marine ecosystems

Findings:

- From a research perspective, the absence of information regarding natural pH dynamics is a critical data gap for the biological and ecological arm of the multidisciplinary investigation of OA
- These biome-specific pH signatures disclose current levels of exposure to both high and low dissolved CO2, often demonstrating that resident organisms are already experiencing pH regimes that are not predicted until 2100
- Overall, the patterns of pH recorded at each of the 15 deployment sites (shown in Figure 1, Table 1) were strikingly different.
- In terms of general patterns amongst the comparative datasets, the open ocean sites (CCE1 and Kingman Reef) and the Antarctic sites (Cape Evans and Cindercones) displayed the least variation in pH over the 30-day deployment period.
    - For example, pH range fluctuated between 0.024 to 0.096 at CCE1, Kingman Reef, Cape Evans, and Cindercones
- In distinct contrast to the stability of the open ocean and Antarctic sites, sensors at the other five site classifications (upwelling, estuarine/ near-shore, coral reef, kelp forest, and extreme) captured much greater variability (pH fluctuations ranging between 0.121 to 1.430) and may provide insight towards ecosystem-specific patterns.

- The greatest transitions in pH over time were observed at locations termed our

‘‘Extreme’’ sites - a CO2 venting site in Italy (site S2 in ref. [36]) and a submarine spring site in Mexico. For these sites, the patterns were extremely variable and lacked a detectable periodicity

- Due to local temperature differences, variable total alkalinity, and seasonal differences between deployment dates at each site, a comparison of average pH across the datasets would be somewhat misleading. However, some information can be gleaned from an examination of the averages: the overall binned average of all 15 mean values in Table 1 is 8.0260.1.
- This pH value is generally in agreement with the global open ocean mean for 2010 of 8.07, a value generated by combining climatology data for temperature, salinity, phosphate, silicate [41–43], total alkalinity [44], and pCO2 [45] for the year 2000, corrected to 2010 using the average global rise of 1.5 matm pCO2 yr21
- Three other types of study sites – the coastal upwelling, kelp forest and estuarine/near-shore sites – all exhibited variability due to a combination of mixing, tidal excursions, biological activity, and variable residence time (Fig. 2).
- Although these sites are all united by fairly obvious heterogeneity in pH, organisms living in these areas encounter unique complexities in seawater chemistry that will influence their physiological response, resilience, and potential for adaptation.
- In contrast to more stochastic changes in pH that were observed in some sites, our coral reef locations displayed a strikingly consistent pattern of diel fluctuations over the 30-day recording period.
    - MEANING- reef organisms may be able to acclimatize to consistent but moderate changes in carbonate system.
- Across the existing datasets in tropical reef ecosystems, the biological response of calcifying species to variation in seawater chemistry is complex because all corals or calcifying algal species will not respond similarly

.

Quotes:
“The sites examined in this study do not comprehensively represent pH variability in coastal ecosystems, partly because we focused on surface epipelagic and shallow benthic pH variability. Many organisms that may be impacted by pH variability and ocean acidification reside at intermediate (.10 m) to abyssal depths.”

“The variability in seawater pH was higher at both the groundwater springs off the coast of Mexico High-Frequency Dynamics of Ocean pH and the natural CO2 vents off the coast of Italy than at any of the other sensor locations. Offshore of Puerto Morelos, Mexico (and at other sites along the Mesoamerican Reef), natural low-saturation (V,0.5, pH 6.70–7.30, due to non-ventilated, high CO2, high alkalinity groundwater) submarine springs have been discharging for millennia. Here, variability in pH is due to long-term respiration driving a low ratio of alkalinity to dissolved inorganic carbon in effluent ground water.”

Holmes, G., & Johnstone, R. W. (2010). The role of coral mortality in nitrogen dynamics on coral reefs. *Journal of Experimental Marine Biology and Ecology, 387*(1-2), 1-8.

Abstract: Understanding the dynamics of coral reef nutrients, particularly nitrogen, following a coral mortality event is imperative for the prediction of further possible outcomes on impacted reefs, and as such, for the identification of potential management interventions. This study used both acetylene reduction and 15N techniques to investigate the dynamics of nitrogen associated with microbial communities that develop on coral skeletons following bleaching-induced mortality. The results show that nitrogen fixation activity increases dramatically in the initial 3 months following coral mortality with

fixation rates as much as an order of magnitude higher than those observed on older hard substrate material throughout the study sites. Rates of acetylene reduction up to 70.5 nmol $cm^{-2}h^{-1}$ were observed on post-bleached Montastraea faveolata skeletons while nitrogen fixation rates using 15N up to 112 μmol $N_2m^{-2}h^{-1}$ were observed on post-bleached Acropora aspera skeletons. These rates are among the highest reported for coral reefs. Nitrogen fixation activity was found to be influenced by environmental parameters such as nutrient loading and light levels. The results of this study suggest that rates of nitrogen fixation following bleaching-induced mortality may depend on the pre-existing characteristics of a reef, and be sufficient to direct an affected ecosystem toward a phase change from coral to algal dominance.

Questions this article answers: what are the dynamics of coral reef nutrients, especially nitrogen, following a coral mortality event? How does this help predict possible outcomes on impacted reefs?

Methodology: Acetylene reduction and 15N techniques to investigate the dynamics of nitrogen associated with microbial communities that develop on coral skeletons following bleaching-induced mortality

Findings:
- The nitrogen fixation (acetylene reduction) rates observed in this study are comparable with those of previous studies, with similar trends being observed
- The highest rate observed in the current study was 70.5 nmol $cm^{-2}h^{-1}$ on M. faveolata (above previously reported rates)
- The type of mortality event may not be significant in influencing the function of nitrogen fixing microbial communities except in the short term
- Nitrogen fixation activity increases dramatically in the initial 3 months following coral mortality with fixation rates as much as an order of magnitude higher than those observed on older hard substrate material throughout the study sites
- Nitrogen fixation activity was found to be influenced by environmental parameters such as nutrient loading and light levels
- Results of this study suggest that rates of nitrogen fixation following bleaching-induced mortality may depend on the pre-existing characteristics of a reef, and be sufficient to direct an affected ecosystem toward a phase change from coral to algal dominance.

Houk, P., Musburger, C., & Wiles, P. (2010). Water quality and herbivory interactively drive coral reef recovery patterns in american samoa. *PLoS One, 5*(11).

Abstract: Background: Compared with a wealth of information regarding coral-reef recovery patterns following major disturbances, less insight exists to explain the cause(s) of spatial variation in the recovery process.
Methodology/Principal Findings: This study quantifies the influence of herbivory and water quality upon coral reef assemblages through space and time in Tutuila, American Samoa, a Pacific high island. Widespread declines in dominant corals (Acropora and Montipora) resulted from cyclone Heta at the end of 2003, shortly after the study began. Four sites that initially had similar coral reef assemblages but differential temporal

dynamics four years following the disturbance event were classified by standardized measures of 'recovery status', defined by rates of change in ecological measures that are known to be sensitive to localized stressors. Status was best predicted, interactively, by water quality and herbivory. Expanding upon temporal trends, this study examined if similar dependencies existed through space; building multiple regression models to identify linkages between similar status measures and local stressors for 17 localities around Tutuila. The results highlighted consistent, interactive interdependencies for coral reef assemblages residing upon two unique geological reef types. Finally, the predictive regression models produced at the island scale were graphically interpreted with respect to hypothesized site-specific recovery thresholds.
Conclusions/Significance: Cumulatively, our study purports that moving away from describing relatively well-known patterns behind recovery, and focusing upon understanding causes, improves our foundation to predict future ecological dynamics, and thus improves coral reef management.

Questions this article answers: what is the influence of herbivory and water quality on coral reef assemblages thought space and time in Tutuila, American Samoa?

Methodology: Quantifiably measured herbivory and water quality at 17 monitoring sites on a rotational basis between 2003 and 2008

Findings:

- Water quality and herbivory interactively accounted for the temporal and spatial variances associated with 'favorable' coral assemblage dynamics in American Samoa
- Desirable ecological status wasn't always recovery to reef's pre-existing state
- Shifting assemblages- a sign of reduced recovery, but also represent probable mechanisms to maintain ecosystem function after disturbance
- Moving away from describing relatively well-known patterns behind recovery, and focusing upon understanding causes, improves our foundation to predict future ecological dynamics

Hughes, T. P., Rodrigues, M. J., Bellwood, D. R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., ... & Willis, B. (2007). Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Current Biology*, *17*(4), 360-365.

Abstract: Many coral reefs worldwide have undergone phase shifts to alternate, degraded assemblages because of the combined effects of overfishing, declining water quality, and the direct and indirect impacts of climate change [1–9]. Here, we experimentally manipulated the density of large herbivorous fishes to test their influence on the resilience of coral assemblages in the aftermath of regional-scale bleaching in 1998, the largest coral mortality event recorded to date. The experiment was undertaken on the Great Barrier Reef, within a no-fishing reserve where coral abundances and diversity had been sharply reduced by bleaching. In control areas, where fishes were abundant, algal abundance remained low, whereas coral cover almost doubled (to 20%)

over a 3-year period, primarily because of recruitment of species that had been locally extirpated by bleaching. In contrast, exclusion of large herbivorous fishes caused a dramatic explosion of macroalgae, which suppressed the fecundity, recruitment, and survival of corals. Consequently, management of fish stocks is a key component in preventing phase shifts and managing reef resilience. Importantly, local stewardship of fishing effort is a tractable goal for conservation of reefs, and this local action can also provide some insurance against larger-scale disturbances such as mass bleaching, which are impractical to manage directly.

Questions this article answers: What is the influence of large herbivorous fishes on the resilience of coral assemblages in the aftermath of regional-scale bleaching in 1998?

Methodology: three experimental treatments- fully meshed and roofed cages to exclude medium to larger sized fishes; experimentally induced phase shift

Findings:

- We define resilience as the ability of reefs to absorb recurrent disturbances (e.g., from cyclones, outbreaks of predators, or coral bleaching events) and rebuild coral-dominated systems. Loss of resilience can lead to a phase or regime shift to an alternate assemblage that is typically characterized by hyper abundances of fleshy seaweeds or other opportunistic species.
- We demonstrate that exclusion of larger fishes profoundly erodes the resilience of coral reefs and their ability to regenerate after bleaching, with major implications for reef ecology, conservation, and management.
- Loss of coral-reef resilience can be readily quantified with several metrics (e.g., depletion of key functional groups of fishes, reduced rates of coral recruitment and population regeneration, sublethal impacts, etc.).
- Local management efforts in support of resilience can afford significant protection against threats that are much larger in scale.

Quotes:

"Preventing coral bleaching is not a tractable management goal at meaningful spatial or temporal scales, and a long-term solution will require global reductions of greenhouse gases over decadal timeframes. On the other hand, supporting resilience in anticipation of bleaching and other recurrent disturbances can be achieved locally by changing destructive human activities (e.g., overfishing and pollution) and thereby reducing the likelihood of undesirable phase shifts." 363

"A resilience-based approach represents a fundamental change of focus, from reactive to proactive management, aimed at sustaining the socioeconomic and ecological value of coral reefs in an increasingly uncertain world." 636

Johansen, J. L., & Jones, G. P. (2011). Increasing ocean temperature reduces the metabolic perfomance and swimming ability of coral reef damselfishes. *Global Change Biology, 17*, 2971-2979.

Abstract: Tropical coral reef teleosts are exclusively ectotherms and their capacity for physical and physiological performance is therefore directly influenced by ambient temperature. This study examined the effect of increased water temperature to 3 1C above ambient on the swimming and metabolic performance of 10 species of damselfishes (Pomacentridae) representing evolutionary lineages from two subfamilies and four genera. Five distinct performance measures were tested: (a) maximum swimming speed (Ucrit), (b) gait-transition speed (the speed at which they change from strictly pectoral to pectoral-and-caudal swimming, Up_c), (c) maximum aerobic metabolic rate (MO2_MAX), (d) resting metabolic rate (MO2_REST), and (e) aerobic scope (ratio of MO2_MAX to MO2_REST, ASC). Relative to the control (29 1C), increased temperature (32 1C) had a significant negative effect across all performance measures examined, with the magnitude of the effect varying greatly among closely

related species and genera. Specifically, five species spanning three genera (Dascyllus, Neopomacentrus and Pomacentrus) showed severe reductions in swimming performance with Ucrit reduced in these species by 21.3–27.9% and Up_c by 32.6–51.3%. Furthermore, five species spanning all four genera showed significant reductions in metabolic performance with aerobic scope reduced by 24.3–64.9%. Comparisons of remaining performance capacities with field conditions indicate that 32 1C water temperatures will leave multiple species with less swimming capacity than required to overcome the water flows commonly found in their respective coral reef habitats. Consequently, unless adaptation is possible, significant loss of species may occur if ocean warming of _ 3 1C arises.

Questions this article answers: What is the effect of increased water temperature to 3 degrees above ambient on the swimming and metabolic performance of 10 species of damselfishes? Can anything be deduced form the fishes' evolutionary history?

Methodology: Ten species of tropical damselfishes (Pomacentridae) were selected representing evolutionarylineages from two subfamilies and four different genera . Measured five performance measures: 120 fish in tanks to quantitatively measure performance.

Findings:

- A temperature rise from 29 to 32 1C had a highly significant overall effect on the resting metabolic rate of these species and there was a clear interaction between temperature and species on the swimming performance and metabolic performance examined
- Although there was an overall effect of temperature, the level of effect and the particular variables affected differed between species and genera
    - Of the four genera examined the posttest planned comparisons showed Chromis as the least affected by the elevated 32 1C temperature: only specific changes in the metabolic performance of C. ternatensis with this species demonstrating a 26% reduction in ASC
- All species within the Dascyllus genus were significantly affected by the elevated temperature
- Within the Neopomacentrus genus N. cyanomos showed significant reductions in both swimming ability and metabolic performance
- Finally, the Pomacentrus genus was significantly affected in both swimming ability and metabolic performance.
- The effect of increased temperature on physiological performance could not be ascribed to phylogenetic distance from the most thermally tolerant species
    - Closely related species and genera showed very different performance characteristics, and this pattern was repeated within both subfamilies examined
        - For instance, Chromis was the least affected genera while the closely related Dascyllus was among the most affected
- Increasing temperatures not only reduce the aerobic scope of multiple coral reef

damselfishes, including several evolutionary lineages within this family, but also greatly reduce the swimming performance of certain species
- There was no discernible pattern in regard to species relatedness or phylogenetic distance. However, some species may be significantly more affected by temperature changes than others
- Loss of swimming performance can be detrimental for any fish living in habitats where optimized swimming abilities are necessary for continued survival

Jokiel, P. L., Rodgers, K. S., Kuffner, I. B., Andersson, A. J., Cox, E. F., & Mackenzie, F. T. (2008). Ocean acidification and calcifying reef organisms: a mesocosm investigation. *Coral Reefs*, *27*(3), 473-483.

Abstract: A long-term (10 months) controlled experiment was conducted to test the impact of increased partial pres- sure of carbon dioxide (pCO2) on common calcifying coral reef organisms. The experiment was conducted in replicate continuous flow coral reef mesocosms flushed with unfil- tered sea water from Kaneohe Bay, Oahu, Hawaii. Mesocosms were located in full sunlight and experienced diurnal and seasonal fluctuations in temperature and sea water chemistry characteristic of the adjacent reef flat. Treatment mesocosms were manipulated to simulate an increase in pCO2 to levels expected in this century [midday pCO2 levels exceeding control mesocosms by 365 ± 130 latm (mean ± sd)]. Acidification had a pro- found impact on the development and growth of crustose coralline algae (CCA) populations. During the experiment, CCA developed 25% cover in the control mesocosms and only 4% in the acidified mesocosms,

representing an 86% relative reduction. Free-living associations of CCA known as rhodoliths living in the control mesocosms grew at a rate of 0.6 g buoyant weight year-1 while those in the acidified experimental treatment decreased in weight at a rate of 0.9 g buoyant weight year-1, representing a 250% differ- ence. CCA play an important role in the growth and stabilization of carbonate reefs, so future changes of this magnitude could greatly impact coral reefs throughout the world. Coral calcification decreased between 15% and 20% under acidified conditions. Linear extension decreased by 14% under acidified conditions in one experiment. Larvae of the coral Pocillopora damicornis were able to recruit under the acidified conditions. In addition, there was no significant difference in production of gametes by the coral Montipora capitata after 6 months of exposure to the treatments.

Jones, A. M., Berkelmans, R., van Oppen, M. J., Mieog, J. C., & Sinclair, W. (2008). A community change in the algal endosymbionts of a scleractinian coral following a natural bleaching event: field evidence of acclimatization. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1641), 1359-1365.

Abstract: The symbiosis between reef-building corals and their algal endosymbionts (zooxanthellae of the genus Symbiodinium) is highly sensitive to temperature stress, which makes coral reefs vulnerable to climate change. Thermal tolerance in corals is known to be substantially linked to the type of zooxanthellae they harbour and, when multiple types are present, the relative abundance of types can be experimentally manipulated to increase the thermal limits of individual corals. Although the potential exists for this to translate into substantial thermal acclimatization of coral communities, to date there is no evidence to show that this takes place under natural conditions. In this study, we show field evidence of a dramatic change in the symbiont community of Acropora millepora, a common and widespread Indo-Pacific hard coral species, after a natural bleaching event in early 2006 in the Keppel Islands (Great Barrier Reef). Before

bleaching, 93.5% (nZ460) of the randomly sampled and tagged colonies predominantly harboured the thermally sensitive Symbiodinium type C2, while the remainder harboured a tolerant Symbiodinium type belonging to clade D or mixtures of C2 and D. After bleaching, 71% of the surviving tagged colonies that were initially C2 predominant changed to D or C1 predominance. Colonies that were originally C2 predominant suffered high mortality (37%) compared with D-predominant colonies (8%). We estimate that just over 18% of the original A. millepora population survived unchanged leaving 29% of the population C2 and 71% D or C1 predominant six months after the bleaching event. This change in the symbiont community structure, while it persists, is likely to have substantially increased the thermal tolerance of this coral population. Understanding the processes that underpin the temporal changes in symbiont communities is key to assessing the acclimatization potential of reef corals.

Questions that this article answers: What is the change in the symbiont community of Acropora millepora (Indonesia hard coral species) after a natural bleaching event in 2006?

Methodology: Random sampling of colonies- quantitatively measured mortality of corals

Findings:

- Nuclear ribosomal and chloroplast DNA markers show that the genus Symbiodinium is highly diverse. The genus is currently divided into eight distinct clades (categorized as A–H), each containing multiple subclades, strains or types
    - Symbiodinium C is the most common symbiont type in Acropora corals on the Great Barrier Reef and certain types within this clade have been shown to be particularly sensitive to heat stress
    - Symbiodinium clade D is common in Acropora corals on shallow and inshore reefs and has been shown to be relatively tolerant to high temperatures
- One way in which this change can occur is by the predominant, thermally sensitive symbiont population being replaced by a population of thermally tolerant symbionts that arise from the presence of less abundant 'background' symbionts (Baker 2003). As a result, the entire coral colony becomes more thermally tolerant. – (the acclimatization mechanism)
- We have shown field evidence of a dramatic shift in the symbiont community in a reef-building coral as a result of bleaching.
- While these numbers are event, population and location specific, they do confirm that several interrelated processes play a role in shaping reef symbiont communities after bleaching episodes
- Mathematical modelling of the recovery of symbiont populations after bleaching suggests that such rapid changes are more easily explained by upward and downward regulations of existing symbiont populations
- Our results strongly support the reinterpreted adaptive bleaching hypothesis of Buddemeier et al. (2004), which postulates that a continuum of changing environmental states stimulates the loss of bleaching-sensitive symbionts in favour of symbionts that make the new holobiont more thermally tolerant.

- However, such a change may come at a physiological cost such as loss of photosynthetic efficiency leading to lower energy reserve and slower growth

Quotes:
"At this stage, it is unknown whether the increased thermal tolerance, even if it persists, will necessarily translate into increased reef resilience, particularly if growth and carbonate accretion are depressed to levels whereby bioerosion outweighs net accretion." 1363

Keller, B. D., Gleason, D. F., McLeod, E., Woodley, C. M., Airamé, S., Causey, B. D., ... & Steneck, R. S. (2009). Climate change, coral reef ecosystems, and management options for marine protected areas. *Environmental management*, *44*(6), 1069-1088.

Abstract: Marine protected areas (MPAs) provide place-based management of marine ecosystems through various degrees and types of protective actions. Habitats such as coral reefs are especially susceptible to degradation resulting from climate change, as evidenced by mass bleaching events over the past two decades. Marine ecosystems are being altered by direct effects of climate change including ocean warming, ocean acidification, rising sea level, changing circulation patterns, increasing severity of storms, and changing freshwater influxes. As impacts of climate change strengthen they may exacerbate effects of existing stressors and require new or modified management approaches; MPA networks are generally accepted as an improvement over individual MPAs to address multiple threats to the marine environment. While MPA networks are considered a potentially effective management approach for conserving marine biodiversity, they should be established in conjunction with other management strategies,

such as fisheries regulations and reductions of nutrients and other forms of land-based pollution. Information about interactions between climate change and more ''traditional'' stressors is limited. MPA managers are faced with high levels of uncertainty about likely outcomes of management actions because climate change impacts have strong interactions with existing stressors, such as land-based sources of pollution, overfishing and destructive fishing practices, invasive species, and diseases. Management options include ameliorating existing stressors, protecting potentially resilient areas, developing networks of MPAs, and integrating climate change into MPA planning, management, and evaluation.

Questions this article answers: How can MPAs best mitigate coral reef damage and support resilience?

Methodology: literature review

Findings:

- There is growing recognition among scientists and marine resource managers that ecosystem-based approaches may help sustain the wide array of services provided by marine ecosystems
- Marine protected areas (MPAs), particularly no-take marine reserves, can help restore ecosystem structure and function and help protect marine biodiversity and associated ecosystem services
- While MPA networks are considered a critical management tool for conserving marine biodiversity, they must be established in conjunction with other management strategies to be effective
- MPAs are vulnerable to activities beyond their boundaries- uncontrolled pollution and unsustainable fishing outside protected areas can adversely affect species and ecosystem functions within protected areas
- Done (2001; see also Marshall and Schuttenberg 2006b) presented a decision tree for identifying areas that would be suitable for MPAs under a global warming scenario.
    - Two types of favorable outcomes included reefs that survived bleaching (i.e., were resilient) and reefs that were not exposed to elevated sea surface temperatures (e.g., may be located within refugia such as areas exposed to upwelling or cooler currents).
- On a small scale, MPA managers may be able to select sites that are naturally shaded by high islands, emergent rocks or corals overhead.
- On a larger scale, managers should protect mangrove shorelines and support restoration of areas where mangroves have been damaged or destroyed because tannins and dissolved organic compounds from decaying mangrove vegetation contribute to absorbing light and reducing stress on adjacent coral reefs
- A set of recommendations has been developed to aid MPA network design and implementation, which include MPA size and spacing, risk spreading, protection of critical areas, connectivity, ecosystem function, and ecosystem- based management
- There are several recommendations about proportions or numbers of habitat types

to protect. For example, it has been recommended that more than 30% of appropriate habitats should be included in no-take marine reserves

Kemp, D. W., Oakley, C. A., Thornhill, D. J., Newcombs, L. A., Schmidt, G. W., & Fitt, W. K. (2011). Catastrophic mortality on inshore coral reefs of the Florida keys due to severe low-temperature stress. *Global Change Biology, 17*, 3468-3477.

Abstract: Coral reefs of the Florida Keys typically experience seasonal temperatures of 20–31 °C. Deviation outside this range causes physiological impairment of reef-building corals, potentially leading to coral colony death. In January and February 2010, two closely spaced cold fronts, possibly driven by an unusually extreme Arctic Oscillation, caused sudden and severe seawater temperature declines in the Florida Keys. Inshore coral reefs [e.g., Admiral Reef (ADM)] experienced lower sustained temperatures (i.e., < 12 °C) than those further offshore [e.g., Little Grecian Reef (LG), minimum temperature = 17.2 °C]. During February and March 2010, we surveyed ADM and observed a mass die-off of reef-building corals, whereas 12 km away LG did not exhibit coral mortality. We subsequently measured the physiological effects of low-temperature stress on three common reef-building corals (i.e., Montastraea faveolata, Porites astreoides, and Siderastrea siderea) over a range of temperatures that replicated the inshore cold-water anomaly (i.e., from 20 to 16 to 12 °C and back to 20 °C). Throughout the temperature modulations, coral respiration as well as endosymbiont gross photosynthesis and

maximum quantum efficiency of photosystem II were measured. In addition, Symbiodinium genotypic identity, cell densities, and chlorophyll a content were determined at the beginning and conclusion of the experiment. All corals were significantly affected at 12 °C, but species-specific physiological responses were found indicating different coral and/or Symbiodinium cold tolerances. Montastraea faveolata and P. astreoides appeared to be most negatively impacted because, upon return to 20 °C, significant reductions in gross photosynthesis and dark respiration persisted. Siderastrea siderea, however, readily recovered to pre-treatment rates of dark respiration and gross photosynthesis. Visual surveys of inshore reefs corroborated these results, with S. siderea being minimally affected by the cold-water anomaly, whereas M. faveolata and P. astreoides exhibited nearly 100% mortality. This study highlights the importance of understanding the physiological attributes of genotypically distinct coral-Symbiodinium symbioses that contribute to tolerance, recovery, and consequences to an environmental perturbation. These data also document effects of a rarely studied environmental stressor, possibly initiated by remote global climate events, on coral-Symbiodinium symbioses and coral reef communities.

Questions this article answers: What are the physiological effects of low-temperature stress on three common reef-building corals?

Methodology: reef assessment and temperature measurements: Seawater temperatures were recorded at each site using HOBO Pro v2 underwater temperature loggers; reef locations: Three species of corals, M. faveolata, P. astreoides, and S. siderea, were collected in February 2010 from two reefs separated by approximately 12 km in the upper Florida Keys; coral collection and maintenance: Coral fragments approximately 5–8 cm in diameter were collected via SCUBA using a hammer and chisel and immediately transported to the laboratory in a seawater-filled cooler; experimental treatment: We simulated the cold-water temperatures recorded on ADM from January 10 to January 15, 2010, by maintaining corals at 20 °C for 2 days, then reducing water temperatures to 16 °C (overnight) for 24 h before reducing the temperature to 12 °C (overnight).

Findings:

- Admiral Reef sustained abnormally low temperatures (<18 °C) for 11 days including 3 days _ 12 °C in early 2010
    - To put the abnormally low temperatures in context, from 2007 to 2009 the minimum temperature recorded by our data loggers was 19.7 °C and the mean winter temperature (January–February) from 2007 to 2009 was 23.3
    - The sustained low temperatures at ADM probably stressed many common reef-building corals, resulting in mass mortality
- Compared with the inshore ADM, offshore LG did not experience the same severity of low-temperature stress. LG experienced temperature <18 °C for several hours, hitting a minimum temperature of 17.2 °C
- Clearly, the 2010 winter cold-water perturbation was a significant stressor to inshore corals of the upper Florida Keys, causing mortality of numerous corals, including some M. faveolata colonies estimated to be more than 200 years old
- Species-specific coldwater susceptibility and survivorship was observed on

inshore reefs (e.g., ADM) located in the upper Florida Keys.

- Cold-water simulation experiments confirmed that S. siderea (offshore) and their associated Symbiodinium populations showed a high level of resilience to initial drops in temperatures and exhibited the greatest recovery in dark respiration and gross photosynthesis after experimental cold-water treatments
- Maintenance of membrane fluidity is a major adaptation influencing metabolic function and photosynthesis of low-temperature adapted organisms
    - o Elevated polyunsaturated fatty acid concentrations have been detected in many low-temperature adapted phototrophic organisms including sea ice diatoms, dinoflagellates, and green algae (reviewed in Morgan-Kiss et al., 2006). Therefore, it is likely that some Symbiodinium, such as phylotypes from S. siderea, may share similar biochemical adaptations that enable restoration of photosynthetic capacity after exposure low temperatures
- All corals were significantly affected at 12 °C, but species-specific physiological responses were found indicating different coral and/or Symbiodinium cold tolerances.
- Montastraea faveolata and P. astreoides appeared to be most negatively impacted because, upon return to 20 °C, significant reductions in gross photosynthesis and dark respiration persisted. Siderastrea siderea, however, readily recovered to pre-treatment rates of dark respiration and gross photosynthesis

Quotes:
"This potential increase of cold anomalies poses alarming consequences for coral reef ecosystems that are critically threatened by numerous environmental stressors (i.e., increased frequency of warm-water bleaching, coral diseases, removal of grazers, increased nutrient loading, ocean acidification, among other threats). If coral 'bleaching' occurs during both summer and winter months, it probably will result in ecosystem-wide catastrophe" 3476

Kiessling, W., Simpson, C., Beck, B., Mewis, H., & Pandolfi, J. M. (2012). Equatorial decline of reef corals during the last pleistocene interglacial. *Proceedings of the National Academy of Sciences of the United States of America, 109*(52), 21378-21378.

Abstract: The Last Interglacial (LIG; *ca.* 125,000 y ago) resulted from rapid global warming and reached global mean temperatures exceeding those of today. The LIG thus offers the opportunity to study how life may respond to future global warming. Using global occurrence databases and applying sampling-standardization, we compared reef coral diversity and distributions between the LIG and modern. Latitudinal diversity patterns are characterized by a tropical plateau today but were characterized by a pronounced equatorial trough during the LIG. This trough is governed by substantial range shifts away from the equator. Range shifts affected both leading and trailing edges of species range limits and were much more pronounced in the Northern Hemisphere than south of the equator. We argue that interglacial warming was responsible for the loss of equatorial diversity. Hemispheric differences in insolation during the LIG may explain the asymmetrical response. The equatorial retractions are surprisingly strong given that only small temperature changes have been reported in the LIG tropics. Our results suggest that the poleward range expansions of reef corals occurring with intensified

global warming today may soon be followed by equatorial range retractions.

Questions this article answers: How does the LIG suggest life may respond to future global warming?

Methodology: compare latitudinal patterns of global reef coral distributions and diversity (number of species) from raised reef terraces of the LIG

Findings:

- The less common a species is today, the less probable is its occurrence in the LIG
- Changes in reef range were more common in the northern hemisphere than the southern
    - Max latitudinal expansion range of leading edges is ~800 km
    - True rates of latitudinal shifts may thus have been on the same order of magnitude as observed today.(considering glacial ranges)
- LIG warming was more modest than suggested by temperature reconstructions from Arctic and Antarctic ice cores
- Although global average temperatures were 1.5 °C warmer than today average SST may only have been 0.7 °C higher
- Results would even fit a scenario of polar range expansions due to warming and equatorial retractions driven by cooling
- Equatorial cooling hypothesis rejected because:
- One of the regions where tectonic uplift made coral reefs accessible on land outside the peak interglacials is Huon Peninsula of Papua New Guinea (records coral reef terraces from times when SST in the LIG was substantially lower than today but coral diversity wasn't depressed)
- Proxy data are often contradictory (i.e., faunal proxies give cooler temperatures than geochemical proxies; refs. 16 and 36) or are at odds with modeling results such that they cannot be taken at face value at the resolution relevant for this study
- Temperature rise during the LIG caused dramatic range shifts of reef corals
- Leading-edge expansions we observed in the LIG relative to today are similar to present-day expansions of reef corals

Kiessling, W., & Simpson, C. (2010). On the potential for ocean acidification to be a general cause of ancient reef crises. *Global Change Biology*, *17*(1), 56-67.

Abstract: Anthropogenic rise in the carbon dioxide concentration in the atmosphere leads to global warming and acidification of the oceans. Ocean acidification (OA) is harmful to many organisms but especially to those that build massive skeletons of calcium carbonate, such as reef corals. Here, we test the recent suggestion that OA leads not only to declining calcification of reef corals and reduced growth rates of reefs but may also have been a trigger of ancient reef crises and mass extinctions in the sea. We analyse the fossil record of biogenic reefs and marine organisms to (1) assess the timing and intensity of ancient reef crises, (2) check which reef crises were concurrent with inferred pulses of carbon dioxide concentrations and (3) evaluate the correlation between reef crises and mass extinctions and their selectivity in terms of inferred physiological buffering. We conclude that four of five global metazoan reef crises in the last 500 Myr were probably at least partially governed by OA and rapid global warming. However, only two of the big five mass extinctions show geological evidence of OA.

Questions this article answers: does OA lead to declining calcification of reef corals? Does it reduce growth rates of reefs? Was OA a trigger of ancient reef crises and mass extinctions in the sea?

Methodology: Fossil analysis of biogenic reefs and marine organisms

Findings:

- Empirical evidence does suggest that coral reefs are especially affected by OA because the major reef builders, scleractinian corals and coralline red algae, respond readily by reduced growth rates, abundance and increased postmortem dissolution
- The current anthropogenic rise in pCO2 is dramatic (IPCC, 2007) but perhaps not unprecedented in the geologic record
- Extinctions were highly selective against unbuffered organisms, and there was a pronounced depression in the preservation of unbuffered organisms in the Early Triassic
- The earliest Jurassic reef crisis fits most of the hypothetical scenarios shown in Fig. 1. The reef crisis was massive, the end-Triassic mass extinction was highly selective against hypercalcifying sponges and corals and physiologically unbuffered taxa, and the preservation of unbuffered genera dropped markedly in the earliest Jurassic
- The Paleocene–Eocene boundary is probably the time for which OA is best documented- OA is manifested directly by a shallowing of the calcium carbonate compensation depth in the deep ocean, but substantial effects on shallow water biota have also been suggested
    - Not all effects were negative. For example, the productivity of oceanic plankton seems to have increased
- Extinctions of corals and other unbuffered organisms were modest according to the raw data (Fig. 4), but the corrected rates are significantly elevated for unbuffered organisms, reaching almost the values of the end-Cretaceous mass extinction.
- OA might preferentially affect those regions where the ocean is already less saturated with respect to calcium carbonate. These are high latitude and deeper water areas were corals are considered especially vulnerable to OA
    - On the other hand, deep water corals might be adapted to low saturation levels and thus less sensitive to drops in pH or hypercapnia
- Neither all mass extinction events nor all metazoan reef crises were caused by OA- reef crises and mass extinction are not always coincident
- The four out of five matches between inferred OA events and metazoan reef crises is indeed impressive, although global warming associated with these events is at least as probable as a trigger as is OA
- The double strike of OA and rapid warming thus seems to be really deleterious for reefs, to a degree that this can almost be seen as a general cause of reef crises.

Kittinger, J. N., Pandolfi, J. M., Blodgett, J. H., Hunt, T. L., Jiang, H., Maly, K., . . . Wilcox, B. A. (2011). Historical reconstruction reveals recovery in hawaiian coral reefs. *PLoS One, 6*(10)

Abstract: Coral reef ecosystems are declining worldwide, yet regional differences in the trajectories, timing and extent of degradation highlight the need for in-depth regional case studies to understand the factors that contribute to either ecosystem sustainability or decline. We reconstructed social-ecological interactions in Hawaiian coral reef environments over 700 years using detailed datasets on ecological conditions, proximate anthropogenic stressor regimes and social change. Here we report previously undetected recovery periods in Hawaiian coral reefs, including a historical recovery in the MHI (,AD 1400–1820) and an ongoing recovery in the NWHI (,AD 1950–2009+). These recovery periods appear to be attributed to a complex set of changes in underlying social systems, which served to release reefs from direct anthropogenic stressor regimes. Recovery at the ecosystem level is associated with reductions in stressors over long time periods (decades+) and large spatial scales (.103 km2). Our results challenge conventional assumptions and reported findings that human impacts to ecosystems are cumulative and lead only to long-term trajectories of environmental decline. In contrast, recovery periods reveal that human societies have interacted sustainably with coral reef environments over long time periods, and that degraded ecosystems may still retain the adaptive capacity

and resilience to recover from human impacts.

Questions this article answers: What have been the social-ecological interactions in Hawaiian coral reef environments over the past 700 years?

Methodology: case study of Hawaiian coral reef history (in depth- regional case study)

Findings:

- Our reconstruction reveals that trajectories of change in ecological condition differed among coral reef guilds and between regions of the Hawaiian archipelago
- The Main Hawaiian Islands:
- Voyaging Polynesians arrived in the Hawaiian archipelago sometime around AD 1250 [22,23], and archaeological midden remains and later recorded ethnohistoric accounts reveal that coral reef species were commonly exploited by Polynesian colonizers
    - Firstly nearshore and reef-associated biota comprise the major marine source of protein and are more prevalent in the archaeological record than pelagic, riparian, estuarine and aquacultured species. Second, some studies show consistent evidence of overexploitation, but these patterns appear to be most consistent for nearshore shellfish species only
    - Overexploitation in these cases is evidenced in taxa size reductions and changes in the dominant taxa of species recovered through time
    - In several well-described sites, fish remains recovered from archaeological deposits suggest a shift from a predominance of inshore carnivorous reef fish to inshore herbivorous reef fish
    - Marine exploitation was highest in the early period after Polynesian settlement and subsequently decreased through time
- By the late prehistoric period (. AD 1400), however, reef-derived protein sources are less prevalent than domesticates, suggesting a shift in the basic modes of subsistence and exploitation patterns in prehistoric Hawaiian societies
- In sum, multiple independent observations of high abundances of reef taxa in ethnohistoric and observational data indicate further recovery of free-living reef biota after western contact
- These trends suggest a period of sustained recovery spanning the late prehistoric to the early historic period (,AD 1400–1820)

The Northwestern Hawaiian Islands:

- Coral reefs in the NWHI have functioned as a geographic refuge since prehistoric times due to the region’s isolation, limited human habitability, and the dispersed geography of NWHI reefs and atolls, but they have not been free from human impact

  Though prehistoric impacts appear to be minimal, reefs in the NWHI suffered impacts in the post-contact period from the same historical activities affecting MHI reefs, as fishers and maritime industries moved from locally accessible MHI reefs to resource pools further afield in the NWHI
- After western contact, reef recovery in the MHI is attributed to extensive

indigenous depopulation due to disease epidemics and changes in labor and the modes of production

- Long-term trajectories of change in reef ecosystems in the Hawaiian archipelago reveal that coral reefs may be resilient to human activities if the intensity and ecological breadth (number of guilds affected) of proximate stressors are reduced over long time periods (decades+) and large spatial scales (.103 km2).
- While coral reef ecosystems in the MHI are highly degraded, NWHI reefs are healthy and in good condition by global standards
- Reefs in the MHI have been declining over the past 150+ years and deleterious phase shifts observed in other regional reef ecosystems [97,98] point to the existence of degradation thresholds beyond which recovery is doubtful.

Quotes:
"The ethnohistoric and archaeological record confirm that these systems included gender- and class-specific consumption restrictions on many marine species and a suite of coral reef ecosystem conservation strategies which may have enabled resource extraction while preventing overuse and collapse."

"Integrated approaches to understanding the co-evolution of human and natural systems are necessary to understand the complex interactions between societies and the ecosystems upon which they rely. Long-term social-ecological reconstructions allow us to address contemporary environmental challenges by providing baselines of previous ecosystem conditions and reciprocal cultural responses, the states and transformations these linked systems have undergone, and the factors associated with sustainability, degradation or collapse"
Klein, C. J., Ban, N. C., Halpern, B. S., & et al. (2010). Prioritizing land and sea conservation investments in coral reefs. *PLoS One, 5*(8)

Abstract: Background: Coral reefs have exceptional biodiversity, support the livelihoods of millions of people, and are threatened by multiple human activities on land (e.g. farming) and in the sea (e.g. overfishing). Most conservation efforts occur at local scales and, when effective, can increase the resilience of coral reefs to global threats such as climate change (e.g. warming water and ocean acidification). Limited resources for conservation require that we efficiently prioritize where and how to best sustain coral reef ecosystems. Methodology/Principal Findings: Here we develop the first prioritization approach that can guide regional-scale conservation investments in land- and sea-based conservation actions that cost-effectively mitigate threats to coral reefs, and apply it to the Coral Triangle, an area of significant global attention and funding. Using information on threats to marine ecosystems, effectiveness of management actions at abating threats, and the management and opportunity costs of actions, we calculate the rate of return on investment in two conservation actions in sixteen ecoregions. We discover that marine conservation almost always trumps terrestrial conservation within any ecoregion, but terrestrial conservation in one ecoregion can be a better investment than marine conservation in another. We show how these results could be used to allocate a limited budget for conservation and compare them to priorities based on individual criteria.

Conclusions/Significance: Previous prioritization approaches do not consider both land and sea-based threats or the socioeconomic costs of conserving coral reefs. A simple and transparent approach like ours is essential to support effective coral reef conservation decisions in a large and diverse region like the Coral Triangle, but can be applied at any scale and to other marine ecosystems.

Questions this article answers: How and where can coral reefs be best conserved? How can you prioritize regional-scale conservation investments to cost-effectively mitigate threats to coral reefs?

Methodology: using information on threats to marine ecosystems, effectiveness of management actions at abating threats, and the management and opportunity costs of actions, we calculate the rate of return on investment in two conservation actions in sixteen ecoregions

Findings:

- Invest in projects where the rates of return on investment are the highest- apply this to marine conservation, as it is in terrestrial conservation
- Objective is to maximize threat reduction to coral reefs across the Coral Triangle's ecoregions through investment in land- and sea-based conservation actions
- Steps taken: define conservation objective, identify threats to ecosystem, indentify conservation actions to abate threats, calculate costs of implanting actions, and invest where the rate of return is the highest
- The method can also be applied at a local-scale (e.g. provincial or catchment level), using more conservation actions (e.g., run-off management, improved agricultural practices, fishing gear-based management).
- Prioritization on species information alone, for example, will not be able to inform how funding should be divided between management actions on the land and in the sea
- Marine conservation almost always trumps terrestrial conservation within any ecoregion, but terrestrial conservation in one ecoregion can be a better investment than marine conservation in another (within sixteen ecoregions)

Kleypas, et al. (2011). Coral Reefs Modify their seawater carbon chemistry- case study from a barrier reef.

Abstract: Changes in the carbonate chemistry of coral reef waters are driven by carbon fluxes from two sources: concentrations of CO2 in the atmospheric and source water, and the primary production/respiration and calcification/dissolution of the benthic community. Recent model analyses have shown that, depending on the composition of the reef community, the air-sea flux of CO2 driven by benthic community processes can exceed that due to increases in atmospheric CO2 (ocean acidification). We field test this model and examine the role of three key members of benthic reef communities in modifying the chemistry of the ocean source water: corals, macroalgae, and sand. Building on data from previous carbon flux studies along a reef-flat transect in Moorea (French Polynesia), we illustrate that the drawdown of total dissolved inorganic carbon (CT) due to photosynthesis and calcification of reef communities can exceed the draw down of total alkalinity (AT) due to calcification of corals and calcifying algae, leading to a net increase in aragonite saturation state (Ωa). We use the model to test how changes in atmospheric CO2 forcing and benthic community structure affect the overall calcification rates on the reef flat. Results show that between the preindustrial period and 1992, ocean acidification caused reef flat calcification rates to decline by an estimated 15%, but loss of coral cover caused calcification rates to decline by at least three times

that amount. The results also show that the upstream– downstream patterns of carbonate chemistry were affected by the spatial patterns of benthic community structure. Changes in the ratio of photosynthesis to calcification can thus partially compensate for ocean acidification, at least on shallow reef flats. With no change in benthic community structure, however, ocean acidification depressed net calcification of the reef flat consistent with findings of previous studies.

Questions this article answers: What is the role of benthic primary producers and calcifiers in altering seawater chemistry as it flows over reefs? How do changes in atmospheric CO2 and benthic community structure affect overall calcification rates of a reef flat?

Methodology: a field test of three members benthic reef communities: coral, microalgae, and sand (modeled the effects of photosynthesis-respiration and calcification- dissolution on seawater chemistry as offshore water traversed over coral/algae/sediment communities along the same Tiahura reef flat transect studied by Gattuso et al. (1996b).)

Findings:

- Coral reef communities have long been known to alter their own seawater chemistry, through processes of photosynthesis, respiration, calcification, and dissolution
- The community composition of a coral reef can greatly alter the carbon chemistry of seawater flowing across the system
- Water depths across the reef flat are fairly uniform, about 1– 2 m depth
- The calcification rate of Tiahura reef flat sediments (gs) was much lower than that of the coral/mixed communities, and was the only community component that exhibited net dissolution
- Changes in the percent coral and algal cover affected whether the reef flat was a source or sink of CO2.
    - As expected, increasing the percent coral cover intensified the reef's role as a net source of CO2, while the reef acted as a net CO2 sink when the percent algae cover was increased
- Coral reef communities can have a strong impact on the chemistry of reef waters. Large variations in reef seawater chemistry have been observed at multiple reef sites
- Changes in seawater chemistry of the source water due to ocean acidification are likely to significantly affect net calcification on the reef.
- Algal growth would have to be increased by more than fivefold to make up for the reduction in calcification due to ocean acidification.

Quotes:

"Our simulations do not include two potentially important factors. First, we assume that primary production by macroalgae or corals is not stimulated by elevated pCO2 . An increase in production would draw down some of the CO2 absorbed from the atmosphere and offset the decreases in calcification (see discussion below). Second, we do not include the effects of CaCO3 dissolution in our equations, except for the base rate of nighttime dissolution in the carbonate sediments.macroalgae or corals is not stimulated by elevated pCO2 . An increase in production would draw down some of the CO2 absorbed from the atmosphere and offset the decreases in calcification." -3675

Kleypas, J. A., Danabasoglu, G., & Lough, J. M. (2008). Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. *Geophysical Research Letters*, *35*(3), L03613.

Abstract: Several negative feedback mechanisms have been proposed by others to explain the stability of maximum sea surface temperature (SST) in the western Pacific warm pool (WPWP). If these ''ocean thermostat'' mechanisms effectively suppress warming in the future, then coral reefs in this region should be less exposed to conditions that favor coral reef bleaching. In this study we look for regional differences in reef exposure and sensitivity to increasing SSTs by comparing reported coral reef bleaching events with observed and modeled SSTs of the last fifty years. Coral reefs within or near the WPWP have had fewer reported bleaching events relative to reefs in other regions. Analysis of SST data indicate that the warmest parts of the WPWP have warmed less than elsewhere in the tropical oceans, which supports the existence of thermostat mechanisms that act to depress warming beyond certain temperature thresholds.

Questions this article answers: What are the regional differences in reef exposure and sensitivity to increasing SSTs?

Methodology: Comparative study- reported coral bleaching events with observed and modeled SSTs (past fifty years)

Findings:

- SSTs are expected to increase further with increasing atmospheric greenhouse gas concentrations, leaving coral reef ecosystems increasingly vulnerable to future coral bleaching events.
- A factor that may affect bleaching frequency in the future is the hypothesized ‘‘ocean thermostat.’’ This proposes that maximum SSTs in the ocean should be around 30–31 degrees C, (theory and observations)

- Three main processes that limit open ocean SSTs have been proposed: (1) latent heat flux or evaporation-wind-SST feedback; (2) cloud-SST feedback or cloud shortwave radiative forcing; and (3) ocean dynamics
- and heat transport
- The thermostat hypothesis has mixed support from paleontological modeling and observations
- Over the past 50–60 years, SSTs in the warmest parts of the oceans have warmed less than in surrounding areas
- Coral bleaching is affected by other climatic factors such as solar radiation, wind and water flow, but are not addressed here as they are usually related to the same factors that determine SST. Many non-climatic factors, however, determine the sensitivity
- The percentage of reefs affected by bleaching appears to be lowest in and near the WPWP where SSTs have warmed the least since the 1950s

Quotes:

- “Coral sensitivity to elevated SST varies across species and coral communities. It also varies with reef habitat and across oceans, which is determined in part by the natural variability of the system; e.g., sensitivity to SST extremes is inversely related to the natural SST variability”

Knowlton, N., & Jackson, J. B. (2008). Shifting baselines, local impacts, and global change on coral reefs. *PLoS biology*, *6*(2), e54.

Abstract: This lack of a baseline for pristine marine ecosystems is particularly acute for coral reefs, the so-called rainforests of the sea, which are the most diverse marine ecosystems and among the most threatened [4–8]. Most of the world's tropical coastal oceans are so heavily degraded locally that "pristine" reefs are essentially gone, even if one ignores changes associated with already rising temperatures and acidity. Most modern (post-SCUBA) ecological studies have focused on reef ecosystems that are moderately to severely degraded, and we have a much better understanding of transitions between human-dominated and collapsed reefs than between human-dominated and quasi-pristine reefs. We are left without a clear understanding of how reefs functioned in the absence of major human impacts. This is the problem of shifting baselines, which is at the root of ongoing controversy about the relative importance of and synergies among the major factors driving coral reef decline (overfishing, land-based pollution, and global change) and what, if anything, can be done to stop it.

Questions this article answers: How does local management work to conserve coral reefs? Are there critical breakpoints and thresholds that coral reefs cannot recover from?

Methodology: literature review

Findings:

- The greatest scientific uncertainties in the debate about coral reef decline concern interactions between local versus global disturbance, a debate that is aggravated by the tendency among reef ecologists to attribute changes to single factors rather than the synergies among them
- Of particular importance are the effects of resource extraction and lowered water quality on reef ecosystems and their effects on corals via overgrowth of macroalgae and disease
- We have little understanding of even the basic shape of these relationships (human impacts on biology of reefs) across a truly broad spectrum of human influence
- Resistance and resilience are measures of the ability of ecosystems to withstand or recover from anthropogenic and natural stresses.
- For coral reefs, the most important data concern the corals themselves, since they provide the three-dimensional structure upon which much of the entire reef ecosystem depends, either directly or indirectly
- The best-understood aspects of coral resistance and resilience relate to the effects of overfishing, degraded water quality, and increased macroalgal abundance on coral recruitment (resilience) and coral disease (resistance).

Quotes:
"Coral reef ecology needs to be more focused and coordinated on a global scale, with research strategies comparable to the network of tropical forest studies that makes all data available in a consistent and easily accessible format" 219
Kuwahara, V. S., Nakajima, R., Othman, B. H. R., & et al. (2010). Spatial variability of UVR attenuation and bio-optical factors in shallow coral-reef waters of malaysia. *Coral Reefs, 29*(3), 693-704.

Abstract: Biologically diverse coral-reef ecosystems are both directly and indirectly susceptible to changes in the spectral ultraviolet radiation (UVR) distribution. The purpose of this study was to (1) measure the variability of UVR and photosynthetically active radiation (PAR) penetration in the water above coral reefs around the Malaysian peninsula, (2) measure the variability and distribution of UVR-specific biogeochemical factors, and (3) determine the impact of biogeochemical variability as it affects the UVR:PAR ratio. Downwelling UVR and PAR irradiance and bio-optically derived biogeochemical factors were measured at 14 coral survey stations around the Malaysian peninsula from August 10–29, 2007. The West Coast was characterized by relatively shallow mean 10% UV-B (320 nm) penetration (1.68 ± 1.12 m), high chlorophyll (3.00 ± 4.72 lg l-1), high chromophoric dissolved organic matter (CDOM; 6.61 ± 3.31 ppb), high particulate organic carbon (POC; 190.65 ± 97.99 mg m-3), and low dissolved organic carbon (DOC; 1.34 ± 0.65 mg m-3). By contrast, the East Coast was characterized by relatively deep mean 10% UV-B penetration (5.03 ± 2.19 m), low chlorophyll (0.34 ± 0.22 lg l-1), low CDOM (1.45 ± 0.44 ppb), low POC (103.21 ± 37.93 mg m-3), and relatively high DOC (1.91 ± 1.03 mg m-3). The UVR:PAR ratio was relatively higher on the East Coast relative to the West Coast, suggesting variable concentrations of UVRspecific absorbing components. At all sites, UVR attenuation coefficients showed significant correlations with CDOM, but were spatially dependent with regard to

chlorophyll a, POC, and DOC. The results suggest that biooptically significant CDOM and DOC factors are uncoupled in coral-reef communities of Malaysia. Furthermore, the results support prior studies that show chromophorically active concentrations of DOM and POC are significantly altering the amount of UVR penetration above coral reefs and may be notable factors in regulating intricate biogeochemical cycles around benthic coral communities in Malaysia.

Questions this article answers: what is the variability of UVR and photosynthetically active radiation (PAR) penetration in the water above coral reefs around the Malaysian peninsula? What is the variability and distribution of UVR-specific biogeochemical factors? What is the impact of biogeochemical variability as it affects the UVR/PAR ratio?

Methodology: Downwelling UVR and PAR irradiance and bio-optically derived biogeochemical factors were measured at 14 coral survey stations around the Malaysian peninsula from August 10–29, 2007

Findings:
- The West Coast was characterized by relatively shallow mean 10% UV-B (320 nm) penetration (1.68 ± 1.12 m), high chlorophyll (3.00 ± 4.72 lg l-1), high chromophoric dissolved organic matter (CDOM; 6.61 ± 3.31 ppb), high particulate organic carbon (POC; 190.65 ± 97.99 mg m-3), and low dissolved organic carbon (DOC; 1.34 ± 0.65 mg m-3). By contrast, the East Coast was characterized by relatively deep mean 10% UV-B penetration

- The UVR:PAR ratio was relatively higher on the East Coast relative to the West Coast, suggesting variable concentrations of UVRspecific absorbing components
- The results support prior studies that show chromophorically active concentrations of DOM and POC are significantly altering the amount of UVR penetration above coral reefs and may be notable factors in regulating intricate biogeochemical cycles around benthic coral communities in Malaysia
- In future studies, it will be increasingly important to determine how these UV-induced photoreactions and potential byproducts are produced and affect the overall health and diversity of coral-reef ecosystems, in Malaysia and elsewhere. Also, the decoupling between CDOM and DOC concentrations as it relates to UVR penetration requires further investigation to clarify how coral reefs in Malaysia are affected

Kuffner, I. B., Andersson, A. J., Jokiel, P. L., Rodgers, K. U. S., & Mackenzie, F. T. (2007). Decreased abundance of crustose coralline algae due to ocean acidification. ***Nature Geoscience*, *1*(2), 114-117.**

Abstract: Owing to anthropogenic emissions, atmospheric concentrations of carbon dioxide could almost double between 2006 and 2100 according to business-as-usual carbon dioxide emission scenarios. Because the ocean absorbs carbon dioxide from the atmosphere increasing atmospheric carbon dioxide concentrations will lead to increasing dissolved inorganic carbon and carbon dioxide in surface ocean waters, and hence acidification and lower carbonate saturation state. As a consequence, it has been suggested that marine calcifying organisms, for example corals, coralline algae, molluscs and foraminifera, will have difficulties producing their skeletons and shells at current rateswith potentially severe implications for marine ecosystems, including coral reefs. Here we report a seven-week experiment exploring the effects of ocean acidification on crustose coralline algae, a cosmopolitan group of calcifying algae that is ecologically important in most shallow-water habitats. Six outdoor mesocosms were continuously supplied with sea water from the adjacent reef and manipulated to simulate conditions of either ambient or elevated seawater carbon dioxide concentrations. The recruitment rate and growth of crustose coralline algae were severely inhibited in the elevated carbon dioxide mesocosms. Our findings suggest that ocean acidification due to human activities could cause significant change to benthic community structure in shallow-warm-water carbonate ecosystems.

Question this article answers: What are the effects of ocean acidification on crustose coralline algae?

Methodology: Quantitative study: simularing conditions of either ambient of elevated seawater carbon dioxide concentrations

Findings:

- Recruitment rates and growth of crustose coralline algae- severely inhibited in the elevated carbon dioxed mesocosms
- Ocean acidification (anthropogrnic) – could cause significant change to benthic community structure
  - -This is in shallow-warm-water carbonate ecosystems

Lawton, R. J., Massmer, V., Pratchett, M. S., & Bay, L. A. (2011). High gene flow across large geographic scales reduces extinction risk for a highly specialised coral feeding butterflyfish. ***Molecular Ecology, 20*****, 3584-3598.**

Abstract: The vulnerability of ecologically specialised species to environmental fluctuations has been well documented. However, population genetic structure can influence vulnerability to environmental change and recent studies have indicated that specialised species may have lower genetic diversity and greater population structuring compared to their generalist counterparts. To examine whether there were differences in population genetic structure between a dietary specialist (Chaetodon trifascialis) and a dietary generalist (Chaetodon lunulatus) we compared the demographic history and levels of gene flow of two related coral-feeding butterflyfishes. Using allele frequencies of ‡11 microsatellite loci and >350 bases of mitochondrial control region sequence our analyses of C. trifascialis and C. lunulatus from five locations across the Pacific Ocean revealed contrasting demographic histories and levels of genetic structure. Heterozygosity excess tests, neutrality tests and mismatch distributions were all highly significant in the dietary specialist C. trifascialis (all $P < 0.01$), suggesting genetic bottlenecks have occurred in all locations. In contrast, we found little evidence of genetic bottlenecks for the dietary generalist C. lunulatus. High gene flow and low genetic structuring was detected among locations for C. trifascialis (AMOVA: $R_{ST} = 0.0027$, $P = 0.371$; $F_{ST} = 0.068$, $P < 0.0001$). Contrary to our expectations, a greater level of genetic structuring between locations was detected for C. lunulatus (AMOVA: $R_{ST} = 0.0277$, $F_{ST} = 0.166$, both $P < 0.0001$). These results suggest that dietary specialisation may affect demographic history

through reductions in population size following resource declines, without affecting population structure through reductions in gene flow in the same way that habitat specialization appears to. Although C. trifascialis is highly vulnerable to coral loss, the high gene flow detected here suggests populations will be able to recover from local declines through the migration of individuals.

Questions this article answers: Are there differences in population genetic structure between a dietary specialist (Chaetodon trifascialis) and a dietary generalist (Chaetodon lunulatus)? What is their vulnerability to environmental change (two reef species)?

Methodology: This study compared the demographic history and levels of gene flow of two related coral-feeding butterflyfishes. Used a mitochondrial control region sequence to analyze C. trifascialis and C. lunulatus from five locations across the Pacific Ocean: compared history an dpopulation genetic structure

Findings:

- Coral reef butterflyfishes (Family Chaetodontidae) provide an ideal model in which to investigate questions regarding dietary specialisation, vulnerability to environment change, extinction risk and population genetic structure because members of this diverse family display a range of ecological attributes.
    - The geographic range size and abundance of species within this family vary by several orders of magnitude (Jones et al. 2002; Pratchett et al. 2008). The dietary preferences and ecological specialisation of individual species also vary significantly and range from species such as Chaetodon kleinii that feed on soft corals, hard corals, reef substrates and other macro-invertebrates, to species such as Chaetodon baronessa that only feed on a small number of hard coral species
- Our specific aims were to (i) detect evidence of population declines at any of the sampling locations; (ii) estimate levels of gene flow between sampling locations to enable predictions of likely recovery potential; and (iii) compare recent and historical patterns in demographic history and population structure to provide an overall estimate of vulnerability for both species.
- Genetic diversity- high: microsatellite loci were highly polymorphic in both species; The number of detected alleles per locus across all locations ranged from 9 to 31 for C. lunulatus, and from 10 to 38 for C. trifascialis; Within locations, the number of detected alleles per locus ranged from 4 to 26 alleles with a mean of 14.6 (±0.8 SE) alleles in C. lunulatus, and from 4 to 29 alleles with a mean of 14.1 (±0.9 SE) in C. trifascialis.
- Demographic history- Heterozygosity excess tests showed no evidence of recent genetic bottlenecks for the dietary generalist C. lunulatus at any location except Heron Island; In contrast, a highly significant heterozygosity excess was detected in the dietary specialist C. trifascialis at all five locations under the IAM, providing strong evidence for recent genetic bottlenecks
    - For both species, heterozygosity excess tests were non-significant for all locations under the TPM and the SMM
- Population structure: analyses for both species revealed that almost all of the

genetic variation in both microsatellite and mtDNA data was within locations
    - Very little variation was attributed among locations
- This study revealed marked differences in the population genetic structure of two species with contrasting levels of dietary specialization
    - C. trifascialis and C. lunulatus exhibit very different demographic histories and patterns of genetic structure despite similar life histories and comparable levels of genetic diversity
- In contrast to our expectations, the dietary generalist C. lunulatus had higher levels of population structure than C. trifascialis.
    - Due to its extremely specialised diet, C. trifascialis is highly vulnerable to declining abundance of the tabular Acropora corals it preferentially feeds on
- Our results have important implications for the vulnerability of the specialised coral-feeder C. trifascialis to predicted coral loss in the future
    - The historical genetic bottlenecks and recent population declines detected here indicate this species will be highly vulnerable to any future loss of the Acropora corals it preferentially consumes
    - Our finding of high gene flow between locations over both recent and historical timeframes suggests there is potential that C. trifascialis populations will be able to recover from local declines

Lefevre, C. D., & Bellwood, D. R. (2011). Temporal variation in coral reef ecosystem processes: Herbivory of macroalgae by fishes. ***Marine Ecology Progress Series, 422*****, 239.**

Abstract: Despite the widely accepted importance of fish herbivory on coral reefs, few studies have considered the temporal variability in the nature of algal–herbivore interactions. We therefore quantified monthly feeding intensity on *Sargassum* sp. bioassays for 12 mo with remote underwater video cameras deployed to identify the herbivores responsible for macroalgal removal on an inshore island of the Great Barrier Reef, Australia. Significantly higher removal rates were observed during the summer months whereas winter months were characterized by 4 times lower removal rates. However, rather than being simply changes in the feeding activity of a single species, this temporal pattern in herbivory also incorporated changes in the species responsible for the removal of *Sargassum*. Video analyses revealed that, of the 43 herbivore species recorded from the bay, only 3 played a significant role in *Sargassum* removal: *Kyphosus vaigiensis*, *Naso unicornis* and *Scarus rivulatus*. *K. vaigiensis*, a rudderfish, was primarily responsible for the removal of *Sargassum* during the summer months (83% of the total recorded bites; 85553 bites). There was almost no feeding activity on *Sargassum* by *K. vaigiensis* during the winter months (82 bites). However, there was a reciprocal increase in feeding intensity on *Sargassum* by parrotfishes in the winter months, particularly *S. rivulatus* (71 bites during summer versus 2884 bites in winter). This temporal variability in herbivore functional roles suggests that functional redundancy on reefs may be less than previously assumed in that the feeding activities of fishes may be

both spatially and temporally constrained.

Questions this article answers: is there temporal variability in the nature of algal-herbivore interactions?

Methodology: quantified monthly feeding intensity on *Sargassum* sp. bioassays for 12 mo with remote underwater video cameras deployed to identify the herbivores responsible for macroalgal removal on an inshore island of the Great Barrier Reef, Australia

Findings:

- Of the 43 herbivore species recorded from the bay, only 3 played a significant role in *Sargassum* removal: *Kyphosus vaigiensis*, *Naso unicornis* and *Scarus rivulatus*. *K. vaigiensis*, a rudderfish, was primarily responsible for the removal of *Sargassum* during the summer months
- There was almost no feeding activity on *Sargassum* by *K. vaigiensis* during the winter months (82 bites).
- There was a reciprocal increase in feeding intensity on *Sargassum* by parrotfishes in the winter months, particularly *S. rivulatus* (71 bites during summer versus 2884 bites in winter)
- This temporal variability in herbivore functional roles suggests that functional redundancy on reefs may be less than previously assumed in that the feeding activities of fishes may be both spatially and temporally constrained

Levy, G., Shaish, L., Haim, A., & et al. (2010). Mid-water rope nursery testing design and performance of a novel reef restoration instrument. *Ecological Engineering, 36*(4), 560-569

Abstract: Fast degradation of coral reefs worldwide has promoted the exploitation of active restoration instruments, one of which is the 'gardening concept'. This concept comprises two phases: (1) establishing in situ coral nurseries for rearing large numbers of coral fragments; (2) their transplantation onto denuded reefs. This study tested the design and performance of a novel mid-water floating nursery instrument, a 'rope nursery'. This nursery accommodated small coral fragments attached to a rope, creating an easily constructed nursery bed that is rapid and inexpensive. Two sets of experiments were conducted: the first tested two mid-water rope nursery prototypes in small-scale trials that tested depth, coral genotypes and construction stability, whereas the second set incorporated lessons learned from the first set, and was designed to carry larger numbers of colonies. These highly economical nurseries (US$ 0.11/fragment) revealed high survivorship low detachment and fast growth rates compared to previous coral-nursery types. Moreover, the coiling force of the ropes adequately held fragments without adhesives, and the minimal surface area of rope nursery beds provided not only improved water flux around farmed corals, but also reduced proliferation of fouling organisms. The rope nursery prototypes studied here attest to the diversity of their potential uses under various conditions and demands, making the construction of large scale nurseries a very feasible target. This restoration instrument was proven to be an effective coral reef rehabilitation tool.

Questions this article answers: what is the design and performance of the rope nursery?

Methodology: two sets of experiments were conducted: the first tested two mid-water rope nursery prototypes in small-scale trials that tested depth, coral genotypes and construction stability, whereas the second set incorporated lessons learned from the first set, and was designed to carry larger numbers of colonies

Findings:

- Typically, a rope nursery is constructed of small coral fragments that are inserted into the coiling of a rope

- In the first set of experiments they studied nine genotypes taken from three coral species and in the second, 12 genotypes from four coral species (addition of P. damicornis) were used
- Restoration measures on denuded reef areas is hindered by lack of approved tools and methodologies for reef restoration and by the growing reef crisis,
    - The current best management tools employed in coral reefs worldwide have failed to achieve conservation objectives and the coral reefs continue to degrade
- This study presents such a novel instrument for reef restoration based on the 'gardening concept'- small coral fragments (about 4 cm long) are successfully developed into grown colonies in low-tech and economically feasible rope nursery
- The coiling force of the rope can hold fragments without adhesives as detachment values of branching and encrusting species have been lower than in other nursery prototypes
- The 'floating nursery' is the easiest and fastest to construct of all the tested prototypes, making it more favorable in sites with wide tidal amplitudes and in sheltered places with minor surface water movement
- In the 'tied to bottom' nursery, both species (M. digitata and M. scabricula) showed improved survivorship and growth rates in 3 m as compared to 1 and 4 m
- The minimal surface area of the rope nursery bed (merely made of ropes carrying coral fragments) provides good water flux around the farmed corals and reduced proliferation of fouling organisms, including algae and sedentary animals, allowing coral fragments to grow in all directions
- The rope nurseries are also more cost effective than all previously tested coral nurseries, because inserting fragments is more than 3-folds less expensive than the Red Sea mid-water prototype and more than 7-folds less expensive than the nearby previously studied 'suspended nursery'

Quotes:

"The simplicity of the rope nursery saves time and money on materials and labor and it makes the construction of large scale nurseries possible even in remote areas with limited material supplies and low budgets. Furthermore, this study shows that rope nurseries are emerged as coral management structures that enhance coral growth rates, improve water fluxes and reduce fouling proliferation, revealing potential uses in different condition-demands and site specifications."

Linden, B., & Rinkevich, B. (2011). Creating stocks of young colonies from brooding coral larvae, amenable to active reef restoration. ***Journal of Experimental Marine Biology and Ecology, 398*****(1-2), 40-46.**

Abstract: Coral reefs are declining worldwide, even though traditional reef practices continuously underlie reef protection. This calls for exploration and integration of novel restoration techniques and tools, such as the "gardening" concept. The gardening approach, which has been successfully applied in various reef sites worldwide, is based on farming coral stocks in mid-water nurseries. To date, the farming of asexually produced coral material has chiefly been studied. Here, we test the performance of a novel spat-stocking tool for planulae of Stylophora pistillata, a brooding coral species. Two prototypes of a new settlement apparatus and one original apparatus made of Petri dishes lined with preconditioned transparency (Mailer's paper) disks had been stocked with N3730 planulae. After 96 h, only 95.3% of N2080 settlers were found on the Mailer paper provided. One-month-old survivors (80.8% of initial settlements) that were kept ex situ in a flow through seawater table were detached from the papers, "transglued" onto plastic pins, and transferred to midwater coral nursery, where the trays were covered with fitted plastic nets (1 cm2 mesh) to prevent predation and detachment. Four months later, more than 89% survivorship was documented, with colonies starting to form 3D structures. We estimate that 676 person-hours would be required to create 10,000 5-month-old genotypes of equal size to small branch fragments. This novel methodology allows farming of large quantities of colonies originating from sexually produced planulae and may enhance local populations' genetic variability within a short period.

This method is inexpensive and easy to perform in remote places for incorporation in coral reef management practices.

Questions this article answers: Is the gardening approach successful for planulae of Stylophora pistillata, a brooding coral species? How does it react to the spat-stocking tool?

Methodology: case study: planulae of Stylophora pistillata

Findings:

- Applying "active" restoration methods to the already existing management measures might help restore otherwise denuded reefs or encouraging reefs towards natural recovery
- Used two apparati (treatments B and C) that are more efficient than the previously used apparatus (treatment A) for settling planulae of brooding coral species
- The B and C treatments are highly efficient in establishing coral spat stocking following a short settlement period
- Another benefit of the spat stocking methodology is the reduction of chimerism (fusion between different spats of the same species) and competition to which coral spats are exposed after collective settlement
    - Chimerism is a common outcome in spat aggregates and reduces the number of available individuals
- A short (one month) ex situ farming protocol prior to transferring the spat to nursery conditions yields not only high survivorship (89% in 4-month period) and fast growth rates (enhanced rates as compared to ex situ conditions; unpublished) but also reduced maintenance efforts
    - High survivorship is similar to the survivor values of S. pistillata nubbins under nursery conditions
- Together with farming of fragments and nubbins, it is possible to farm large quantities of sexually produced S. pistillata, for restocking genetic variation of local populations within a short period

Quotes:
"The above results refute the general assumption that sexually produced material, while being an invaluable tool for active reef restoration, is difficult to use in large restoration projects because it is time-consuming and costly to grow coral colonies from the larval stage. Whereas we successfully used a model brooder, hermaphroditic species, the applicability of the novel methodology on other brooder species has yet to be demonstrated."

Lybolt, M., Neil, D., Zhao, J., & et al. (2011). Instability in a marginal coral reef: The shift from natural variability to a human-dominated seascape. *Frontiers in Ecology and the Environment, 9*(3), 154-160.

Abstract: As global climate change drives the demise of tropical reef ecosystems, attention is turning to the suitability of refuge habitat. For the Great Barrier Reef, are there historically stable southern refugia where corals from the north might migrate as climate changes? To address this question, we present a precise chronology of marginal coral reef development from Moreton Bay, southeast Queensland, Australia. Our chronology shows that reef growth was episodic, responding to natural environmental variation throughout the Holocene, and that Moreton Bay was inhospitable to corals for about half of the past 7000 years. The only significant change in coral species composition occurred between ~200 and ~50 years ago, following anthropogenic alterations of the bay and its catchments. Natural historical instability of reefs, coupled with environmental degradation since European colonization, suggests that Moreton Bay offers limited potential as refuge habitat for reef species on human time scales.

Questions this article answers: For the Great Barrier Reef, are there historically stable southern refugia where corals from the north might migrate as climate changes?

Methodology: chronology of marginal coral reef development from Moreton Bay, southeast Queensland, Australia- historical study of range of bay impacts

Findings:

- Three notable patterns emerged from the 57 coral samples from Moreton Bay.
- Development of coral communities was episodic through time
- There was a depth-related shift through time, with younger corals observed at progressively deeper sites than older corals
- An abrupt change in coral dominance, from branching *Acropora* to massive *Favia* corals, occurred
- There was a significant negative correlation between coral age and water depth
- The only significant change in the composition of coral assemblages occurred between ~200 and ~50 years ago
- Bay-wide gradients in water quality did not structure the historical coral assemblages
- Over millennial time scales – natural reef growth in the bay was episodic and shifted toward deeper water
- Two ecosystem states – coral-dominated and non-coral-dominated – persisted on time scales from centuries up to about two millennia
- Relative to conditions in the tropics, the environmental conditions on subtropical marginal reefs include more extreme variations in light, temperature, salinity, aragonite saturation, and population connectivity
- The modern coral assemblage in Moreton Bay is dominated by massive *Cyphastraea, Favia*, and *Goniopora* spp
    - Unprecedented in historical record: dominated in all other times by branching *Acropora* cora
    - The shift suggests a mechanism between 1842 and 1956
    - European settlement began around 1824 and by 1880 the Brisbane River catchment was largely deforested, livestock numbered ~300 000, and soil depletion was cited as a serious concern by settlers
- Moreton Bay has poor refuge potential: it's highly sensitive to anthropogenic change; as a consequence of this sensitivity, the area currently supports few vibrant communities of branching *Acropora*, which are the dominant structural components of the GBR
    - The restriction of corals from the shallows is a non-linear response that dramatically reduced the quantity of substrate suitable for corals
    - This subtropical habitat was conducive to reef growth only about 50% of the time over the past 7000 years, and only once were reefs stable on millennial time scales

MacNeil, M. A., & Graham, N. A. J. (2010). Enabling regional management in a changing climate through bayesian meta-analysis of a large-scale disturbance. *Global Ecology and Biogeography, 19*(3), 412-421.

Abstract: Aim: Quantifying and predicting change in large ecosystems is an important research objective for applied ecologists as human disturbance effects become increasingly evident at regional and global scales. However, studies used to make inferences about large-scale change are frequently of uneven quality and few in number, having been undertaken to study local, rather than global, change. Our aim is to improve the quality of inferences that can be made in meta-analyses of large-scale disturbance by integrating studies of varying quality in a unified modelling framework that is informative for both local and regional management.

Innovation: Here we improve conventionally structured meta-analysis methods by including imputation of unknown study variances and the use of Bayesian factor potentials. The approach is a coherent framework for integrating data of varying quality across multiple studies while facilitating belief statements about the uncertainty in parameter estimates and the probable outcome of future events. The approach is applied to a regional meta-analysis of the effects of loss of coral cover on species richness and the abundance of coral-dependent fishes in the western Indian Ocean (WIO) before and after a mass bleaching event in 1998.

Main conclusions: Our Bayesian approach to meta-analysis provided greater precision of parameter estimates than conventional weighted linear regression meta-analytical techniques, allowing us to integrate all available data from 66 available study locations in

the WIO across multiple scales. The approach thereby: (1) estimated uncertainty in site-level estimates of change, (2) provided a regional estimate for future change at any given site in the WIO, and (3) provided a probabilistic belief framework for future management of reef resources at both local and regional scales.

Questions this article answers: What meta-analysis can be made about large-scale disturbances in a changing climate?

Methodology: integrated studies of varying quality in a unified modelling framework that is informative for both local and regional management; collected data from scientists for all available field studies conducted later than 1990 and prior to the 1998 coral bleaching event, reef surveys and fish surveys (case studies)

Findings:

- Corallivores are likely to decline in direct proportion to future losses in coral cover from bleaching throughout the WIO
    - This is a clearly defined threat to specific functional groups that may be critical in facilitating the resistance and resilience of their reef resources
- There appeared to be little relationship between the precision gains and model accuracy, but the reduced uncertainty among observations at the regional level support that the the regional-level inferences made through the Bayesian approach provide more precise estimators of the probability of future change at the regional level

- Bayesian approach to meta-analysis provided greater precision of parameter estimates than conventional weighted linear regression meta-analytical techniques
- Approach: estimated uncertainty in site-level estimates of change
    - Provided a regional estimate for future change at any given site in the WIO
    - Provided a probabilistic belief framework for future management of reef resources at both local and regional scales

Quotes:
"Although large-scale environmental degradation is difficult to predict, limited resources can be targeted more effectively by knowing which areas aremost likely to be hit with severely negative effects and how different components of the ecosystem will react. While these approaches have a high degree of uncertainty, they can provide governments with some understanding of the decisions most likely to be required in the future, making maximum use of the information available."

Manzello, D. P. (2010). Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific. *Coral Reefs*, *29*(3), 749-758.

Abstract: The rapid growth of scleractinian corals is responsible for the persistence of coral reefs through time. Coral growth rates have declined over the past 30 years in the western Pacific, Indian, and North Atlantic Oceans. The spatial scale of this decline has led researchers to suggest that a global phenomenon like ocean acidification may be responsible. A multi-species inventory of coral growth from Pacific Panama´ confirms that declines have occurred in some, but not all species. Linear extension declined significantly in the most important reef builder of the eastern tropical Pacific, Pocillopora damicornis, by nearly one-third from 1974 to 2006. The rate of decline in skeletal extension for P. damicornis from Pacific Panama´ (0.9% year-1) was nearly identical to massive Porites in the Indo- Pacific over the past 20–30 years (0.89–1.23% year-1). The branching pocilloporid corals have shown an increased tolerance to recurrent thermal stress events in Panama´, but appear to be susceptible to acidification. In contrast, the massive pavonid corals have shown less tolerance to thermal stress, but may be less sensitive to acidification. These differing sensitivities will be a fundamental determinant of eastern tropical Pacific coral reef community structure with accelerating climate change that has implications for the future of reef communities worldwide.

Questions this article answers: What are the differing sensitivities in eastern tropical Pacific coral reef community with accelerating climate change? What are the implications for future reef communities worldwide?

Methodology: Coral growth rates (skeletal extension, density, and calcification) were measured in six species over 2 years (2003–2004, 2005–2006) from the Uva Reef in the Gulf of Chiriquı´ of Pacific Panama

Findings:

- Coral mortality events illustrate an endpoint of the dynamics between reef construction and destruction, as they are usually followed by a decline in topographic complexity and can even result in the loss of framework structures
- Ocean acidification is the progressive decline in seawater pH due to the oceanic uptake of anthropogenic CO2
- Rapid growth of pocilloporid corals provides a competitive advantage for space on ecological timescales, while high skeletal density imparts a greater preservation potential on geologic timescales
    - Two species are dominant reef builders throughout the eastern tropical Pacific
- The rate of decline in skeletal extension for Pocillopora damicornis from Pacific Panama´ (0.9% year-1) is nearly identical to that reported for massive Porites in the Indo-Pacific over the past 20–30 years (0.89–1.23% year-1
- Edmunds (2007) found that juvenile corals in St. John grew at one-tenth to one-third the rate shown in historical investigations (C25 years prior) over a recent 9-year period (1996–2005).
    - This large discrepancy between historical and recent growth rates for juvenile corals is puzzling, but may indicate that the younger life stages of corals are particularly vulnerable to climate change stressors
- Pocilloporid corals at the Uva Reef had a lower prevalence of bleaching (loss of symbiotic algae due to high temperature) and mortality associated with the 1997–1998 El Nin˜o-Southern Oscillation (ENSO) relative to the 1982– 1983 event, despite a comparable amount of thermal stress
- If the frequency of thermal stress events increases or if temperatures surpass the optimal range for coral growth, warming would then act like a chronic disturbance and any associated growth declines would increase accordingly
- The growth and calcification of coral populations and reefs will decline from bleaching mortality, regardless of acidification (models only represent those individual corals that are able to survive the lethal effects of acute thermal stress)

Manzello, D. P., Kleypas, J. A., Budd, D. A., Eakin, C. M., Glynn, P. W., & Langdon, C. (2008). Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO2 world. *Proceedings of the National Academy of Sciences*, *105*(30), 10450-10455.

Abstract: Ocean acidification describes the progressive, global reduction in seawater pH that is currently underway because of the accelerating oceanic uptake of atmospheric CO2. Acidification is expected to reduce coral reef calcification and increase reef dissolution. Inorganic cementation in reefs describes the precipitation of CaCO3 that acts to bind framework components and occlude porosity. Little is known about the effects of ocean acidification on reef cementation and whether changes in cementation rates will affect reef resistance to erosion. Coral reefs of the eastern tropical Pacific (ETP) are poorly developed and subject to rapid bioerosion. Upwelling processes mix cool, subthermocline waters with elevated pCO2 (the partial pressure of CO2) and nutrients into the surface layers throughout the ETP. Concerns about ocean acidification have led to the suggestion that this region of naturally low pH waters may serve as a model of coral reef development in a high-CO2 world. We analyzed seawater chemistry and reef framework samples from multiple reef sites in the ETP and found that a low carbonate saturation state (_) and trace abundances of cement are characteristic of these reefs. These low cement abundances may be a factor in the high bioerosion rates previously reported for ETP reefs, although elevated nutrients in upwelled watersmayalso be limiting cementation and/or stimulating bioerosion. ETP reefs represent a real-world example of coral reef growth in low-_ waters that provide insights into how the biological–geological interface of coral reef ecosystems will change in a high-CO2 Cementation is the precipitation of secondary CaCO3 that acts
to bind framework components and occlude porosity world.

Questions this article answers: Can the eastern tropical Pacific serve as a model of coral reef development in a high- CO2 world?

Methodology: analyzed seawater chemistry and reef framework samples from multiple reef sites in the ETP

Findings:

- Low carbonate saturation site and trace abundances of cement are characteristic of ETP reefs
- Cementation is the precipitation of secondary CaCO3 that acts to bind framework components and occlude porosity
- When data were pooled and season was ignored, salinity, TCO2, TA, pH, and pCO2 were no different between Panamanian gulfs, yet temperature and _arag were significantly higher in the Gulf of Chiriquı´
- ETP reefs provide a real-world example of coral reef growth and development in low-_ waters.

- In turn, poorly cemented reef framework components are only held in place by a thin envelope of encrusting organisms, namely crustose coralline algae (CCA) and an organic matrix of sponges and other infauna
    - This point is important given that the geologic record suggests that encrustation by CCA is insignificant and subordinate to cementation in the construction and binding of framework structures
- Bioerosion rates in the Gala´pagos Islands and Panama´ are among the highest measured for any reef system to date
- In summary, this study suggests a link between _arag, inorganic reef cementation, and coral reef development in the ETP.
- These results will likely not apply to highly cemented coral reef frameworks that developed in high-_ seawater. Rather, this study implies that new reef development and accretion may be limited in a high-CO2 world

Maynard, J. A., Baird, A. H., & Pratchett, M. S. (2008). Revisiting the Cassandra syndrome; the changing climate of coral reef research. *Coral Reefs*, *27*(4), 745-749.

Abstract: Climate change will be with us for decades, even with significant reductions in emissions. Therefore, predictions made with respect to climate change impacts on coral reefs need to be highly defensible to ensure credibility over the timeframes this issue demands. If not, Cassandra syndrome could be created whereby future more well-supported predictions of the fate of reefs are neither heard nor acted upon. Herein, popularizing predictions based on essentially untested assumptions regarding reefs and their capacity to cope with future climate change is questioned. Some of these assumptions include that: all corals live close to their thermal limits, corals cannot adapt/acclimatize to rapid rates of change, physiological trade-offs resulting from ocean acidification will lead to reduced fecundity, and that climate-induced coral loss leads to widespread fisheries collapse. We argue that, while there is a place for popularizing worst-case scenarios, the coral reef crisis has been effectively communicated and, though this communication should be sustained, efforts should now focus on addressing critical knowledge gaps.

Questions this article answers: What are the critical knowledge gaps regarding the coral reef crisis? Have coral reefs really reached their thermal limits, and can they really not acclimitize?
The question is are they, like Cassandra, correct, or are these the false prophets that Grigg (1992) warned us of 15 years ago?

Methodology: literature review

Findings:

- First, we challenge the proposition that all coral species are living close to their upper thermal limit. Second, we point out that the data to determine whether corals can acclimatize or adapt to accelerating rates of environmental change are not available. Third, we argue that the experimental data do not yet exist to support suggestions that physiological trade-offs needed to cope with ocean acidification will lead to reduced reproductive potential. Last, we question whether ongoing climate-induced coral loss will cause fisheries to collapse
- Most pertinently, little is known about the sensitivity of population growth to climate-induced changes in vital rates

- A large body of evidence, however, supports temperature tolerance varying among species, populations, communities, and reef regions
- That corals lack the capacity to adapt to projected rates of environmental change is a hypothesis based on three key assumptions: (1) that generation times are too long to allow for adaptation over the required timeframes; (2) that the scale of dispersal is too large to allow for adaptation to local conditions; and, (3) that there is insufficient genetic diversity in existing symbionts and corals
- There is also strong evidence that coral populations are already locally adapted to specific environmental conditions, including temperature
    - While most corals have larvae capable of spending many months in the plankton, the actual dispersal distances are often in the order of 10 to 100 km
    - While coral bleaching can affect coral fecundity and egg quality, most surviving individuals of even highly susceptible species produce viable gametes following bleaching, ensuring thermal tolerance can pass between generations
- Acclimation through symbiont shuZing from less to more stress-resistant clades is another mechanism by which corals may increase the thermal tolerance of the holobiont.
    - Shifts in the patterns of association between host and symbiont may occur between generations in species which do not transmit symbionts in the gametes
- However, the extent to which changes in the structure of coral reef communities will affect ecosystem function, productivity and fisheries yields is far from certain
    - No studies have actually shown that total catch, catch composition, or fisheries value have been significantly affected by severe mass bleaching
- Declines in reef rugosity do not always occur, and depend on relative contributions of contemporary coral growth versus erosion of the underlying reef framework

Quotes:
"Effects of climate change on fisheries yields will have significant ramifications, especially in tropical countries that rely extensively on small-scale reef-based fisheries (Brander 2007). However, it is premature to suggest that widespread reef collapse is a certain consequence of ongoing bleaching, or that this will inevitably lead to fisheries

collapses."

McClanahan, T. R. (2008). Response of the coral reef benthos and herbivory to fishery closure management and the 1998 ENSO disturbance. *Oecologia*, *155*(1), 169-177.

Abstract: The hypothesis that herbivory is higher in areas without fishing and will increase the rate at which hard coral communities return to pre-disturbance conditions was tested in and out of the marine protected areas (MPA) of Kenya after the 1998 El Niño Southern Oscillation (ENSO). Herbivory was estimated by assay and biomass methods, and both methods indicated higher herbivory in fishery closures. Despite higher herbivory, the effect of the ENSO disturbance was larger within these closures, with reefs undergoing a temporary transition from dominance by hard and soft coral to a temporary dominance of turf and erect algae that ended in the dominance of calcifying algae, massive *Porites*, *Pocillopora* and a few faviids six years after the disturbance. The fished reefs changed the least but had a greater cover of turf and erect algae and sponge shortly after the disturbance. Higher herbivory in the fishery closures reduced the abundance and persistence of herbivore-susceptible erect algae and created space and appropriate substratum for recruiting corals. Nonetheless, other post-settlement processes may have had strong influences such that annual rates of coral recovery were low (»2%) and not different between the management regimes. Recovery, as defined as and measured by the return to predisturbance coral cover and the dominant taxa, was slower in fishery closures than unmanaged reefs.

Questions this article answers: How does higher herbivory in fish closures affect coral recovery? Are there differences between fishery closures and fished reefs?

Methodology: Direct method- sea grass soaked at sites and quantitatively measured bitten leaves. Indirect method- biomass of herbivorous fish and sea urchins were measured- herbivory was estimated as part of body weight

Findings:

- There were higher grazing rates by fishes in the unfished reefs by both measures of herbivory
- The biomass method- herbivory fish was nearly 30 times higher in unfished than fished areas
- Sea urchin herbivory was about five times higher in fished than unfished reefs by the biomass method (not statistically different by the herbivory assay method)
- Differences in the abundance and diversity of corals that are associated with fished and unfished management systems off the coastline of Kenya
- Hard coral cover is ~75% and coral diversity if 60% higher in unfished than fished reefs
- Recovery defined as regaining something lost or taken away (but can be measured many ways)

Quotes:

"MPAs in this region have the attribute of protecting a high diversity of species and their complex interactions, particularly those of corals and fish."

"The more diverse unfished reefs may maintain greater stability in the process of calcification, although not from hard corals alone, while the lower diversity fished reefs may exhibit community structure stability and return to their original state sooner."

McClanahan, T. R., Maina, J. M., & Muthiga, N. A. (2011). Associations between climate stress and coral reef diversity in the western indian ocean. *Global Change Biology, 17*(6), 2023-2032.

Abstract: Climatic–oceanographic stress and coral reef diversity were mapped in the western Indian Ocean (WIO) in order to determine if there were associations between high diversity coral reefs and regions with low-to-moderate climate stress. A multivariate stress model developed to estimate environmental exposure to stress, an empirical index of the coral community's susceptibility to stress, and field data on numbers of fish and corals taxa from 197 WIO sites were overlain to evaluate these associations. Exposure to stress was modeled from satellite data based on nine geophysical– biological oceanographic characteristics known to influence coral bleaching (i.e. temperature, light, and current variables). The environmental stress model and the coral community's susceptibility index were moderately correlated (r5_0.51) with southern and eastern parts of the WIO identified as areas with low environmental stress and coral communities with greater dominance of bleaching stress-sensitive taxa. Numbers of coral and fish taxa were positive and moderately correlated (r50.47) but high diversity regions for fish were in the north and west while diversity was highest for corals in central regions from Tanzania to northwestern Madagascar. Combining three and four of these variables into composite maps identified a region from southern Kenya to northern Mozambique across to northern–eastern Madagascar and the Mascarene Islands and the Mozambique–South Africa border as areas where low-moderate environmental exposure overlaps with moderate-high taxonomic diversity. In these areas management efforts aimed at maintaining high-diversity and intact ecosystems are considered least likely to be undermined by climate disturbances in the near term. Reducing additional human disturbances, such as fishing and pollution, in these areas is expected to improve the chances for their persistence. These reefs are considered a high priority for increased local, national, and international management efforts aimed at establishing coral reef

refugia for climate change impacts.

Questions this article answers: Are there associations between high diversity coral reefs and regions with low-to-moderate climate stress?

Methodology: uses measures of environmental stress and taxonomic richness, evaluating each of four variables separately and then combining them into a map based on the normalized layers.

Findings:

- Whereas highbiodiversity areas with high local human threats are considered a priority for conservation planning and reducing threats, climate change impacts are not locally manageable
- Prioritization is focused on identifying areas with low exposure to climate threats and managing to reduce local human impacts
- There is some potential refugia within the WIO but also weak and often conflicting associations between measures of environmental stress and diversity
- It is difficult to clearly identify locations that have all the attributes of high numbers of taxa for different threatened species assemblages and low environmental stress, which is a common problem for coral reef taxa
- Diversity measures suggest more fish diversity in the north and coral diversity at intermediate southern latitudes
- The impacts of climate change on corals will have indirect negative effects on coral reef fish, particularly coral-dependent and small-bodied species
    - These two groups are appropriate taxa for prioritizing climate change disturbances
- The region from southern Kenya to northern Mozambique across to Madagascar and the Mascarene Islands is a regional priority area for conservation based on the overlap in environmental stress and biodiversity measures
- The region is exposed to numerous local human use and threats, particularly widespread fishing but also agricultural and, to a lesser extent, urban runoff
- The most common recommendation to reduce climate change impacts is to reduce additional human disturbances through restrictions on fishing and improved watershed and waste management
- Coastal people in the WIO have a high dependency on marine natural resources, a high poverty level, and low institutional capacity to address adverse changes in the environment

McClanahan, T. R., Muthiga, N. A., & Coleman, R. A. (2011). Testing for top-down control: can post-disturbance fisheries closures reverse algal dominance? *Aquatic Conservation: Marine and Freshwater Ecosystems, 21*(7), 658-675.

Abstract: 1. The response of fish, sea urchins, benthic cover, herbivory, and predation on sea urchins were studied over a 14-year period in and out of a recently established fully closed and fished atoll reef lagoon of the remote Glover's Reef, Belize.
2. Closure from fishing was predicted to result in the recovery of predatory fish and herbivores, herbivory rates, and subsequently reduce erect algae and lead to the recovery of herbivore resistant and calcifying taxa such as hard corals and calcifying algae. Recovery of predatory fishes was the largest response to closure and the herbivore response was weak and no corals and calcifying algae changed in the predicted direction.
3. Hard corals declined where they weremost abundant and all sites appear to have reached a stable point of ~15% cover by the end of the study. Generalized and possibly opportunistic carnivores, such as jacks, barracuda, groupers, snappers, grunts, and sparids showed the greatest increases and there was a trend towards more small-bodied herbivores such sea urchins and damselfish in the open and a slight gain in large herbivores in the closed area, but this had little effect in increasing total herbivory.
4. Factors that may have influenced this unexpected response include: (1) a complex food web that did not produce a simple cascade response; (2) attenuation of the cascade effect towards the lower trophic levels; (3) insufficient compliance, closure time, and space; (4) a post- rather than pre-disturbance establishment of the closure; 5) habitat or site specificity; and (6) overriding environmental disturbances, such as oceanographic oscillations and a warming climate.
5. The results suggest a need to further evaluate fisheriesmanagement systems, contingencies, and interventions that will promote coral reef resilience to climate change and ecosystem sustainability.

Questions this article answers: What are the results of closing a fishing site completely (Glover's Reef, Belize) on fish, sea urchins, benthic cover, and predation on sea unrchins> Does this reduce algal dominance? How effective is top-down control in this scenario?

Methodology: Field data collection occurred over a 14-year period on eight patch reefs, divided equally between the two management zones that were repeatedly but episodically sampled across years with sampling always undertaken between May and July. Benthic substratum measurements were completed 10 times while sea urchin and fish densities and predation and herbivory assays were undertaken 8 to 10 times between1996 and 2009.

Water temperature, water flow, and water quality measurements (nutrients concentrations) were taken during the middle of the survey to test for possible differences between the two management zones.

Fisheries catch data from the Glover's reef atoll were compiled from a monitoring programme designed to determine trends in landings and fishing pressure at the atoll

Findings:

- Physico-chemical results: average daily water temperatures ranged from 21 C in December/January to 31 C in September/October and did not differ significantly between the two management zones although temperature varied more in the Conservation than in the General Use zone
- Coral reef fish abundance: the overall abundances of finfish depended on the trophic groups, the family and the species of fish
    - In general, the larger-bodied carnivorous species including piscivores (jacks, barracuda, groupers, and trumpetfish), and sea urchin predators (mostly porgies and hogfish) showed significantly higher abundances in the Conservation than the General Use zone and increased significantly over the sampling period
    - Total herbivore numbers were not different between zones, and small herbivores showed a general decline over time in both zones and were more abundant in the General Use zone
- Sea urchins and predation: Within each patch reef, rates of predation on tethered E. viridis were generally low (<35% eaten) but significantly higher along the deeper than shallower transects
    - Predation rates increased quickly in the Conservation zone after 1996 then slowly decreased between 1998 and 2004 and increased again until 2009
- Herbivory: The two management zones had similar levels of herbivory during the initial part of the study (~20%) and appeared to track each other over time.
- Benthic substratum: erect fleshy algae (~46%) dominated the benthic cover followed by hard coral (~17%), turf algae, red coralline, and green calcareous algae (9%, 8%, 5% respectively) while sand, sponge, and seagrass were<6% of the substratum cover
    - Hard coral cover on the other hand showed a weakly significant decline in

the Conservation zone; most of this occurred between 1998 and 2001

- The development of areas closed to fishing is likely to be one of the primary management tools that can potentially reverse or rehabilitate reefs that have undergone the reported ecological change in the Caribbean and elsewhere
- The trophic cascade and herbivore-control model could help local management of what are, at a minimum, regional-, but largely global-level changes associated with some combination of warming sea water, increased disease, declining consumers and herbivores, and strong oceanographic oscillations
- Fisheries closures have the potential for improved management and resilience to climate disturbances but empirical tests at the appropriate scale and against but alternative hypotheses are needed before the recommendation can be broadly supported.

McCormick, M. I., Moore, J. A. Y., & Munday, P. L. (2010). Influence of habitat degradation on fish replenishment. *Coral Reefs, 29*(3), 537-546.

Abstract: Temperature-induced coral bleaching is a major threat to the biodiversity of coral reef ecosystems. While reductions in species diversity and abundance of fish communities have been documented following coral bleaching, the mechanisms that underlie these changes are poorly understood. The present study examined the impacts of coral bleaching on the early life-history processes of coral reef fishes. Daily monitoring of fish settlement patterns found that ten times as many fish settled to healthy coral than sub-lethally bleached coral. Species diversity of settling fishes was least on bleached coral and greatest on dead coral, with healthy coral having intermediate levels of diversity. Laboratory experiments using light-trap caught juveniles showed that different damselfish species chose among healthy, bleached and dead coral habitats using different combinations of visual and olfactory cues. The live coral specialist, Pomacentrus moluccensis, preferred live coral and avoided bleached and dead coral, using mostly visual cues to inform their habitat choice. The habitat generalist, Pomacentrus amboinensis, also preferred live coral and avoided bleached and dead coral but selected these habitats using both visual and olfactory cues. Trials with another habitat generalist, Dischistodus sp., suggested that vision played a significant role. A 20 days field experiment that manipulated densities of P. moluccensis on healthy and bleached coral heads found an influence of fish density on juvenile weight and growth, but no significant influence of habitat quality. These results suggests that coral bleaching will affect settlement patterns and species distributions by influencing the visual and olfactory cues that reef fish larvae use to make settlement choices. Furthermore, increased fish density within the remaining healthy coral habitats could play an important role in influencing population dynamics.

Questions this article answers: what are the mechanisms underlying the reduction in species diversity and abundance of fish communities after coral bleaching? What is the impact of coral bleaching on the early-life history processes of coral reef fishes?

Methodology: study conducted at Lizard Island (northern GBR); damselfish species monitored for settlement- 20 day field experiment that manipulated densities of P. moluccensis on healthy and bleached coral heads

Findings:

- With the increase of CC- sensory cues that were once reliable indicators of habitat quality will become less dependable, thereby ‘trapping’ animals in sub-optimal habitats
- Selecting a suitable habitat at the end of the larval stage is critical to postsettlement survival and success for coral reef fishes
- Habitat choice was mediated by sensory mechanisms, which enable individuals to discriminate between habitat patches in different biological condition
- Changes in coral health may strongly impact fish communities through the modified recruitment of fishes that target live coral and that density-dependent processes may play an important role in influencing the dynamics on remnant patches of live coral
- It’s likely that larvae will increasingly encounter bleached corals at settlement.
    - Could lead to increased settlement to patches of live coral compared with nearby bleached coral
- The cost of inhabiting bleached coral may only be realised for P. moluccensis if the coral dies
- Recovery and resilience of fish populations following major coral bleaching episodes may in part depend on the flexibility of individuals in choosing settlement habitat

McKoy, H., Kennedy, D. M., & Kench, P. S. (2010). Sand cay evolutino on reef platforms, mamanuca islands, fiji. ***Marine Geology, 269*****(1-2), 61-73.**

Abstract: The sedimentary link between reef islands and their surrounding platforms is critical to understand if the morphological response of these systems to future boundary condition changes such as associated with human-induced climate change is to be understood. The sand cays of the Mamanuca Islands in Fiji are an ideal system to investigate this link between reef and the islands that have developed on them. The Mamanuca's are a relatively simple sedimentary system being characterised by oval shaped platform reefs with a relatively uniform and horizontal reef crest and flat. Nine islands were investigated within the group through GPS and auto level surveying, with associated surface and subsurface sediment sampling. The islands are composed of a typical chlorozoan sediment assemblage which is well mixed across each reef and island. This mixing is related to the high transport capacity across the reef platforms with waves able to move sediment for at least 50% of the tidal cycle. Radiocarbon dating indicates the islands are young, with modern ages returned on sand from the reef flat and ages of 500–600 years CalBP from the island beaches. Dating from the centre of the islands at 2 m depth indicate island formation was occurring from at least 2260–2110 years CalBP. The young age of the sediments combined with the high transport potential suggests each cay is linked to the contemporary reefs that the islands are developed on. It is inferred that the islands in the Mamanuca Group initially started as a subtidal gravel accumulation. Once wave energy is dissipated enough intertidal sands start to accumulate and eventually the islands reach a critical size where vegetation may colonise. The contemporary development of the reef islands in the Mamanuca's and their links to sediment production on the reef flat suggests that they may be able to adjust their morphology to future environmental conditions

Questions this article answers: what is the sedimentary link between reef islands and their surrounding platforms? How is this connected to boundary condition changes as human-induced climate change increases?

Methodology: Field investigations were undertaken on 9 sand/gravel cays in the Mamanuca Island group, Fiji, in January 2006

Findings:

- Coral islands are known to be morphologically sensitive to shortterm extreme events (e.g. storms and cyclones) and to longer term changes in wave climate
    - There is significant global concern over the physical vulnerability of reef islands in response to climatic change including sea-level rise and increased storminess
- In contrast on the mainland coast of Viti Levu extensive fringing reefs are found which are exposed at low tide
- The variation in sediment composition is greatest between each reefisland rather than between each biosedimentary zone on an individual reef
- The island surfaces in the Mamanuca's are young, all with an age of <700 years BP
- While bulk dating indicated island accretion occurred in a discrete phase between 4000–2500 years ago, component specific dating implies a continual sand accumulation over the past 3000 years.
- The evolution of the islands within the Mamanuca Island group is a recent process occurring after the mid Holocene sea-level highstand.
- Their evolution must be related to a combination between sediment supply and energy available for transport. Smaller reefs may not be able to accumulate sediment as wave energy remains high across the entire platform
- They may be very sensitive to environmental change as any perturbation to the reefs ability to produce sediment will immediately affect the islands

McLeod, E., Moffitt, R., Timmermann, A., & et al. (2010). Warming seas and the coral triangle: Coral reef vulnerability and management implications. *Coastal Management, 38*(5), 518-539.

Abstract: The highest diversity coral reefs in the world, located in the Coral Triangle, are threatened by a variety of local stresses including pollution, overfishing, and destructive fishing in addition to climate change impacts, such as increasing sea surface temperatures (SSTs), and ocean acidification. As climate change impacts increase, coral reef vulnerability at the ecoregional scale will have an increasingly important influence on conservation management decisions. This project provides the first detailed assessment of past and future climatic stress, thermal variability, and anthropogenic impacts in the Coral Triangle at the ecoregional level, thus incorporating both local (e.g., pollution, development, and overfishing) and global threats (increasing SSTs). The development of marine protected area (MPA) networks across the Coral Triangle is critical for the region to address these threats. Specific management recommendations are defined for MPA networks based on the levels of vulnerability to thermal and local stress. For example, coral reef regions with potentially low vulnerability to thermal stress may be priorities for establishment of MPA networks, whereas high vulnerability regions may require selection and design principles aimed at building resilience to climate change. The identification of climate and other human threats to coral reef systems and ecoregions can help conservation practitioners prioritize management responses to address these threats and identify gaps in MPA networks or other management mechanisms (e.g., integrated coastal management).

Questions this article answers: what are past and future climatic stresses, thermal variability, and anthropogenic impacts in the Coral Triangle at the ecoregional level?

Methodology: literature review (detailed assessment); Coupled general circulation models (CGCMs) are commonly used to simulate the climate system and its response to past and future perturbations; a thermal stress index

Findings:

- Even if corals are able to adapt to increasing SSTs, it is uncertain whether their adaptation could keep pace with the rate and scale of future climate change
- Local scale thermal variability is unpredictable due to the influences of water column stratification, alongshore currents and their interaction with the shelf break, and local topography, and is not well captured in SST data
- Adaptive management approach promotes flexible decision-making and supports managers in taking immediate actions using the best available information while allowing for refinements through an iterative learning process
- Through a multilateral partnership called the *Coral Triangle Initiative* (CTI), the six governments of the Coral Triangle countries have committed to protect the region's marine resources by establishing resilient networks of MPAs
    - BUT less than 5% of all ecoregions, including both reef and non-reef areas, are protected in MPAs and more will need to be established and incorporated in networks
- Strategies that facilitate coral reef recovery following bleaching events- maintain herbivores, water quality, and access to coral recruits
- Need to monitor the cumulative effects of multiple stressors, both local and climatic, in these areas
- Areas with high thermal vulnerability but low vulnerability to human activities- focus on the rigorous application of resilience principles to MPA network design, especially the identification and protection of bleaching resistant coral communities
- Ecoregions with a wide range in annual temperature may have corals that are acclimated to deal with thermal stress.
    - It's important to monitor the impacts of coral bleaching events and recovery following these events to determine if some coral species or reef areas are more resistant or resilient to climate change impacts
- This analysis suggests that the Palawan/North Borneo ecoregion may be a good area for future investment in coral reef conservation, assuming that protection is directed at low risk areas

Quotes:
"Factors such as high biodiversity combined with high levels of recruitment and fast rates of growth and recovery are likely to help coral reefs in the Coral Triangle survive climate change longer than areas that lack these attributes. Reef areas in the region that exhibit slower rates of change in temperature and acidity may provide refuges and larval sources to help damaged areas recover following mass bleaching events. Ensuring that these refuges are included in MPAs is a priority to protect the future of coral reefs in the region."

McMurray, S. E., Blum, J. E., Leichter, J. J., & Pawlik, J. R. (2011). Bleaching of the giant barrel Spong Xestospongia muta in the florida keys. ***Limnology and Oceanography, 56*****(6), 2243-2250.**

Abstract: The giant barrel sponge Xestospongia muta is now the dominant habitat-forming organism on many Caribbean coral reefs and has been observed to undergo cycles of bleaching similar to those seen for reef-building corals. We examined bleaching of X. muta at 15-m, 20-m, and 30-m depths over 2000–2005 on Conch Reef, Key Largo, Florida, to determine the spatial and temporal patterns of bleaching, whether bleaching affected sponge mortality, and whether there was a relationship between bleaching and seawater temperatures. Bleaching increased significantly with depth and was greater in autumn than spring, but the response was not uniform across the sponge population. Bleaching of X. muta did not result in sponge mortality, corroborating the conclusion that cyanobacterial symbionts of the sponge provide little or no benefit to the host. There was greater sponge bleaching with higher minimum daily seawater temperature anomalies within 30 d of surveys in the spring. For both the spring and autumn, there was greater bleaching with a higher number of positive 0.5uC daily anomalies within 14 d before surveys. Anomalously warm seawater temperatures fail to completely explain the variability of the observed bleaching response, however, and additional work would be required to conclusively determine whether a causal relationship between bleaching and temperature exists. As has been described for corals, bleaching of X. muta is likely a complex response that may be affected by multiple factors, including light availability and differences in bleaching susceptibility among Synechococcus symbionts.

Questions this article answers: what are the spatial and temporal patterns of bleaching? Does bleaching affect sponge mortality? Is there a relationship between bleaching and seawater temperatures?

Methodology: case study of giant barrel Spong Xestospongia muta: examined bleaching at 15 m, 20m, and 30m (depth) between 2000-2005. Three permanent 16-m-diameter circular plots were established at 15-m, 20-m, and 30-m depths. Within each plot, each sponge was mapped and given a unique tag on a masonry nail driven next to the base of the sponge. Surveys were conducted in the spring and autumn of every year (generally May and Oct, respectively), but due to inclement weather, surveys were not conducted in the autumn of 2000 and the spring of 2004 at the 20-m and 30-m sites

Findings:

- Bleaching of X. muta was observed in both the spring and autumn of every year surveyed. Across all years, spotted bleaching of sponge tissue was most prevalent, while severe bleaching was the least common form of bleaching at each depth
- There was a large range in bleaching across years and between seasons
- For all depths collectively, bleaching was greatest in the autumn of 2003, and lowest in the spring of 2001
    - Bleaching was significantly greater in the autumn compared to the spring for all depths
- Bleaching significantly increased with depth on Conch Reef, but this relationship varied with season.
    - In the autumn, significantly more bleaching occurred at 30 m compared to 20 m bleaching did not differ between 15-m and 20-m depths
    - In the spring, bleaching was significantly greater at 30 m compared to 15 m and 20 m compared to 15 m but bleaching did not differ between 30-m and 20-m depth
- There was no significant effect of bleaching on sponge mortality. Bleached sponges were regularly observed to survive bleaching and regain their normal pigmentation in subsequent field seasons
- Corals from all depths experienced seasonal changes in algal densities, with lowest algal densities experienced in the late summer or autumn and highest densities during the coldest part of the year (but coral bleaching isn't always visually obvious)
    - In contrast, bleaching of X. muta was observed in both the spring and autumn of every year, and is commonly observed throughout the year
    - Bleaching of X. muta observed to increase with increasing depth (in contrast with typical bleaching patterns)
- Decreased light intensity has been shown to reduce cyanobacterial abundance in X. muta and may partially explain why bleaching is greater at depth
- In contrast to reef-building corals, bleaching did not result in mortality of X. muta
- There was a significant correlation between anomalously warm seawater temperatures and bleaching of X. muta
- In conclusion, bleaching of X. muta was greatest in the autumn compared to spring, and increased with depth on Conch Reef
- Bleaching also appears to be a cyclic response by the cyanobacteria symbionts of X. muta that has no negative effect on the host sponge
- These findings suggest that bleaching is correlated with anomalously warm seawater temperatures characterized by decreases in the magnitude and duration of persistent cold-water intrusions on Conch Reef

Melbourne-Thomas, J., Johnson, C. R., Alino, P. M., & et al. (2011). A multi-scale biophysical model to inform regional management of coral reefs in the western philippines and south china sea. ***Environmental Modelling and Software, 26*****(1), 66-82.**

Abstract: The health and functioning of coral reef ecosystems worldwide is in decline, and in the face of increasing anthropogenic stress, the rate of decline of these important ecosystems is set to accelerate. Mitigation strategies at regional scales are costly, but nevertheless critical, as reef systems are highly connected across regions by ocean transport of both larval propagules and pollutants. It is essential that these strategies are informed by sound science, but the inherent complexity of coral reef systems confers significant challenges for scientists and managers. Models are useful tools for dealing with complexity and can inform decision making for coral reef management. We develop a spatially explicit biophysical model for a general coral reef system. The model couples dynamics from local (102 m) to regional (106 m) scales, and explicitly incorporates larval connectivity patterns derived from sophisticated larval dispersal models. Here, we instantiate and validate the model for coral reefs in the Philippines region of the South China Sea. We demonstrate how the model can be used in decision support for coral reef management by presenting two examples of regional-scale scenario projection relating to key management issues in the Philippines: (i) marine reserve design and the recovery of fish stocks; and (ii) synergistic effects between coral bleaching and poor water quality. These scenarios highlight the importance of considering multiple stressors to reef health and patterns of larval connectivity in regional-scale management decisions.

Questions this article answers: How can complex mitigation models be utilized for scientists and managers to make informed management decisions?

Methodology: Developed spatially explicit biophysical model for a general coral reef system: coral reefs in the Philippines region of the South China Sea

Findings:

- Resource managers require tools that can capture the multi-level complexity of both biophysical processes and human activities that affect coral reef systems, but at the same time are accessible and simple to use and interpret.
- Examining sourcee-sink relationships through the use of larval dispersal

simulations can provide important information for coral reef-management at subregional and regional scale

- Study has two examples of scenario testing that demonstrate how CORSET can be used to inform management responses to threats to reef health in the PSCS region
- In our first example we used patterns of larval connectivity to inform marine reserve placement
    - While marine reserves can contribute to effective fisheries management (and undeniably provide a range of other benefits such as biodiversity reservoirs and scientific baselines) alternative, complementary management approaches outside reserves are important to achieve sustainable harvesting of coral reef (and many other) fisheries
- In our second example we demonstrated that the modeled effects of low water quality can reduce reef resilience to coral bleaching events at a regional scale. In reality, issues of coral bleaching risk and water quality management are also likely to inform marine reserve design.
- Simulation models such as CORSET are a way to assess the effects of individual and combined stressors and disturbances and to evaluate different options for management in the light of combined effects
- In considering reef futures under climate change scenarios, potential effects of ocean acidification on reef accretion and stability are important
    - Should use CORSET model along with other natural resource management strategies

Melbourne-Thomas, J., Johnson, C. R., & Fulton, E. A. (2011). Regional-sclae scenario analysis for the meso-american reef system: Modelling coral reef futures under multiple stressors. *Ecological Modelling, 222*(10), 1756-1770.

Abstract: Coral reefs worldwide are under threat from a wide variety of stressors and disturbances, many of which act in a synergistic manner to affect reef health. The future of coral reef ecosystems at local, regional, and global scales is highly uncertain, which poses a challenge to decision makers in designing appropriate strategies for managing human activities that affect reef resilience. Scenario analysis using simulation models can inform decision making be exploring possible futures under alternative management frameworks. Here, we use a spatially explicit, regional-scale simulation model for coral reefs in the Meso-American Reef system to explore the effect of multiple stressors and disturbances on reef state. Two complimentary approaches to scenario analysis help to characterize potential reef responses to the combined impacts of climate and land-use change in the Meso-American Reef region. Sedimentation and nutrification emerge as key factors in decreasing the resilience of reef systems to climate change effects. The average community composition of degraded reef systems exposed to high levels of stress and disturbance tens to be more predictable than community composition on reefs that are subject to lower levels of stress and disturbance because degraded reefs tend to a common composition. This observation applies at both subregional and regional scales and reflects a finite bound to the effects of degradation on coral reef communities.

Questions this article answers: How should decision makers go forth in designing appropriate strategies for managing human activities that affect reef resilience?

Methodology: scenario analysis using simulation models (explores possible futures under alternative management frameworks)

Findings:

- CORSET is a spatially explicit simulation model that couples eco- logical dynamics from local scales (102 m) to regional scales (106 m) through ocean transport of larvae
- Under best-case scenarios for climate change impacts- coral bleaching mortality would occur with a long-term frequency of once a decade; hurricanes (categories 1-5) to occur with long-term frequency of once every 20 yrs

- Under worst-case scenario- coral bleaching mortality to occur with once every five years; intense hurricanes (categories -5) to occur with a long-term frequency of once every 20 years
- Importantly, reduction of terrestrial run-off is a possible management lever in the MAR
- Management actions could include replanting mangroves to trap sediment, maintaining vegetative barriers along waterways, and building terraces to reduce soil erosion
- In our four scenarios for land-use and climate change, we saw increased dispersion in community composition at regional and subregional scales under regulated land-use scenarios where the impacts of nutrification and sedimentation were low
- This result could potentially be interpreted as enhanced adaptive capacity of reef communities to climate change effects when multiple stres- sors are managed at subregional and regional scales. However, the relationship between predictability of modelled reef states and adaptive capacity requires further examination beyond the scope of this study.

Mellin, C., Huchery, C., Caley, M. J., & et al. (2010). Reef size and isolation determine the temporal stability of coral reef fish populations. *Ecology, 91*(11), 3138-3145.

Abstract: Temporal variance in species abundance, a potential driver of extinction, is linked to mean abundance through Taylor's power law, the empirical observation of a linear log–log relationship with a slope between 1 and 2 for most species. Here we test the idea that the slope of Taylor's power law can vary both among species and spatially as a function of habitat area and isolation. We used the world's most extensive database of coral reef fish communities comprising a 15-year series of fish abundances on 43 reefs of Australia's Great Barrier Reef. Greater temporal variances were observed at small and isolated reefs, and lower variances at large and connected ones. The combination of reef area and isolation was associated with an even greater effect on temporal variances, indicating strong empirical support for the idea that populations on small and isolated reefs will succumb more frequently to local extinction via higher temporal variability, resulting in lower resilience at the community level. Based on these relationships, we constructed a regional predictive map of the dynamic fragility of coral reef fish assemblages on the Great Barrier Reef.

Questions this article answers: Can the slope of Taylor's power law can vary both among species and spatially as a function of habitat area and isolation?

Methodology: Between 1992 and 2006, reef communities of the GBR have been monitored yearly by the Australian Institute of Marine Science's (AIMS) Long Term Monitoring Program; fish communities have been surveyed on 48 reefs in six sectors.

Findings:

- For 18 fish species of the Great Barrier Reef, smaller reef area and greater reef isolation were associated with greater temporal variance in abundance
- These patterns suggest a hierarchy of drivers of the temporal stability of fish assemblages: life-history characteristics of species such as body size interplay with influences like spatial arrangements and sizes of reefs
- Small-bodied fish species probably dominate bundances and exhibit higher temporal variation because small body size is often associated with reduced longevity, early maturity and high mortality

- Immigration to isolated reefs should occur less often and be more variable in size than on better connected reefs.
- Small reefs might also be subject to greater fluctuations in abundance because smaller areas support fewer species. among which strong interactions are assumed to elicit high temporal variation in an individual species' population dynamics
- Population dynamics on larger and more connected reefs are probably affected by a greater number of species interlinked by relatively weaker interactions, including competition and predation
- Fish assemblages associated with small and isolated reefs have been slower to recover from habitat loss caused by major disturbances than fish assemblages on larger, more connected continental reefs

- Small and isolated reefs might thus be more susceptible to climate change-driven degradation than continental reef systems where larval replenishment from less-impacted reefs is more likely

Quotes:
"Our results therefore support the idea that small and isolated reefs are more susceptible to local species extinctions because of the inherent tendency for their resident populations to be more variable, and slower to recover from disturbance because of low and variable immigration."

Mumby, P. J., & Steneck, R. S. (2008). Coral reef management and conservation in light of rapidly evolving ecological paradigms. *Trends in ecology & evolution*, *23*(10), 555-563.

Abstract: Decades surprised experienced managers and researchers. It shattered old paradigms that these diverse ecosystems are spatially uniform and temporally stable on the scale of millennia. We now see reefs as heterogeneous, fragile, globally stressed ecosystems structured by strong positive or negative feedback processes. We review the causes and consequences of reef decline and ask whether management practices are addressing the problem at appropriate scales. We conclude that both science and management are currently failing to address the comanagement of extractive activities and ecological processes that drive ecosystems (e.g. productivity and herbivory). Most reef conservation efforts are directed toward reserve implementation, but new approaches are needed to sustain ecosystem function in exploited areas.

Questions this article answers: What are the causes and consequences of reef decline? Are management practices addressing the problems at appropriate scales?

Methodology: literature review

Findings:

- Coral reefs are among the most diverse and productive ecosystems on Earth. They are the world's largest biogenic structures and the only such structure visible from space. Coral reefs are also perhaps the most globally endangered of ecosystems.
- For management to move forward, it must assimilate the ever-growing body of scientifically relevant information, and adapt efforts toward the evolving best practices
- The 1970s (i.e. 58%) focused on patterns of diversity and habitat use, most citations in the 1980s and 1990s focused on explanatory processes such as reproduction, recruitment, herbivory and predation. Disturbances of reef ecosystems (primarily due to disease and bleaching but also overfishing) became the hot new topics of the 1990s, garnering 35% of the citations in that decade. Since 2000, 85% of citations have focused on those disturbances, but with overfishing now leading the list.
- The relative importance of nutrients versus herbivory in driving phase shifts in coral community structure has been one of the most divisive issues in reef science
- Indeed, experimental evidence that algal blooms can occur if herbivory is reduced

is unequivocal, even though specific algal responses vary among studies

    - Herbivory is an area-specific rate (i.e. proportion of grazable substrate grazed per unit time) and therefore sudden changes to the area of grazable substrate will strongly impact grazing intensity (at least until herbivores can respond by altering their population density). This is a critical concept, because the rapid die-off of coral or other algal-suppressing substrates can greatly increase substrate availability to grazers and therefore facilitate algal blooms by inadvertently reducing the intensity of herbivory and providing new opportunities for macroalgae to escape predation.

- Reductions in coral cover, as a result of bleaching, have strongly reduced the abundance and diversity of fishes that have a direct obligate dependence on live coral for settlement habitat or food
- Today, however, the phenomenon of habitat loss is occurring at such large scales (thousands of kilometres) that it might encompass most subpopulations of a metapopulation and therefore reduce population stability.
- Many reef fish undertake developmental migrations from lagoonal habitats (mangroves and seagrass beds) where they settle as larvae to coral reefs where they live as adults.
- But how should living corals be managed? The largest-scale and arguably most severe problems facing corals relate to climate change, which has no direct local or short-term management solution
- To date, the vast majority of efforts have focused on the implementation of marine reserves (Table 1). Reserves do indeed play important roles (Table 2), but reserves alone are inadequate for 'confronting the coral reef crisis' at an appropriate scale.
    - Coral bleaching is an acute radiative stress caused by elevated temperature, and it is unreasonable to expect that a cessation in fishing will influence such physical stress, particularly when thermal climatologies have never been incorporated explicitly into reserve design.
    - The role of reserves is usually to reduce biological stress rather than physical stress (although pollution is more likely to be controlled within reserves than elsewhere).
- Reef fisheries management has focused on the sustainability of harvested species and usually ignored the impacts of harvesting on the ecological processes that drive the ecosystem (including providing habitat for various fisheries species).
- Recent research suggests that exploitation-related degradation and the seeds of recovery can and should be managed locally.

Munday, P. L., Leis, J. M., Lough, J. M., Paris, C. B., Kingsford, M. J., Berumen, M. L., & Lambrechts, J. (2009). Climate change and coral reef connectivity. *Coral Reefs*, *28*(2), 379-395.

Abstract: This review assesses and predicts the impacts that rapid climate change will have on population connectivity in coral reef ecosystems, using fishes as a model group. Increased ocean temperatures are expected to accelerate larval development, potentially leading to reduced pelagic durations and earlier reef-seeking behaviour. Depending on the spatial arrangement of reefs, the expectation would be a reduction in dispersal distances and the spatial scale of connectivity. Small increase in temperature might enhance the number of larvae surviving the pelagic phase, but larger increases are likely to reduce reproductive output and increase larval mortality. Changes to ocean currents could alter the dynamics of larval supply and changes to planktonic productivity could affect how many larvae survive the pelagic stage and their condition at settlement; however, these patterns are likely to vary greatly from place-to-place and projections of how oceanographic features will change in the future lack sufficient certainty and resolution to make robust predictions. Connectivity could also be compromised by the increased fragmentation of reef habitat due to the effects of coral bleaching and ocean acidification. Changes to the spatial and temporal scales of connectivity have implications for the management of coral reef ecosystems, especially the design and placement of marine-protected areas. The size and spacing of protected areas may need to be strategically adjusted if reserve networks are to retain their efficacy in the future.

Questions this article answers: What are the impacts of rapid climate change on population connectivity in coral reef ecosystems?

Methodology: case study of fish as model organisms to understand connectivity between fish populations; modeling to understand changes in ocean currents

Findings:

- Population connectivity is a whole-of-life process that depends on adults producing eggs and larvae that disperse between patchily distributed populations and the survival of those offspring in the new population until they breed and reproduce
- Predicting how climate change will affect connectivity in coral reef ecosystems is important because dispersal of larvae between reefs is a key component of population dynamics for most coral reef organisms
- Understanding the scale of connectivity is also an important consideration for

designing effective networks of marine-protected areas (MPAs) and managing coral reef fisheries

- Changes to ocean circulation could also influence population connectivity through impacts on ocean productivity. Increased thermal stratification of the ocean surface layer is expected to reduce the mixing of cool nutrient-rich waters from below the thermocline into warmer surface waters, with consequences for the productivity and structure of plankton communities that are food for the larvae of most coral reef
- organisms.
- Experiments have also shown that growth and skeletal calcification of some invertebrate larvae is reduced at CO2 concentrations predicted to exist by 2100
    - Disrupted skeletal development has the potential to affect the survival and dispersal patterns of larvae of susceptible species. In addition to affecting calcification rates, increased levels of dissolved CO2 and reduced pH could potentially affect the reproductive success or physiological performance of some marine larvae
- Cyclones are short-duration events that could affect the localized dispersal patterns and survival probability of coral reef larvae, but which are unlikely to affect dispersal at most other times or places
- Climate change will alter patterns of population connectivity on coral reefs; at the same time the patterns of connectivity between populations will influence the ability of coral reef organisms to adapt to rapid climate change
- The optimal size and spacing of protected areas should differ between networks established for fisheries purposes (where the goal is to maximize recruitment into non-reserve areas) versus biodiversity conservation (where the goal is to maximize recruitment of many species within and between reserve areas)

Quotes:
"It is clear that climate change could alter patterns of population connectivity of coral reef organisms through a range of effects on adult and larval life stages. However, we are still a long way from predicting the significance of these effects for the sustainability of reef fish populations. There are major gaps in our knowledge about how the tropical marine climate will change, how fishes and other organisms will respond to these changes and the relative magnitude of these changes in comparison to existing variation in patterns of population connectivity." 395

Munday, P. L., Crawley, N. E., & Nilsson, G. E. (2009). Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. ***Marine Ecology, Progress Series*****,** ***388*****, 235-242.**

Abstract: Concerns about the impacts of ocean acidification on marine life have mostly focused on how reduced carbonate saturation affects calcifying organisms. Here, we show that levels of CO_2-induced acidification that may be attained by 2100 could also have significant effects on marine organisms by reducing their aerobic capacity. The effects of temperature and acidification on oxygen consumption were tested in 2 species of coral reef fishes, *Ostorhinchus doederleini* and *O. cyanosoma*, from the Great Barrier Reef, Australia. The capacity for aerobic activity (aerobic scope) declined at temperatures above the summer average (29°C) and in CO_2-acidified water (pH 7.8 and ~1000 ppm CO_2) compared to control water (pH 8.15). Aerobic scope declined by 36 and 32% for *O. doederleini* and *O. cyanosoma* at temperatures between 29 to 32°C, whereas it declined by 33 and 47% for *O. doederleini* and *O. cyanosoma* in acidified water compared to control water. Thus, the declines in aerobic scope in acidified water were similar to those caused by a 3°C increase in water temperature. Minimum aerobic scope values of ~200 mg O_2 kg^{-1} h^{-1} were attained for both species in acidified water at 32°C, compared with over 600 mg O_2 kg^{-1} h^{-1} in control water at 29°C. Mortality rate increased sharply at 33°C, indicating that this temperature is close to the lethal thermal limit for both species. Acidification further increased the mortality rate of *O. doederleini*, but not of *O. cyanosoma*. These results show that coral reef fishes are sensitive to both higher temperatures and increased levels of dissolved CO_2, and that the aerobic performance of some reef fishes could be significantly reduced if climate change continues unabated.

Questions this article answers: how does CO_2 affect marine organisms' aerobic capacity?

Methodology: Capacity of aerobic activity on two species of coral fish

Findings:
See abstract.

Munday, P. L., Kingsford, M. J., O'Callaghan, M., & Donelson, J. M. (2008). Elevated temperature restricts growth potential of the coral reef fish Acanthochromis polyacanthus. *Coral Reefs*, *27*(4), 927-931

Abstract: In order to test the effect of temperature variation on the growth of a common coral-reef fish, Acanthochromis polyacanthus, juveniles, sub-adults and adults were reared on either high or low food rations at temperatures corresponding to the long-term (14 year) minimum, average and maximum summer sea-surface temperatures (26, 28 and 31_C respectively) at Orpheus Island, Great Barrier Reef, Australia. Both temperature and food supply affected the growth of juvenile and adult A. polyacanthus. Individuals grew more on high food rations, but growth declined with increasing temperature. Importantly, at 31_C, the growth of juveniles and adults on the high food ration was nearly identical to growth on the low food ration. This indicates that the capacity for growth is severely limited at higher ocean temperatures that are predicted to become the average for Orpheus Island within the next 100 years as a result of rapid climate change.

Questions this article answers: What is the effect of temperature variation on the growth of Acanthochromis polyacanthus, a common coral reef fish?

Methodology: environmentally controlled aquarium facility and monitored temperature and food given to juveniles, sub-adults, and adults

Findings:

- Elevated water temperature had a significant effect on the growth of juvenile and adult A. polyacanthus.
- Lower growth rates at higher temperatures are expected when the food ration is fixed, because more energy is used for maintenance activities at higher temperatures, and, therefore, individuals would need to consume additional food to maintain growth rates
    - These results suggest that the benefits of additional food supply on juvenile growth become diminished at higher temperatures in A. polyacanthus.
- Slower growth at higher temperatures increases the mortality risk of juveniles because they remain in the vulnerable small size classes for longer. Reduced potential for growth could also affect the reproductive success of adults.
- Even if more food was available, the results from this study show that individuals that increase their consumption rates still suffer a decline in growth if future temperatures exceed the local thermal optimum.
- Genetic adaptation could moderate the effects of rapid climate change

Quotes:

"Many coral reef fishes have short generation times and some mid-latitude populations exhibit strong genetic connectivity with low latitude populations already living at higher temperatures. Short generation times and gene flow from low-latitude populations might assist mid-latitude populations, such as those at Orpheus Island, adapt to increased temperature” -930

Munday, P. L., Dixson, D. L., McCormick, M. I., Meekan, M., Ferrari, M. C., & Chivers, D. P. (2010). Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences*, *107*(29), 12930-12934.

Abstract: There is increasing concern that ocean acidification, caused by the uptake of additional CO2 at the ocean surface, could affect the functioning of marine ecosystems; however, the mechanisms by which population declines will occur have not been identified, especially for noncalcifying species such as fishes. Here, we use a combination of laboratory and field-based experiments to show that levels of dissolved CO2 predicted to occur in the ocean this century alter the behavior of larval fish and dramatically decrease their survival during recruitment to adult populations. Altered behavior of larvae was detected at 700 ppm CO2, with many individuals becoming attracted to the smell of predators. At 850 ppm CO2, the ability to sense predators was completely impaired. Larvae exposed to elevated CO2 were more active and exhibited riskier behavior in natural coral-reef habitat. As a result, they had 5–9 times higher mortality from predation than current-day controls, with mortality increasing with CO2 concentration. Our results show that additional CO2 absorbed into the ocean will reduce recruitment success and have far-reaching consequences for the sustainability of fish populations.

Questions this article answers: Can levels of dissolved CO2 alter the behavior of larval fish? Will it impact survival during recruitment to adult populations?

Methodology: laboratory and field-based experiments

Findings:

- Altered behavior of larvae was detected at 700 ppm CO2, with many individuals becoming attracted to the smell of predators
- At 850 ppm CO2, the ability to sense predators was completely impaired
- Larvae exposed to elevated CO2 were more active and exhibited riskier behavior in natural coral-reef habitat
- they had 5–9 times higher mortality from predation than current-day controls, with mortality increasing with CO2 concentration
- Our results show that additional CO2 absorbed into the ocean will reduce recruitment success and have far-reaching consequences for the sustainability of fish populations

Nilsson, G. E., Ostlund-Nilsson, S., & Munday, P. L. (2010). Effects of elevated temperature on coral reef fishes: Loss of hypoxia tolerance and inability to acclimate. ***Comparative Biochemistry and Physiology A-Molecular & Integrative Physiology, 156*****(4), 389-393.**

Abstract: Water temperature is expected to rise on coral reefs due to global warming. Here, we have examined if increased temperature reduces the hypoxia tolerance of coral reef fish (measured as critical [O2]), and if temperature acclimation in adults can change the resting rate of O2 consumption and critical [O2]. Two common species from Lizard Island (Great Barrier Reef, Australia) were tested, Doederlein's cardinalfish (Ostorhinchus doederleini) and lemon damselfish (Pomacentrus moluccensis). In both species, a 3 °C rise in water temperature caused increased oxygen consumption and reduced hypoxia tolerance, changes that were not reduced by acclimation to the higher temperature for 7 to 22 days. Critical [O2] increased by 71% in the cardinalfish and by 23% in the damselfish at 32 °C compared to 29 °C. The higher oxygen needs are likely to reduce the aerobic scope, which could negatively affect the capacity for feeding, growth and reproduction. The reduced hypoxia tolerance may force the fishes out of their nocturnal shelters in the coral matrix, exposing them to predation. The consequences for population and species survival could be severe unless developmental phenotypic plasticity within generations or genetic adaptation between generations could produce individuals that are more tolerant to a warmer future.

Questions this article answers: Does increased water temperature reduce the hypoxia tolerance of coral reef fish? Does temperature acclimation in adults change the resting rate of O2 consum[tion and critical O2?

Methodology: December 2008 and January 2009 at Lizard Island Research Station (north GBR); two common species from Lizard Island were tested: Doederlein's cardinalfish (Ostorhinchus doederleini) and lemon damselfish (Pomacentrus moluccensis)

Findings:

- The two coral reef fish species studied lack the ability to acclimate their metabolic rate (measured as oxygen consumption) and hypoxia tolerance to an increase in ambient temperature, at least as adults.
- P. moluccensis and O. doederleini represent two major families of coral reef fish, damselfishes (Pomacentridae) and cardinal fishes (Apogonidae)
- Increased water temperature had a larger effect on hypoxia tolerance in the cardinalfish than it did in the damselfish
- There was a significant correlation between the increase in MO2 and [O2]crit for both species of fish.
    - A higher minimum level of oxygen will be needed to sustain a higher rate of oxygen consumption, and this type of relationship has been observed

previously

- Hypoxia tolerance is probably needed to allow them to seek nocturnal shelter from predators in the coral matrix—a habitat that can become severely hypoxic at night
- A future loss of hypoxia tolerance could force coral reef fishes out of their nocturnal shelters and thereby expose them to an increased risk of predation, with potentially negative consequences at the population and species level.
- Adult coral reef fishes have no significant capacity to acclimate to elevated water temperatures as adults
- Exposure to elevated temperatures early in life may condition enzymatic systems to operate more efficiently at elevated temperature

Obura, D., & Mangubhai, S. (2011). Coral mortality associated with thermal fluctuations in the pheonix islands, 2002-2005. *Coral Reefs, 30*, 607-609.

Abstract: The Phoenix Islands (Republic of Kiribati, 172–170_Wand 2.5–5_S) experience intra- and inter-annual sea surface temperature variability of &2_C and have few local anthropogenic impacts. From July 2002, a thermal stress event occurred, which peaked at 21 Degree Heating Weeks (DHW) in January 2003 and persisted for 4 years. Such thermal stress was greater than any thermal event reported in the coral reef literature. Reef surveys were conducted in July 2000, June 2002, and May 2005, for six of the eight islands. Sampling was stratified by exposure (windward, leeward, and lagoon) and depth (5, 10, 15, and 25 m). The thermal stress event caused mass coral mortality, and coral cover declined by approximately 60% between 2002 and 2005. However, mortality varied among sites (12–100%) and among islands (42–79%) and varied in accordance with the presence of a lagoon, island size, and windward vs. leeward exposure. Leeward reefs experienced the highest and most consistent decline in coral cover. Island size and the presence of a lagoon showed positive correlations with coral mortality, most likely because of the longer water residence time enhancing heating. Windward reefs showed cooler conditions than leeward reefs. Recently dead corals were observed at depths[35 m on windward and[45 m on leeward reefs. Between-island variation in temperature had no effect on between-island variation in coral mortality. Mortality levels reported here were comparable to those reported for the most extreme thermal stress events of 9–10DHWin other regions. These results highlight the high degree of acclimation and/or adaptation of the corals in the Phoenix Islands to their local temperature regime, and their consequent vulnerability to anomalous events. Moreover, the results suggest the need to adjust thermal stress calculations to reflect local temperature variation.

Questions this article answers: what were the effects of thermal stress on the Pheonix Islands on coral mortality?

Methodology: surveys of the coral reefs of the Phoenix Islands were conducted in July 2000, June 2002, and May 2005 over 11, 21 and 11 days, respectively. Remote sensing and in situ temperature data collected.

Findings:
The coral reefs of the Phoenix Islands in the Republic of Kiribati, in the central Pacific Ocean, are among the most remote in the world

The reefs of the Phoenix Islands have not been subject to commercial fishing, and human settlement has been extremely limited

Thermal stress patterns in the region differ from other coral reef regions globally: low annual range of SST (2-4 degrees C)

In situ SST recorded in the Phoenix Islands ranged between 27.9 and 31.1_C from June 2002 to May 2005

All five sites showed a highly consistent increase in temperatures from June to November 2002, with stable temperatures above 30_C from August/September 2002 to February 2003, with maxima in November/December 2002

After Feb 2003- temps were significantly cooler and showed spatial variation

There were significant differences in hard coral cover and algal turfs between 2000/2002 and 2005

Most dramatic change in coral cover: the lagoon site in kanton: had the highest coral cover of any site in 2002 (79%) and was at 0% by 2005

By visual estimation, the loss of coral cover from 2002 to 2005 was 57%

Coral decline also varied in depth: 2002- coral lcover was the highest on the reef patform at 10 m on leeward reef and in Kanton lagoon

2005- max coral cover decreased on leeward reefs to 15 m and on windward reefs coral cover was uniformly distributed across all depth 5m-25m at 20%

In 2000 and 2002, the coral communities in all habitats consisted of consistent cover of acroporids, and on the fore reefs of pocilloporids and faviids, among others

The appearance of the study in 2005 was completely different: could not be attributed to random placement of sample units

Quotes:

"The coral decline from 2002 to 2005 varied by island and by degree of exposure, but sampling with photograph quadrats was not sufficient to statistically test island/ exposure combinations."

"The 60% decline in coral cover recorded in the Phoenix Islands from 2002 to 2005 is dramatic. However, since direct observations of the decline were not made, it must be determined whether this change was real and if so what was its likely cause. Was it a result of sampling error and/ or methodological artifacts?"

"The islands are flat coralline islands with negligible human habitation and visitation. This rules out the possibility of sedimentation, salinity, pollution, fishing, and construction as potential causes of the coral mortality… The only agent known to cause a massive decline in the cover of corals in a short space of time, and has been documented in the Phoenix Islands, is high-temperature stress."

Ogston, A. S., & Field, M. E. (2010). Predictions of turbidity due to enhanced sediment resuspension resulting from sea-level rise on a fringing coral reef: Evidence from Molokai, Hawaii. ***Journal of Coastal Research, 26*****(6), 1027-1037.**

Abstract: Accelerating sea-level rise associated with global climate change will affect sedimentary processes on coral reefs and other shoreline environments by increasing energy and sediment resuspension. On reefs, sedimentation is known to increase coral stress and bleaching as particles that settle on coral surfaces interfere with photosynthesis and feeding, and turbidity induced by suspended sediment reduces incident light levels. Using relationships developed from observations of wave orbital velocity, water-surface elevation, and suspended-sediment concentration on a fringing reef flat of Molokai, Hawaii, predictions of the average daily maximum in suspended-sediment concentration increase from ,11 mg/l to ,20 mg/l with 20 cm sea-level rise. The duration of time concentrations exceeds 10 mg/l increases from 9% to 37%. An evaluation of the reduction of wave energy flux through breaking and frictional dissipation across the reef flat shows an increase of ,80% relative to the present will potentially reach the shoreline as sea level increases by 20 cm. Where the shoreline exists on low, flat terrain, the increased energy could cause significant erosion of the shoreline. Considering the sediment budget, the sediment flux is predicted to increase and removal of fine-grained sediment may be expedited on some fringing reefs, and sediment in storage on the inner reef could ultimately be reduced. However, increased shoreline erosion may add sediment and offset removal from the reef flat. The shifts in sediment availability and transport that will occur as result of a modest increase in sea level have wide application to fringing coral reefs elsewhere, as well as other shoreline environments.

Questions this article answers: What is predicted turbidity resulting from sea-level rise on a fringing coral reef in Molokai, Hawaii?

Methodology:

Findings:

- The Molokai reef is the largest continuous fringing reef in the main Hawaiian Islands (Figure 1), extending for .50 km along the south-central coast.
    - The fringing reef consists of a broad, shallow (0–2-m water depth) reef flat that extends nearly 1 km offshore, rising to a reef crest that is partially exposed at low tide, and a fore reef that descends gradually offshore to ,30-m water depth.
- There is a general trend in the relationship between the water-surface elevation and the suspended-sediment concentration with increasing concentrations at higher sea levels, but there is much scatter in the data
- The water-surface elevation over fringing reefs may increase by 20 cm in the next three to five decades and that reef accretion will likely not keep up.
- Changes in sediment resuspension on the reef will result in higher shear stresses, and changes predicted in the amount of wave energy that reaches the shoreline will act to erode shoreline sediments

- Resuspension of sediment from the seabed presently occurs on a daily basis
- It is predicted that the average daily maximum in suspended-sediment concentration will increase on Molokai with sea-level rise from ,11 mg/l to 20 mg/
- On the Molokai reef flat, high tide and strong trade winds generally coincide during daylight hours so the reef will experience high levels of turbidity throughout ,4.4 of the daylight hours
    - This might affect the efficiency of photosynthesizing organisms
- An increase of ,80% over the present wave energy will be transferred to the shoreline when the water-surface elevation is increased by 20 cm- increased shore erosion
- Increased sediment in suspension on a daily basis may remove more fine-grained sediment from the reef flat
- Increased shoreline erosion will add sediment to the mud belt and may offset the amount of additional sediment leaving the reef flat through increased resuspension and flux

Pandolfi, J. M., Connolly, S. R., Marshall, D. J., & et al. (2011). Projecting coral reef futures under global warming and ocean acidification. *Science, 333*(6041), 418-422.

Abstract: Many physiological responses in present-day coral reefs to climate change are interpreted as consistent with the imminent disappearance of modern reefs globally because of annual mass bleaching events, carbonate dissolution, and insufficient time for substantial evolutionary responses. Emerging evidence for variability in the coral calcification response to acidification, geographical variation in bleaching susceptibility and recovery, responses to past climate change, and potential rates of adaptation to rapid warming supports an alternative scenario in which reef degradation occurs with greater temporal and spatial heterogeneity than current projections suggest. Reducing uncertainty in projecting coral reef futures requires improved understanding of past responses to rapid climate change; physiological responses to interacting factors, such as temperature, acidification, and nutrients; and the costs and constraints imposed by acclimation and adaptation.

Questions this article answers: Does reef degradation occur with greater temporal and spatial heterogeneity than is currently suggested? What are past responses to rapid climate change? What are physiological responses to interacting factors?

Methodology: literature review

Findings:

- Coral reef organisms will evolve in response to the increased thermal stress and OA associated with climate change, but the impact of this evolution is unclear
- For corals specifically, the issue is complicated by symbiosis: The interdependency of mutualists, such as the coral host and symbiont, can affect rates of evolution
- The generation times of corals are orders of magnitude greater than those of symbionts, so symbionts may show faster evolutionary responses than their hosts
- The generation times of many coral species do not preclude rapid genetic evolution of the host in response to climate change as well:
    - Other organisms have undergone rapid evolution in response to anthropogenic stresses within just a few generations
- There is often a shift to more thermally tolerant symbiont strains after bleaching events
    - This suggests that some acclimation to increasing temperatures is already occurring
- Because bleaching causes mortality of corals and reduces energy available for growth and reproduction among survivors, increases in its frequency and intensity can confidently be expected to reduce coral cover
- The most pessimistic projection is for global-scale losses of coral reefs resulting from annual mass bleaching events
    - The outcome will depend on the extent of thermal adaptation and aggressive emissions reduction:
    - Both appear necessary to avoid extended declines in coral cover to very

low levels

Quotes:
“Range expansions of corals in response to warming temperatures have been recorded (86–88), but we presently lack good estimates of the potential rates of such range expansion under rapid environmental change and models that incorporate such shifts into projections. Such physiological, evolutionary, and biogeographic responses are not free from costs or constraints, but they will influence the nature of reefs’ responses to climate change. Thus, reef degradation resulting from climate change alone is likely to be a more spatially, temporally, and taxonomically heterogeneous process than some projections suggest and could even be slowed where management of local pressures, such as coastal development and overfishing, provides greater opportunity for reefs to cope with increasing ocean temperature and decreasing pH.”

Perry, C. T., Smithers, S. G., Roche, R. C., & Wassenburg, J. (2011). Recurrent patterns of coral community and sediment facies development through successive phases of holocene inner-shelf reef growth and decline. ***Marine Geology, 289*****(1-4), 60-71.**

Abstract: Coral community decline and resultant 'turn-off' of reef accretion potential are commonly predicted outcomes of the increasing environmental stresses experienced by many coral reefs. The potential for coral reef communities to re-establish once environmental conditions ameliorate or new substrates for colonization become available are, however, less well understood. Here we discuss data from a fringing reef at Dunk Island, an inner-shelf high island on Australia's Great Barrier Reef (GBR). Although this reef is spatially contiguous, detailed coring and dating reveal it was constructed in two discrete temporal phases. The inner part of the reef flat formed first, during the late stages of the post-glacial marine transgression-early sea level highstand (~6.9–4.5 k cal yr B.P.), whereas the outer fringe developed after the late-Holocene sea level regression, from ~1.6 k cal yr B.P. to present. A hiatus of almost 3000 years separates the two reef growth phases. Data from this reef thus provide a same-site perspective on the degree of temporal continuity that exists where an actively growing reef slows and eventually ceases to accrete for an extended period, before re-establishing and growing again—a temporal transition equivalent to reef 'turn-off' followed by renewed reef 'turn-on'. The depositional architectures of the two phases of reef growth are very similar, as are patterns of facies and coral assemblage development. This study suggests that reefs, over the timescales at which cycles of reef 'turn-on' and 'turn-off' operate (the centennial to millennial timescale), can not only re-establish successfully, but also that regrowth may be characterised by the establishment of near identical reef-building communities and the development of near identical depositional structures. These findings thus have direct relevance to the on-going debate about whether, and in what form, reef communities will be able to re-establish themselves following periods of suppressed growth, such as those projected for the near-future.

Questions this article answers: What is the potential for reef communities to re-establish once environmental conditions ameliorate or new substrates for colonization become available?

Methodology: case study: fringing reef at Dunk Island- an inner shelf high island on the GBR; surface sediment samples were collected from randomly selected sites across both the reef flat and intertidal zone, and the adjacent shallow sub- tidal areas (points randomly selected from a grid point overlay using GPS mapping software). At each site approximately 100 g of sediment was recovered, either by hand at low water across the exposed reef flat and intertidal environments, or using a hand auger deployed from the boat in sub-tidal areas.

Findings:

- Both reef phases at Dunk Island clearly established within shallow sub-tidal environments (probablyb3 m water depth) and exhibit very similar depositional stratigraphies

- Both also formed above a sequence of shallow sub-tidal and intertidal fine-grained, siliciclastic sands. These sediments were clearly depositionally active immediately prior to reef establishment as indicated by dates from reworked coral clasts in the sands immediately underlying the reef
- From a sedimentological perspective both facies show consistent up-core trends that are remarkably uniform between the two reef growth phases
- The accumulation of reef-derived carbonate produces an 'island' of carbonate-rich sediment within otherwise non-carbonate environments: a pattern noted in other siliciclastic- dominated, inner-shelf environments where localised reef development has occurred

- The depositional architectures of the two phases of reef growth are very similar, as are patterns of facies and coral assemblage development
- Reefs, over the timescales at which cycles of reef 'turn-on' and 'turn-off' operate (the centennial to millennial timescale), can not only re-establish successfully, but also that regrowth may be characterised by the establishment of near identical reef-building communities and the development of near identical depositional structures
    - The coral taxa contributing to reef framework development were very similar during both reef growth phases.
- Striking similarities in the depositional architectures of the two reef growth phases, as well as near identical patterns of facies development and of coral assemblage development (despite an hiatal period between reef-building episodes of ~3000 years), are indicative of the clear potential for reefs to re-establish following mortality (turn-off) events and once environmental conditions improve or new substrate becomes available

Perry, C. T., & Smithers, S. G. (2011). Cycles of coral reef "turn-on", rapid growth and "turn-off" over the past 8500 years: A context for understanding modern ecological states and trajectories. ***Global Change Biology, 17*(1), 76-86.**

Abstract: Human activities threaten reef ecosystems globally, forcing ecological change at rates and scales regarded as unprecedented in the Holocene. These changes are so profound that a cessation of reef accretion (reef 'turn-off') and net erosion of reef structures is argued by many as the ultimate and imminent trajectory. Here, we use a regional scale reef growth dataset, based on 76 core records (constrained by 211 radiometric dates) from 22 reefs along and across the inner-shelf of the Great Barrier Reef, Australia, to examine the timing of different phases of reef initiation ('turn-on'), growth and 'turn-off' during the Holocene. This dataset delineates two temporally discrete episodes of reef-building over the last 8500 years: the first associated with the Holocene transgression-early highstand period [_8.5–5.5 k calibrated years BP (cal yBP)]; the second since _2.3 k cal yBP. During both periods, reefs accreted rapidly to sea level before entering late evolutionary states – states naturally characterized by reduced coral cover and low accretion potential – and a clear hiatus occurs between these reef-building episodes for which no records of reef initiation exist. These transitions mimic those projected under current environmental disturbance regimes, but have been driven entirely by natural forcing factors. Our results demonstrate that, even through the late Holocene, reef health and growth has fluctuated through cycles independent of anthropogenic forcing. Consequently, degraded reef states cannot de facto be considered to automatically reflect increased anthropogenic stress. Indeed, in many cases degraded or nonaccreting reef communities may reflect past reef growth histories (as dictated by reef growth–sea level interactions) as much as contemporary environmental change. Recognizing when changes in reef condition reflect these natural 'turn-on' – growth – 'turn-off' cycles and how they interact with on-going human disturbance is critical for effective coral reef management and for understanding future reef ecological trajectories.

Questions this article answers: What are the timings of different phases of reef initiation, growth, and "turn-off" during the Holocene period?

Methodology: a regional scale reef growth dataset, based on 76 core records (constrained by 211 radiometric dates) from 22 reefs along and across the inner-shelf of the Great Barrier Reef, Australia

Findings:

- In the northern- central GBR, reef 'turn-off' occurred between 6.4 and 4.5 k cal yB
- **Need to consider** when disturbance and change on reefs (as measured over ecological timescales) truly constituted real 'turn-off' phases rather than short-lived ecological hiatus events
- Most of these reefs subsequently shifted to (lateral) progradational growth modes under high, stable and then slowly falling sea levels, before 'turning-off' most cores through inshore reefs on the GBR contain high levels of fine-grained terrigenous sediment during periods of active reef accretion, suggesting that changed sediment yields alone were unlikely to have been the sole driver of reef

turn-off
    - o Multiple stressors, acting within the clear and overarching constraints of reduced accommodation space, may have been involved
- A second period of inner-shelf reef ‘turn-on’ occurred from _2.3 k cal yBP
- Extrinsic (regional scale) controls were important to this event
- Most likely this second ‘turn-on’ event occurred as a function of sea level stabilization through the late Holocene, a transition that facilitated the progressive re-opening of potential reefal habitats as further seaward movement of the previously dynamic TSW ceased
- Coral communities were either able to establish on pre-existing sediment substrates, or utilize newly exposed substrates as the coastline retreated
- ‘Young’ reefs, such as Paluma Shoals South and Lugger Shoal, remain in earlier evolutionary stages, having more recently reached sea level and have incompletely developed reef flats
- Recent declines in coral cover on these, or other, ‘young’ reefs cannot, however, be assumed to solely reflect anthropogenic impacts since many are transforming into less productive states at the end of a natural accretionary cycle
- Under present sea-level conditions, their ultimate fate will be a ‘turn-off’ of carbonate growth potential mirroring that seen on inner-shelf reefs in the period 6.5–4.5 k cal yBP.
- Of particular significance, from an ecological perspective, is that the products of these ‘turn-on’ and ‘turnoff’ phases have been the formation of reef structures that exist in very different evolutionary states
- Continual ecological turnover and low net carbonate production should thus be the expected norm on these reefs. The present low coral cover on the reef flat surfaces and low accretionary potential certainly should not be immediately attributed to anthropogenic stress
- Regional scale loss of reef-building potential is not without precedent in the mid- to late- Holocene
    - o Driven entirely by natural processes – most likely a combination of subtle fluctuations in sea-level and associated shifts in shoreline position, potentially augmented by other factors such as sea surface temperature and inshore water quality

Quotes:
“While the timing and longevity of inner-shelf reef growth has in the recent geological past been profoundly influenced by natural processes, the legacy of which is strongly expressed in contemporary reef ecological states, both natural and more widely discussed anthropogenic factors, need to be integrated into considerations of future reef ecological trajectories.” PG 85

Pini, J., Planes, S., Rochel, E., & et al. (2011). Genetic diversity loss associated to

high mortality and environmenal stress during recruitment stage of a coral reef fish. ***Coral Reefs, 30*(2), 399-404.**

Abstract: We investigated the short-term impact of environmental-induced stress on survival and neutral genetic diversity of recently settled juveniles of a damselfish, Dascyllus aruanus, using spatiotemporal caging experiments in various natural environmental conditions in Moorea (French Polynesia). Juveniles' mortality was followed at five study sites and overall four experiments, mortality rates ranged from 0 to 45%. Mortality rate and average daily water temperature were positively correlated ($P = 0.018$). Juveniles' mortality rate and allelic richness estimated from ten microsatellite loci were negatively correlated ($P = 0.046$). Together, an overdominance of heterozygotes was observed within hostile environments.
These results suggest that an allelic richness loss may be expected as a direct consequence of unfavorable environmental conditions. Thus, a worrisome scenario on demographic and genetic consequences may be expected from habitat degradation in the context of global change and human pressure increases.

Questions this article answers: What is the short-term environmental-induced stress on survival and genetic diversity of juvenile damselfish?

Methodology: spatiotemporal caging experiments in various natural environmental conditions in Moorea (French Polynesia); Juveniles' mortality was followed at five study sites and overall four experiments

Findings:

- Little is known on the consequences of environmental stress on the genetic diversity within populations of reef-associated organisms
- The settlement phase is a critical period for demersal species colonizing benthic habitats
- The number of juveniles surviving each experiment varied from 11 to 20, equivalent to mortality rates of up to 45% in site 1 during the 2nd experiment and in site 3 during the 4th experiment
- In average, the mortality rates observed in the control experimental site (in average 7.5%) were similar to the ones observed in site 4 and site 5
- This suggests that the end of the bay provided adequate conditions for juvenile survival once provided in their natural habitat
- Theoretically, it is expected that population bottlenecks lead to an erosion of genetic diversity due to increased random genetic drift
- The results of our study suggest that increased post-settlement mortality due to environmental-induced stress can lead in parallel to a genetic diversity loss
- Allelic diversity is more sensitive to the effects of short demographic bottlenecks than is heterozygosity
- Evidence for overdominance (i.e., superior viability of heterozygotes) has been shown in several cases

Quotes:

“Our results propose a worrisome scenario that can be placed in the current context of global change and human pressures. Though survival rates during the recruitment stage rely on numerous ecological and biotic factors, our results suggest that settlers surviving the first natural mortality phase and facing environmental-induced stress in terms of higher temperature and/or sedimentation rate (while their coral habitat being maintained) will likely undergo increased mortality, which may result in allelic richness loss in surviving populations.”

Prada, C., Weil, E., & Yoshioka, P. M. (2010). Octoral bleaching during unusual

thermal stress. *Coral Reefs, 29*(1), 41-45.

Abstract: We describe a bleaching event in octocoral communities at four reefs in southwest Puerto Rico during October 2005 following a period of elevated sea surface temperatures. Percentages of colonies bleached varied among taxa, ranging from 0% for Pseudopterogorgia, Eunicea and Gorgonia to over 90% for Muricea. Other taxa exhibiting bleaching included Pseudoplexaura (22.3%), Muriceopsis (36.6%), Briareum (46.1%), Plexaurella (69.6%) and Pterogorgia (84.5%).

Questions this article answers: What is the outcome of octoral bleaching after a time of thermal stress?

Methodology: looked at octocoral communities at four reefs in southwest Puerto Rico during October 2005 following a period of elevated sea surface temperatures

Findings:

- A total of 1,823 colonies from 24 taxa were surveyed
- Pseudopterogorgia Americana and P. acerosa were the most abundant taxa comprising 24% of all colonies
- A total of 330 colonies (18% of the total) were bleached. Relatively high proportions of bleaching ([50% of colonies) were observed for Muricea, Plexaurella, Pseudoplexaura, Pterogorgia, and Briareum
- Except for observations of Eunicea sp. in Panama, bleaching in these species has never beenreported
- Octocoral species differ in their susceptibility to bleaching. Field observations also suggested differences in temporal patterns

- Bleaching of octocorals was preceded by bleaching in scleractinian corals, hydrocorals, and the zoanthid Palythoa caribaeorum
    - Suggests higher tolerance to thermal stress of octocorals compared to the other major cnidarian taxa

Pratchett, M. S., Trapon, M., Berumen, M. L., & et al. (2011). Recent disturbances augment community shifts in coral assemblages in moorea, french polynesia. *Coral*

***Reefs, 30*(1), 183-193**

Abstract: Coral reefs are often subject to disturbances that can cause enduring changes in community structure and abundance of coral reef organisms. In Moorea, French Polynesia, frequent disturbances between 1979 and 2003 caused marked shifts in taxonomic composition of coral assemblages. This study explores recent changes in live cover and taxonomic structure of coral communities on the north coast of Moorea, French Polynesia, to assess whether coral assemblages are recovering (returning to a previous Acropora-dominated state) or continuing to move towards an alternative community structure. Coral cover declined by 29.7% between July 2003 and March 2009, mostly due to loss of Acropora and Montipora spp. Coral mortality varied among habitats, with highest levels of coral loss on the outer reef slope (7–20 m depth). In contrast, there was limited change in coral cover within the lagoon, and coral cover actually increased on the reef crest. Observed changes in coral cover and composition correspond closely with the known feeding preferences and observed spatial patterns of Acanthaster planci L., though observed coral loss also coincided with at least one episode of coral bleaching, as well as persistent populations of the corallivorous starfish Culcita novaeguineae Muller & Troschel. While climate change poses an important and significant threat to the future structure and dynamics coral reef communities, outbreaks of A. planci remain a significant cause of coral loss in Moorea. More importantly, these recent disturbances have followed long-term shifts in the structure of coral assemblages, and the relative abundance of both Pocillopora and Porites continue to increase due to disproportionate losses of Acropora and Montipora. Moreover, Pocillopora and Porites dominate assemblages of juvenile corals, suggesting that there is limited potential for a return to an Acropora-dominated state, last recorded in 1979.

Questions this article answers: What are the recent changes in live cover and taxonomic structure of coral communities on the north coast of Moorea, French Polynesia? Are the corals recovering?

Methodology: This study was conducted on the northern coast of Moorea, French Polynesia; Sampling was conducted at two locations, Vaipahu and Tiahura, separated by approximately 2 kilometres on the north coast of Moore. Coral assemblages were sampled in July 2003, May 2007, and March 2009.

Findings:

- Overall coral cover declined by 44.2% across the two study locations (Tiahura and Viapahu), in July 2003 down to 19.4% in March 2009: significant declines in coral cover, as well as significant changes in coral composition on the north coast of Moorea in the 6 years up to March 2009
- Declines in coral cover were most pronounced on outer reef slope, with greatest loss (93.7% decline) recorded in zone 6
- Declines in coral cover were not equally apportioned among different coral genera
    - In general, Acropora and Montipora declined in abundance from 2003 to 2009, leading to increases in the proportional abundance of Pocilllopora

and/or Porites

- Coral loss recorded during this study coincided with both an outbreak of A. planci, as well as at least one episode of coral bleaching
- The only known occurrence of mass bleaching during this study occurred in late summer (March–April) 2007.
    - Recent bleaching events have caused relatively little coral mortality in Moorea
    - Coral bleaching observed during this study (in May 2007) affected 16–34% of colonies across all reef zones, but bleaching incidence and corresponding loss of live coral were most pronounced on the outer reef slope and tended to increase with increasing depth.
- Recent disturbances have compounded previous disturbances in Moorea, further augmenting community shifts in coral assemblage

Price, N. N., Hamilton, S. L., Tootell, J. S., & et al. (2011). Species-specific consequences of ocean acidification for the calcareous tropical green algae

halimeda. *Marine Ecology Progress Series, 440*, 67-78.

Abstract: Ocean acidification (OA), resulting from increasing dissolved carbon dioxide (CO2) in surface waters, is likely to affect many marine organisms, particularly those that calcify. Recent OA studies have demonstrated negative and/or differential effects of reduced pH on growth, development, calcification and physiology, but most of these have focused on taxa other than calcareous benthic macroalgae. Here we investigate the potential effects of OA on one of the most common coral reef macroalgal genera, *Halimeda*. Species of *Halimeda* produce a large proportion of the sand in the tropics and are a major contributor to framework development on reefs because of their rapid calcium carbonate production and high turnover rates. On Palmyra Atoll in the central Pacific, we conducted a manipulative bubbling experiment to investigate the potential effects of OA on growth, calcification and photophysiology of 2 species of *Halimeda*. Our results suggest that *Halimeda* is highly susceptible to reduced pH and aragonite saturation state but the magnitude of these effects is species specific. *H. opuntia* suffered net dissolution and 15% reduction in photosynthetic capacity, while *H. taenicola* did not calcify but did not alter photophysiology in experimental treatments. The disparate responses of these species to elevated CO2 partial -pressure (pCO2) may be due to anatomical and physiological differences and could represent a shift in their relative dominance in the face of OA. The ability for a species to exert biological control over calcification and the species specific role of the carbonate skeleton may have important implications for the potential effects of OA on ecological function in the future. Ocean acidification (OA), resulting from increasing dissolved carbon dioxide (CO2) in surface waters, is likely to affect many marine organisms, particularly those that calcify. Recent OA studies have demonstrated negative and/or differential effects of reduced pH on growth, development, calcification and physiology, but most of these have focused on taxa other than calcareous benthic macroalgae. Here we investigate the potential effects of OA on one of the most common coral reef macroalgal genera, *Halimeda*. Species of *Halimeda* produce a large proportion of the sand in the tropics and are a major contributor to framework development on reefs because of their rapid calcium carbonate production and high turnover rates. On Palmyra Atoll in the central Pacific, we conducted a manipulative bubbling experiment to investigate the potential effects of OA on growth, calcification and photophysiology of 2 species of *Halimeda*. Our results suggest that *Halimeda* is highly susceptible to reduced pH and aragonite saturation state but the magnitude of these effects is species specific. *H. opuntia* suffered net dissolution and 15% reduction in photosynthetic capacity, while *H. taenicola* did not calcify but did not alter photophysiology in experimental treatments. The disparate responses of these species to elevated CO2 partial -pressure (pCO2) may be due to anatomical and physiological differences and could represent a shift in their relative dominance in the face of OA. The ability for a species to exert biological control over calcification and the species specific role of the carbonate skeleton may have important implications for the potential effects of OA on ecological function in the future.

Questions this article answers: what are the potential impacts of OA on one of the most common coral reef macroalgal genera, *Halimeda?*

Methodology: on Palmyra Atoll in the central Pacific, we conducted a manipulative bubbling experiment to investigate the potential effects of OA on growth, calcification and photophysiology of 2 species of *Halimeda*

Findings:
(See abstract)

Raitsos, D. E., Hoteit, I., Prihartato, P. K., & et al. (2011). Abrupt warming of the

red sea. Geophysical Research Letters, 38

Abstract: Coral reef ecosystems, often referred to as "marine rainforests," concentrate the most diverse life in the oceans. Red Sea reef dwellers are adapted in a very warm environment, fact that makes them vulnerable to further and rapid warming. The detection and understanding of abrupt temperature changes is an important task, as ecosystems have more chances to adapt in a slowly rather than in a rapid changing environment. Using satellite derived sea surface and ground based air temperatures, it is shown that the Red Sea is going through an intense warming initiated in the mid‐90s, with evidence for an abrupt increase after 1994 (0.7°C difference pre and post the shift). The air temperature is found to be a key parameter that influences the Red Sea marine temperature. The comparisons with Northern Hemisphere temperatures revealed that the observed warming is part of global climate change trends. The hitherto results also raise additional questions regarding other broader climatic impacts over the area.

Questions this article answered: What are the temperature changes the Red Sea is undergoing? What are the implications of this on coral reef ecosystems?

Methodology: three different sources of temperature data were used, encompassing a period between 1985 and 2007.

Findings:

- The monthly SST anomaly time series revealed an abrupt warming that was initiated in 1994, while it was stabilized to the new warmer state few years later
- The warming trend is apparent in every month, implying that the change is not driven by seasonality
- The years 1995 and 1998 have ranked as the warmest years of the Northern Hemisphere, while the temperature shift at the end of the 1990s was the most intense change in the last 160 years
- SST data set revealed an intense and abrupt warming in the mid‐90s, but this may be part of a more widespread temperature shift seen at the beginning of the 80s
- The average difference between the two decades registers around +0.62°C and in some areas exceeds the 1°C. It is the central part of the study area that portrays the highest deviations from the mean
- Regardless of its origin, natural and/or anthropogenic, it is widely accepted that oceanic warming is evident worldwide
- The Red Sea is going through an intense warming that was initiated in the mid‐90s, with evidence of an abrupt increase after 1994

Rahul, P. R. C., Salvekar, P. S., Sahu, B. K., & et al. (2010). Role of a cyclonic eddy

in the 7000-year-old mentawai coral reef death during the 1997 indian ocean dipole event. ***IEEE Geoscience and Remote Sensing Letters,*** ***7*****(2), 296-300.**

Abstract: A major discovery on the coral fronts was the death of the 7000-year-old coral reefs along the Mentawai Islands located offshore of southwest Sumatra, Indonesia, in the equatorial eastern Indian Ocean due to the Indian Ocean Dipole event of 1997. Using two ocean general circulation models, the NASA Ocean Biogeochemistry Model and Estimating the Circulation and Climate of the Ocean Model, we investigate the variability in nitrate influx, mixed layer depth (MLD), and surface currents over the region 0◦–8◦ S; 90◦–106◦ E. An enhanced nitrate influx by 6.5 micromoles (3150% higher than the mean), a lower MLD by 5 m (300% lower than the mean), and a massive cyclonic eddy (400 km meridonally and 500 km zonally) are observed over the region 4◦–8◦ S; 94◦–100◦ E (along the region of coralmortality) for three months (November and December 1997 and January 1998). Cyclonic eddies enhance phytoplankton and primary productivity, but when in the proximity of a coral reef, they can destroy the coral colony through asphyxiation caused by massive phytoplankton blooms. The results bring to the fore the importance of mesoscale processes that significantly impact the health of coral reefs.

Questions this article answers: What is the variability in nitrate influx, mixed layer depth (MLD), and surface currents over the Sumatra, Indonesia region?

Methodology: two ocean general circulation models, the NASA Ocean Biogeochemistry Model and Estimating the Circulation and Climate of the Ocean Model- observed region from November and December 1997 and January 1998

Findings:

- Although SSTs in the central–western tropical Indian Ocean were anomalously warm in 1997, the eastern sector was unusually cool
    - The result of recently discovered coupled ocean–atmosphere dynamics, termed the Indian Ocean Dipole (IOD), in its positive phase (cooler and warmer SSTs along the east coast and west coast of the Indian Ocean, respectively)
- The 1997 IOD caused anomalous upwelling, low SSTs, and low sea surface heights along the northeastern Indian Ocean in 1997
- Massive chlorophyll *a* blooms have been reported to occur along the Java and Sumatra coasts as a result of the 1997 IOD-induced upwelling
- There was a massive cyclonic eddy that starts to form by the end of November, intensifies during December, and then enters a diffusive stage by January 1998

Quotes:
"Altered currents, upwelling, and/or vertical mixing caused by changing currents have profound effect on the phytoplankton and, consequently, on primary productivity while the enhanced nutrients clearly stem from the upwelling event, the primary productivity rates could not be sustained by upwelled or aeolian iron (Fe), but additional Fe may have been deposited from the worst wildfires in the recorded history of Southeast Asia, which

co-occurred during the 1997 IOD."

Rodriguez-Ramirez, A., Catalina Reyes-Nivia, M., Zea, S., & et al. (2010). Recent dynamics and condition of coral reefs in the colombian caribbean. *Revista De Biologia Tropical, 58*(1), 107-131.

Abstract: Long-term monitoring data provide a basis to recognize changes in coral reef communities and to implement appropriate management strategies. Unfortunately, coral reef dynamics have been poorly documented at any temporal scale in the Southern Caribbean. Through the "National Monitoring System of Coral Reefs in Colombia" (Spanish acronym: SIMAC), we assessed 32 permanent plots at different depth levels in six reefs areas of the Colombian Caribbean from 1998 to 2004. Temporal trends in coral and algal cover were evaluated by repeated measures ANOVA. The model included the effect of depth levels (a fixed effect), monitoring plots (a random effect) as a nested factor within depths, and time (repeated factor). We found high spatial variability in major benthic components. Overall means indicated that algae were the most abundant biotic component in nearly all areas, ranging from 30.3% at Rosario to 53.3% at San Andrés. Live coral cover varied considerably from 10.1% at Santa Marta up to 43.5% at Urabá. Coral and algae cover *per se* are not always accurate reef indicators and therefore they need supplementary information. Temporal analyses suggested relative stability of coral and algal cover along the study but the causes for the observed trends were rarely identified. A significant decrease (p=0.042) in coral cover was only identified for some monitoring plots in Tayrona-time x plot (depth level) interaction, and importantly, few coral species explained this trend. Significant increase (p=0.005) in algal cover was observed over time for most plots in Rosario. Temporal trajectories in algal cover were influenced by depth-significant time x depth interaction-in San Andrés (increase, p=0.004) and Urabá (decrease, p=0.027). Algae trends were mainly explained by changes in algal turfs. Monitoring programs must focus on the mechanisms mediating the changes, in particular those concerning coral recovery and reef resilience in the current context of climate change.

Questions this article answers: what are the coral reef dynamics occurring at a temporal scale in the Southern Caribbean?

Methodology: assessed 32 permanent plots at different depth levels in six reefs areas of the Colombian Caribbean from 1998 to 2004

Findings:

- The monitoring plots exhibited a wide range of coral (5.4%-67.2%) and algal cover (23.2%-81.8%)
- Spatial patterns are difficult to identify
- Several local studies have also identified high spatial variability not only within and across the main coral reef areas of Colombia
- Two general spatial patterns were identified: 1) algae were predominant over the other living organisms (including corals) and substrate categories and, 2) algal turfs were the most abundant algal component

- This generalized condition appears to be the result of decline processes experienced by coral reefs during the past decades and is mainly associated with a combination of natural and antropogenic factors
- Hard corals displayed two main spatial patterns related to their abundance and composition: 1) percentage cover of individual species rarely exceeded 10% and, 2) total living coral was accounted by few species
- The high abundance of *S. siderea* could have importance in terms of coral reef resistance and resilience. This species appears to be more tolerant than other coral species experiencing similar perturbations in the area

Rushworth, K. J. W., Smith, S. D. A., Cowden, K. L., & Purcell Steven W. (2011). Optimal temperature for growth and condition of an endemic subtropical anemonefish. *Aquaculture, 318*, 479-482.

Abstract: The wide-band anemonefish (Amphiprion latezonatus), a subtropical endemic of Australia, has strong potential as a cultured ornamental. We investigated the effect of seawater temperature (19–29 °C) on hatchery-reared juveniles over two months. Optimum temperatures for highest specific growth rate (SGR) and condition factor (K) were modelled using nonlinear regression. Growth rate increased with temperature to a maximum at 22–23 °C then declined. Optimum SGR, at 22.4 °C, was 0.91%day−1. The condition of juveniles displayed a similar trend but became increasingly variable within groups at higher temperatures and a significant optimum was not elucidated. This finding suggests that dominance behaviour accentuates with increasing temperature. Optimising the temperature for rearing juvenile A. latezonatus will improve efficiency of ornamental mariculture. Especially high rises in sea temperatures predicted for its geographical range are likely to impact the growth in juveniles of this species. Given the relative ease of juvenile culture and its apparent sensitivity to variation in sea temperatures, A. latezonatus should serve as a useful indicator species for studies on climate change impacts.

Questions this article answers: What are the effects of seawater temperature on hatchery-reared juveniles over a span of two months? What are optimum temperatures for the highest growth rates?

Methodology: case study: Two weeks prior to the commencement of the experiment, juvenile A. latezonatus were cultured at the NMSC, Coffs Harbour, Australia, The growth response of juvenile A. latezonatus to varied temperatureswas tested over a 60-day period. Fifteen groups of eight individual fish were prepared

Findings:

- Overall, the mean condition (K) of juvenile A. latezonatus increased with temperature to 22 °C before becoming more variable within groups and generally reduced at higher temperatures
- This study demonstrates that growth rates of juvenile A. latezonatus during culture for the ornamental trade could be optimised at rearing temperatures between 22 and 23 °C.

- The study predicts sharp declines in growth at water temperatures only 2 or 3 °C warmer or cooler than the optimumof 22.4 °C.
- Our results should help the production efficiency for ornamental culture of juvenile A. latezonatus. Growth can be optimised and the time from settling of larvae to saleable-sized juveniles may be substantially reduced
- The relatively low optimal temperature for growth of A. latezonatus juveniles corresponds to sea temperatures within its subtropical range, which is restricted within 4° of latitude and 15° of longitude
- Experimentally elevated sea temperatures can strongly influence larval duration,

swimming competency and growth of tropical reef fish
- The effects of rising seawater temperatures on juvenile subtropical endemics, like A. latezonatus, are likely to affect growth of juveniles, which could impact on their survivorship to adulthood

Selig, E. R., Casey, K. S., & Bruno, J. F. (2010). New insights into global patterns of ocean temperature anomolies: Implications for coral reef health and management. *Global Ecology and Biogeography, 19*(3), 397-411.

Abstract: Aim: Coral reefs are widely considered to be particularly vulnerable to changes in ocean temperatures, yet we understand little about the broad-scale spatio-temporal patterns that may cause coral mortality from bleaching and disease. Our study aimed to characterize these ocean temperature patterns at biologically relevant scales. Location Global, with a focus on coral reefs. **Methods:** We created a 4-km resolution, 21-year global ocean temperature anomaly (deviations from long-term means) database to quantify the spatial and temporal characteristics of temperature anomalies related to both coral bleaching and disease. Then we tested how patterns varied in several key metrics of disturbance severity, including anomaly frequency, magnitude, duration and size. Results: Our analyses found both global variation in temperature anomalies and fine-grained spatial variability in the frequency, duration and magnitude of temperature anomalies. However, we discovered that even during major climatic events with strong spatial signatures, like the El Niño–Southern Oscillation, areas that had high numbers of anomalies varied between years. In addition, we found that 48% of bleaching-related anomalies and 44% of disease-related anomalies were less than 50 km2, much smaller than the resolution of most models used to forecast climate changes. Main conclusions The fine-scale variability in temperature anomalies has several key implications for understanding spatial patterns in coral bleaching- and disease-related anomalies as well as for designing protected areas to conserve coral reefs in a changing climate. Spatial heterogeneity in temperature anomalies suggests that certain reefs could be targeted for protection because they exhibit differences in thermal stress. However, temporal variability in anomalies could complicate efforts to protect reefs, because high anomalies in one year are not necessarily predictive of future patterns of stress. Together, our results suggest that temperature anomalies related to coral bleaching and disease are likely to be highly heterogeneous and could produce more localized impacts of climate change.

Questions this article answers: what broad-scale spatio-temporal patterns that may cause coral mortality from bleaching and disease? What are the characteristics of ocean temperature patterns at biologically relevant scales?

Methodology: We created a 4-km resolution, 21-year global ocean temperature anomaly (deviations from long-term means) database to quantify the spatial and temporal characteristics of temperature anomalies related to both coral bleaching and disease. Then we tested how patterns varied in several key metrics of disturbance severity, including anomaly frequency, magnitude, duration and size.

Findings:

- There was global variation in temperature anomalies and fine-grained spatial variability in the frequency, duration and magnitude of temperature anomalies
- Even during major climatic events with strong spatial signatures, like the El Niño–Southern Oscillation, areas that had high numbers of anomalies varied between years
- 48% of bleaching-related anomalies and 44% of disease-related anomalies were less than 50 km2, much smaller than the resolution of most models used to forecast climate changes
- The fine-scale variability in temperature anomalies has several key implications for understanding spatial patterns in coral bleaching- and disease-related anomalies as well as for designing protected areas to conserve coral reefs in a changing climate
- Temporal variability in anomalies could complicate efforts to protect reefs, because high anomalies in one year are not necessarily predictive of future patterns of stress

Shaish, L., Levy, G., Katzir, G., & et al. (2010). Coral reef restoration (Bolinao, Philippines) in the face of frequent natural catastrophes. *Restoration Ecology, 18*(3), 285-299.

Abstract: Restoration of coral reefs is generally studied under the most favorable of environmental conditions, a stipulation that does not always reflect situations in the field. A 2-year study (2005–2007), employing the "reef gardening" restoration concept (that includes nursery and transplantation phases), was conducted in Bolinao, Philippines, in an area suffering from intense human stressors. This site also experienced severe weather conditions, including a forceful southwesterly monsoon season and three stochastic environmental events: (1) a category 4 typhoon hit the Bolinao's lagoon (May 2006) impacted farmed corals; (2) heavy rains (August 2006) caused seepages of freshwater, followed by reduced salinity that impacted transplanted colonies; and (3) a bleaching event (June 2007) caused by warming of seawater, severely impacted both nursery and transplanted corals. This study analyzes the effects of these natural catastrophes on restoration efforts, and presents the successes and failures of recently used restoration instruments. Our results show that (1) in the nursery phase, consideration should be paid to depthflexible constructions and tenable species/genotypes prioritization and (2) for transplantation acts, site/species deliberation, timing, and specific site selections should be taken into account. Only the establishment of large-scale nurseries and large transplantation measures and the adapting of restoration management to the frequently changing environment may forestall extensive reef degradation due to the combination of continuous anthropogenic and worsening global changes.

Questions this article answers: what does coral reef restoration look like under unfavorable environmental conditions (high human stressors and severe weather conditions)?

Methodology: A 2-year study (2005–2007), employing the "reef gardening" restoration concept (that includes nursery and transplantation phases), was conducted in Bolinao, Philippines; During July and August 2005, two nurseries were constructed, holding 6,824 coral ramets from seven coral species

Findings:

- In the nursery phase, consideration should be paid to depthflexible constructions and tenable species/genotypes prioritization
- For transplantation acts, site/species deliberation, timing, and specific site selections should be taken into account
- The two coral nursery phases suffered from two major environmental catastrophes: the 2006 typhoon and the 2007 bleaching events, the latter being the most devastating
- The combined effects of higher water temperatures and irradiation were predictive early warning signals for coral bleaching
- Improved nursery management, such as lowering of the nursery bed to deeper water during critical periods to reduce the effects of irradiation and water temperature could have prevented bleaching in nursery-farmed coral

- Susceptibility to bleaching was species-specific
- The transplanted colonies withstood two more stochastic natural disturbance events and a tempestuous southwesterly monsoon season, all potentially affecting survival.

Sinutok, S., Hill, R., Doblin, M. A., & et al. (201). Warmer more acidic conditions cause decrease productivity and calcification in subtropical coral reef sediment dwelling calcifiers. *Limnology and Oceanography, 56*(4), 1200-1212.

Abstract: The effects of elevated CO2 and temperature on photosynthesis and calcification in the calcifying algae Halimeda macroloba and Halimeda cylindracea and the symbiont-bearing benthic foraminifera Marginopora vertebralis were investigated through exposure to a combination of four temperatures (28uC, 30uC, 32uC, and 34uC) and four CO2 levels (39, 61, 101, and 203 Pa; pH 8.1, 7.9, 7.7, and 7.4, respectively). Elevated CO2 caused a profound decline in photosynthetic efficiency (FV : FM), calcification, and growth in all species. After five weeks at 34uC under all CO2 levels, all species died. Chlorophyll (Chl) a and b concentration in Halimeda spp. Significantly decreased in 203 Pa, 32uC and 34uC treatments, but Chl a and Chl c2 concentration in M. vertebralis was not affected by temperature alone, with significant declines in the 61, 101, and 203 Pa treatments at 28uC. Significant decreases in FV : FM in all species were found after 5 weeks of exposure to elevated CO2 (203 Pa in all temperature treatments) and temperature (32uC and 34uC in all pH treatments). The rate of oxygen production declined at 61, 101, and 203 Pa in all temperature treatments for all species. The elevated CO2 and temperature treatments greatly reduced calcification (growth and crystal size) in M. vertebralis and, to a lesser extent, in Halimeda spp. These findings indicate that 32uC and 101 Pa CO2, are the upper limits for survival of these species on Heron Island reef, and we conclude that these species will be highly vulnerable to the predicted future climate change scenarios of elevated temperature and ocean acidification.
Questions this article answers: What are the effects of CO2 and temperature on the photosynthesis and calcification in calcifying algae Halimeda macroloba and Halimeda cylindracea and the symbiont-bearing benthic foraminifera Marginopora vertebralis?

Methodology: algae was investigated through exposure to a combo of 4 temp and 4 CO2 levels

Findings:

- Elevated CO2 caused a profound decline in photosynthetic efficiency, calcification, and growth in all species
- The rate of oxygen production declined at 61, 101, and 203 Pa in all temperature treatments for all species
- The elevated CO2 and temperature treatments greatly reduced calcification (growth and crystal size) in M. vertebralis and, to a lesser extent, in Halimeda spp.
- These findings indicate that 32uC and 101 Pa CO2, are the upper limits for survival of these species on Heron Island reef
- These species will be highly vulnerable to the predicted future climate change scenarios of elevated temperature and ocean acidification.
- Noncalcifying macroalgae, which may benefit from near-future climate change scenarios (Gao et al. 1993; Hobday et al. 2006), are expected to exhibit a competitive advantage over calcifying species
- The loss of these calcifying keystone species will affect many other associated species, such as fish communities, in the future

Slattery, M., Lesser, M. P., Brazeau, D., Stokes, M. D., & Leichter, J. J. (2011).

Connectivity and stability of mesophotic coral reefs. ***Journal of Experimental Marine Biology and Ecology, 408*****(1-2), 32-41.**

Abstract: Mesophotic coral ecosystems (MCEs), occurring at depths of 30 to over 150 m, represents the deep continuum of adjacent shallow coral reefs about which little is known. These reefs are most developed, and most frequently studied, in areas where light penetration is high and photosymbiotic reef-builders (corals) can persist as common members of the benthic community. The upper mesophotic zone typically extends to 60 m and comprises communities that are generally similar to those found in shallow reef systems. Below 60 m, the lower mesophotic zone is dominated by sponges and algae that are uncommon or absent from shallower areas, and a fish fauna that is largely specialized to these intermediate depths. It is likely that these ecosystems are much more widespread and important than was previously recognized. MCEs have the potential to function as refugia for shallow reefs because many disturbances in the upper 30 m may leave MCEs largely intact. Ontogenetic movement and spawning migrations by reef fishes provide an important ecological component to connectivity between shallow and mesophotic reefs and may represent the effective range of larval dispersal. However, there is currently limited information on genetic connectivity between deep and shallow coral reef populations, and this is a critical gap in understanding the role of MCEs in coral reef resilience. Here we review the connectivity and trophic relationships between the shallow and mesophotic coral reefs, the potential role of MCEs as refugia, and the effects of a new biological invader that exposes critical gaps in our understanding of the stability of these ecosystems.

Questions this article answers: How widespread and important are MCEs? What is their potential to function as refuge for shallow reefs during times of disturbance?

Methodology: literature review

Findings:

- The advent of technical diving has provided a glimpse into the deep reef communities, now known as “mesophotic coral ecosystems” (MCEs_
- One of the most obvious abiotic differences on MCE reefs is the low irradiance of photosynthetically active radiation
- The productivity and main source of energy for a particular part of the reef largely depends on the availability of solar irradiance, nutrients and suspended organic matter; each of these factors may change with depth
- In the face of overwhelming evidence for deterioration of shallow reef ecosystems, the management concerns for mesophotic ecosystems are heightened on several fronts
- The upper mesophotic zone (30–60 m) apparently serves as a refuge for shallow reef organisms, as indicated by the many shallow reef species that also inhabit this depth stratum
- The lower end of the mesophotic zone (60–150m) may have higher endemism and fewer links to shallow reef habitats and a fauna that depends more on heterotrophy than autotrophy

- While MCEs may have greater stability than shallowreefs across glacial sea level changes, they may be sensitive to disturbances in the upper water column that reduce light penetration
    - They are probably even more vulnerable to stress than shallow reef counterparts, especially near human population centers
    - Could play a large role in explaining the recent changes observed in deep reefs at sites such as the north shore of Jamaica and the leeward shore of Bonaire where development has accelerated in the past decade
- The high biodiversity and endemism in MCEs relative to shallow counterparts can be attributed to:
- Restricted dispersal relative to shallow reef fauna, or 2) greater stability across Pleistocene glacial epoch

Quotes:
"It is likely that the deep reef forms a sink as organic material, detritus and sediment fluxes move downward with gravity. However, little is known about the frequency of occurrence of these processes and future research should focus on quantifying these energy fluxes in order to assess the role of MCEs in the trophic energy budgets, and possible source/sink relationships."

Smale, D. A., Kendrick, G. A., Waddington, K. I., & et al. (2010). Benthic

assemblage composition on subtidal reefs along a latitudinal gradient in Western Australia. ***Estuarine, Coastal, and Shelf Science, 86*****(1), 83-92.**

Abstract: At regional scales, the distribution of species and the structure of assemblages vary with latitude within many marine and terrestrial systems. The oligotrophic coastal waters of Western Australia (WA) support highly speciose and endemic assemblages, yet spatial patterns in benthic structure are currently poorly known. We examined benthic assemblage composition along a latitudinal gradient of 28.5–33.5_S and a depth gradient of 14–62 m, on subtidal reefs in warm-temperate WA. We surveyed benthos using a remotely triggered digital stills camera. In total, we sampled macroalgae and sessile invertebrates at 201 sites spread across four locations. Percent cover of coarse taxonomic groups and dominant species was estimated from over 2000 photoquadrat samples. We recorded significant differences in benthic assemblage composition between locations, and along depth gradients within each location. However, the magnitude of change with depth was not consistent between locations, and shifts in assemblage composition along the depth gradients were not as pronounced as expected. The percent cover of all dominant benthic groupings differed between locations, and several key taxa, such as the kelp Scytothalia dorycarpa, brown foliose macroalgae, hard corals and sponges, changed predictably along the latitudinal gradient. Our study adopted a coarse taxonomic, but assemblage-wide, approach to describing macrobenthic assemblages, and clear differences between locations and depths were detected. The surveys have provided baseline data on broad scale ecosystem structure against which to detect future ecological change.

Questions this article answers: What are the spatial patterns in benthic structure?

Methodology: examined benthic assemblage composition along a latitudinal gradient of 28.5–33.5_S and a depth gradient of 14–62 m, on subtidal reefs in warm-temperate WA; surveyed benthos using a remotely triggered digital stills camera. In total, we sampled macroalgae and sessile invertebrates at 201 sites spread across four locations.

Findings:

- There were highly significant differences in benthic assemblage composition between the locations, both when considering the entire dataset and when standardising for depth
- There was also indication of some partitioning between all locations, and suggested that assemblages at Abrolhos were largely distinct from those at the other locations
- Plots of mean coverage of benthic groupings against depth foreach location suggested that depth related patterns were not consistent between locations
- As could be predicted, the percent cover of the algal groups tended to peak in the shallows (i.e.14–29 m) before decreasing with depth thereafter
- Benthic assemblages on subtidal reefs in nearshore temperate waters of WA were characterized by a dominance of the kelp Ecklonia radiata, a high cover of foliose algae, and a low cover but wide occurrence of sessile invertebrates
- Other studies have documented significant shifts in benthic communities along a

latitudinal cline. These shifts are generally attributed to ‘bottom up’ effects, such as the proximity of upwellings, gradients in sea temperature, and the effects of disturbance and light

- Where gradients in physical conditions are steep and environmental changes occur across smaller distances, shifts in assemblage composition are likely to be more pronounced and easier to distinguish from background (small scale) variability
- The species-rich nearshore assemblages at Ninagloo in the northwest and on the subtidal limestone reefs in the southwest may be partially protected from such warming by wind-driven counter currents, which carry colder water northwards during the summer months
- The LC is a key driver of ecosystem structure in the region, current climate models are unable to predict future changes in the strength of the LC with any certainty.

Quotes:
“The intensity and latitude of storm tracks has changed in the region, but it remains unclear how this will relate to effective hydrodynamic stress on subtidal reefs, which is also a key driver of community structure. Despite this uncertainty, it is highly likely that changes in ecosystem structure will occur in response to climate change, and our surveys have provided baseline data on benthic assemblage composition against which to detect such changes.”

Smith, T. B., Blondeau, J., Nemeth, R. S., & et al. (2010). Benthic structure and cryptic mortality in a caribbean mesophotic coral reef bank system, the hind bank

marine conservation district, U.S. virgin islands. ***Coral Reefs, 29*****(2), 289-308.**

Abstract: Coral reef banks may form an important component of mesophotic coral ecosystems (MCEs) in the Caribbean, but remain poorly explored relative to shallower reefs and mesophotic habitats on slopes and walls. Consequently, the processes structuring mesophotic coral reef communities are not well understood, particularly the role of disturbance. A large and regionally important mesophotic system, the Hind Bank Marine Conservation District (MCD), St. Thomas, USVI, was systematically surveyed. Data were used to construct a comprehensive benthic habitat map for the MCD, describe the abiotic and biotic components of the benthos among habitats, and investigate patterns of coral health among habitats. Two-thirds of the MCD (23.6 km2) was found to be dense coral reef (Coral Cover = 24.1%) dominated by the Montastraea annularis species complex. Coral reef ecosystems were topographically complex, but could be classified into distinct habitat types, including high coral banks (35.8% of the MCD) and two large novel coral reef habitat types corresponding to an extremely flat basin (18%) and a highly rugose hillock basin (6.5%), containing thousands of coral knolls (2–10 m high). An extreme disease event with undescribed signs of mortality occurred on 47% of coral reefs and reached a high prevalence in affected areas (42.4% ± 6.3 SE, N = 26). The disease was significantly clustered in the basin habitats of the western MCD (global Moran's I = 0.32, P\0.01). Observations of the spatial pattern suggested that the driver was specific to the basin habitats and may have been caused by a coherent abiotic event.

Questions this article answers: How are shallow reef and mesophotic habitats on slopes and walls important components to coral ecosystems in the Caribbean?

Methodology: regional case study: comprehensive benthic habitat map

Findings:

- Two-thirds of the MCD (23.6 km2) was found to be dense coral reef (Coral Cover = 24.1%) dominated by the Montastraea annularis species complex
- Coral reef ecosystems were topographically complex, but could be classified into distinct habitat types
  - High coral banks (35.8% of the MCD
  - Two large novel coral reef habitat types corresponding to an extremely flat basin (18%)
  - Highly rugose hillock basin (6.5%), containing thousands of coral knolls (2–10 m high)
- Extreme disease event with undescribed signs of mortality occurred on 47% of coral reefs and reached a high prevalence in affected areas
- Disease was significantly clustered in the basin habitats of the western MCD (global Moran's I = 0.32, P\0.01)
- Suggests that the driver was specific to the basin habitats and may have been caused by a coherent abiotic event

Smith, J. E., Hunter, C. L., & Smith, C. M. (2010). The effects of top-down versus bottom-up control of bent hic coral reef community structure. ***Oecologia, 163*****(2), 497-507.**

Abstract: While climate change and associated increases in sea surface temperature and ocean acidification, are among the most important global stressors to coral reefs, overfishing and nutrient pollution are among the most significant local threats. Here we examined the independent and interactive effects of reduced grazing pressure and nutrient enrichment using settlement tiles on a coral-dominated reef via long-term manipulative experimentation. We found that unique assemblages developed in each treatment combination confirming that both nutrients and herbivores are important drivers of reef community structure. When herbivores were removed, fleshy algae dominated, while crustose coralline algae (CCA) and coral were more abundant when herbivores were present. The effects of fertilization varied depending on herbivore treatment; without herbivores fleshy algae increased in abundance and with herbivores, CCA increased. Coral recruits only persisted in treatments exposed to grazers. Herbivore removal resulted in rapid changes in community structure while there was a lag in response to fertilization. Lastly, re-exposure of communities to natural herbivore populations caused reversals in benthic community trajectories but the effects of fertilization remained for at least 2 months. These results suggest that increasing herbivore populations on degraded reefs may be an effective strategy for restoring ecosystem structure and function and in reversing coral-algal phase-shifts but that this strategy may be most effective in the absence of other confounding disturbances such as nutrient pollution.

Spillman, C. (2011). Advances in forecasting coral bleaching conditions for ref management. ***Bulletin of the American Meteorological Society, 92*****(12), 1586-1591.**

Abstract: he preservation of coral reefs under a changing climate requires a coordinated approach that integrates observational, experimental, and modeling efforts with practical

management and sound government policy. Coral reefs are among the most species-rich habitats in the world, but also among the most vulnerable to our current high-emission path. Observations of the climate system have shown an increase in global average surface temperature during the twentieth century, with an increased rate of warming since 1950. This has been attributed to increased levels of anthropogenic carbon dioxide (CO2) in the atmosphere since the preindustrial era, primarily due to the human activities of fossil fuel combustion and forest logging. Here, we summarize some of the linkages between atmospheric CO2 and the physical and chemical processes that it drives: climate change, increased sea surface temperatures, ocean acidification, tropical cyclone frequency/severity, and sea level rise (Fig. 1). We then draw links between these processes and specific threats to coral reef ecosystems. Finally, we propose a strategic framework for how observations and forecasting systems can be coordinated as part of national meteorological and ocean services, alerting reef managers and policy makers to areas at high risk from both local and global pressures.

Questions this article answers: What are the links between the processes of climate change, increased sea surface temperatures, ocean acidification, tropical cyclone frequency/severity, and sea level rise and specific threats to coral reef ecosystems? What framework can be coordinated to alert reef managers and policy makers about areas at high risk from local and global pressures?

Methodology: Literature review

Findings:

- Projections for most IPCC scenarios predict a rise in sea surface temperatures (SST) of at least 2°C in the twenty-first century.
    - This is likely to push most coral reefs close to or beyond their threshold for bleaching more often, reducing their ability to recover from such events.
- Warming climate- likely to affect the frequency and intensity of tropical cyclones- warm sea surface temperatures are needed for cyclogenesis
    - -Cyclones can be very destructive to coral reefs- relocate large coral colonies, reduce reefs to rubble
- Role of framework for meteorological and ocean services- Participation in (and support of) regional and global observation networks
    - Numerical weather prediction
    - Targeted reef services must be well designed in order to reliably provide useful information in near real-time that allows for rapid management responses to reef threats.
- The development of operational cross-disciplinary reef services will provide improved risk and vulnerability assessments for coral reefs, and can assist in the development of monitoring, conservation, and adaptation strategies
    - Close collaboration between meteorological and ocean services, reef management agencies, and
- The science community is essential the creation of multidisciplinary, cross-institutional research programs that underpin such services is important,

particularly for the investigation of reef ecosystem responses to global warming and ocean acidification, and assessment of associated impacts on ecological, social, and economic systems.

Spillman, C. M. (2011). Operational real-time seasonal forecast for coral reef management. *Journal of Operational Oceanography, 4*(1), 13-22.

Abstract: Mass coral bleaching, associated with anomalously warm ocean temperatures over large regions, poses a serious threat to the future health of the world coral reef

systems. Seasonal forecasts from coupled ocean– atmosphere models can be a valuable resource for reef management, providing early warning of potential bleaching conditions, allowing for a proactive management response. Here, the ability of a dynamical seasonal forecast model (Predictive Ocean Atmosphere Model for Australia, POAMA) to forecast degree heating months (DHMs) in the tropical oceans is assessed, with particular focus on the 1997/98 El Nin˜ o– Southern Oscillation (ENSO) and associated global bleaching events. The model exhibits useful skill in forecasting sea surface temperatures (SSTs) across the tropical oceans for 1982–2006 and reproduced both the magnitude and distribution of DHM values observed during the 1997/98 ENSO event. In general, observed teleconnections between ENSO indices and tropical SST at various lags are well captured by the model. In particular, strong observed correlations between peak ENSO indices and SST in the Caribbean in the following summer were reproduced. The model also shows skill in predicting ocean conditions conducive to bleaching in non-ENSO years, capturing the anomalously warm conditions in the Caribbean region in 2005. Probabilistic forecasts ofDHMvalues above certain thresholds for the Caribbean show useful skill and could be valuable in the assessment of the likelihood of bleaching for the region.

Questions this article answers: how might seasonal forecasts from coupled ocean-atmospheric models be of value to resource management?

Methodology: dynamical seasonal forecast model (Predictive Ocean Atmosphere Model for Australia, POAMA) to forecast degree heating months (DHMs) in the tropical oceans is assessed (focus on the 1997/98 El Nin˜ o– Southern Oscillation (ENSO) and associated global bleaching events)

Findings:

- Teleconnections between ENSO indices and tropical SST at various lags are well captured by the model.
- The model shows skill in predicting SST anomalies across the tropical ocean for both the Northern and Southern Hemisphere summers up to 3 months into the future, with highest skill in the equatorial Pacific
- Strong observed correlations between peak ENSO indices and SST in the Caribbean in the following summer were reproduced
- The model also shows skill in predicting ocean conditions conducive to bleaching in non-ENSO years, capturing the anomalously warm conditions in the Caribbean region in 2005.
- For the global 1997/98 bleaching event, the model reproduces observed DHMvalues across the tropical oceans with accuracy
- Mass coral bleaching events have been linked to largescale coupled ocean–atmosphere phenomena, such as ENSO, the PDO, and possibly the Atlantic multidecadal oscillation (AMO), which can result in sustained regional elevations of ocean temperature
- The largest contributor to the warm temperatures in the tropical Atlantic is climate change. Biological adaptation of coral to warmer ambient conditions is unlikely to keep pace with expected temperature increases

Quotes:
"Management tools such asPOAMA forecasts, which can provide information to reef managers as to the potential risk of bleaching several months in advance, are invaluable as strategies can then be implemented prior to bleaching onset. Knowledge of climate processes and drivers of bleaching, and hence management tools and strategies, must be improved in order to conserve these global resources in the face of climate change."

Stella, J. S., Jones, G. P., & Pratchett, M. S. (2010). Variation in the structure of epifaunal invertebrate assemblages among coral hosts. *Coral Reefs, 29*(4), 957-973.

Abstract: The high biodiversity of coral reefs is attributable to the many invertebrate

group which live in symbiotic relationships with other reef organisms, particularly those which associate with the living coral habitat. However, few studies have examined the diversity and community structure of coral-dwelling invertebrates and how they vary among coral species. This study quantified the species richness and composition of animals associated with four common species of branching corals (*Acropora nasuta*, *A. millepora*, *Pocillopora damicornis*, and *Seriatopora hystrix*) at Lizard Island in the northern Great Barrier Reef. One hundred and seventy-eight nominal species from 12 different phyla were extracted across 50 replicate colonies of each coral host. A single coral colony, approximately 20 cm in diameter, harbored as many as 73 individuals and 24 species. There were substantial differences in invertebrate species composition among coral hosts of different families as well as genera. Twenty-seven species (15% of all taxa collected) were found on only one of the four different coral species, which may potentially indicate some level of specialization among coral hosts. The distinct assemblages on different coral species, and the presence of potential specialists, suggests invertebrate communities will be sensitive to the differential loss of branching coral species resulting from coral reef degradation.

Questions this article answers: What is the diversity and community structure of coral-dwelling invertebrates, and how do they vary among coral species? What are the implications of this with the threat of climate change?

Methodology: quantified the species richness and composition of animals associated with four common species of branching corals (*Acropora nasuta*, *A. millepora*, *Pocillopora damicornis*, and *Seriatopora hystrix*) at Lizard Island in the northern Great Barrier Reef.

Findings:

- A single coral colony, approximately 20 cm in diameter, harbored as many as 73 individuals and 24 species.
- There were substantial differences in invertebrate species composition among coral hosts of different families as well as genera: Even among coral colonies of the same species, there were substantial differences in the abundance (ranging from 1 to 73 individuals) and species richness (ranging from 1 to 24 different taxa)
- Twenty-seven species (15% of all taxa collected) were found on only one of the four different coral species, which may potentially indicate some level of specialization among coral hosts.
- As coral cover declines within the colony, uniformity of habitat is lost and new microhabitats within the colony allow for other species to utilize new resources.
- The large variation in species composition among corals of different families and genera indicates that the occurence of specialization may be high among coral-dwelling invertebrates
- The most abundant taxa for all four coral species studied were the decapod crusctaceans, accounting for up to 66% of all epifaunal animals collected.

Quotes:

“Animals so intimately associated with their habitat may be vital to the maintenance of critical ecological systems pertaining to coral health. As the invertebrate groups account for the greatest numerical abundance and diversity on coral reefs, yet have received the least attention, our knowledge of coral reef ecosystem function is derived from what we know about a relatively small proportion of coral reef species. If preventing the loss of species and reversing declines in biodiversity is the fundamental aim of coral reef conservation, then more research effort on the other possible 9 million species of coral reef invertebrates is clearly needed.”

Tsai, S., Spikings, E., Huang, I. C., & et al. (2011). Study of the mitochondrial activity and membrane potential after exposing later stage oocytes of two gorgonian corals (junceela juncea and junceela fragilis) to cryoprotectants. *Cryoletters, 32*(1), 1-12.

Abstract: Coral reefs provide a valuable habitat for many economically valuable fish and invertebrates. However, they are in serious jeopardy, threatened by increasing over-exploitation, pollution, habitat destruction, disease and global climate change. Here, we examined the effect of cryoprotectant exposure on mitochondrial activity and membrane potential in coral oocytes in order to find suitable cryoprotectants towards their successful cryopreservation. According to the No Observed Effect Concentrations (NOECs), methanol was found to be the least toxic cryoprotectant whilst DMSO was the most toxic cryoprotectant. The results also demonstrated that there were no significant differences ($p > 0.05$) in ATP concentrations between Junceella juncea and Junceella fragilis after exposure to all concentrations of all cryoprotectants for 30 min. Using confocal microscopy, JC-1 (5,50,6,60-tetrachloro-1,10,3,30-tetraethyl-imidacarbocyanine iodide) staining indicated that the mitochondrial membrane potential of Junceella fragilis oocytes reduced after 1 M and 2 M methanol treatment and a loss of the mitochondrial distribution pattern and poor green fluorescence after 3M methanol treatment. Therefore, even oocytes that show no adverse effect of cryoprotectants on survival might suffer some more subtle impacts. The results obtained from this study will provide a basis for development of protocols to cryopreserve the oocytes of gorgonian corals.

Questions this article answers: What is the effect of cryoprotectant exposure on mitochondrial activity and membrane potential in coral oocytes?

Methodology: examined the effect of cryoprotectant exposure on mitochondrial activity and membrane potential in coral oocytes in order to find suitable cryoprotectants towards their successful cryopreservation

Findings:
(see abstract)- need to talk to someone about this one

Van Woesik, Robert and Adan Guillermo Jordan-Garza. (2011). Coral Populations in a Rapidly Changing Environment

Abstract: Contemporary coral populations are being forced to survive through

disturbances at a variety of spatial and temporal scales. Understanding disturbances in the context of ecological processes may lead to models that accurately predict population trajectories. Few studies examine the key ecological processes that drive changes on reefs. Processes of major interest include reproduction, recruitment, post-settlement mortality, coral growth, fragmentation, and mortality. These population processes are dependent on macro-processes, such as predation and herbivory, which in turn vary in accordance with regional oceanography. Some coral reef regions experience high-frequency temperature anomalies, whereas other regions experience lowfrequency anomalies. It may turn out that corals in the high-frequency regions are also most likely to undergo rapid directional selection, and adapt to climate change, because only alleles experiencing persistent selection pressure may attain high frequency. Yet corals are clonal organisms and the same genotypes are often exposed to different environments and to different selective pressures. Therefore, when comparing coral population trajectories across regions and oceans, it is critical to understand the key processes of corals within local, regional, and historical contexts.

Questions this article answers: What are the ecological processes (mostly population processes) that drive changes on reefs? What are the key processes of corals within local, regional, and historical contexts?

Methodology: literature review for reef processes (reproduction, recruitment, post-settlement mortality, coral growth, fragmentation, and mortality)

Findings:

- The basic processes that determine population dynamics are reproduction, recruitment, post-settlement survival, colony growth, and partial and total mortality
- Coral population dynamics and macro-processes are in turn influenced by local and regional oceanography.
- Micro-evolutionary of corals may differ depending on high or low frequency of thermal stress, for example
- In the case of corals, defining a population is a complex task because of the patchy nature of coral reefs, and the difficulty of estimating connectivity among subpopulations
- Colony size determined the onset of reproduction of Porites astreoides, whereas polyp age determined fecundity.
- Who cares: moving to a non-analog climate where coral colonies will be undergoing unprecedented rates of fragmentation
- **Reproduction:** Will corals revert back to immaturity upon fragmentation? Depends on the corals- some use size of coral colony as marker and revert back with fragmentation- others age, rather than size to mark maturity
- **Recruitment:** the abundance of small colonies does not indicate that the colonies are active contributors to local or regional populations.
- Recruitment clearly requires locally gravid adult coral colonies to supply larvae, and the amount of space available to settle
- **Physiological trade-offs:** attempting to sustain three functions- maintenance,

growth, and reproduction

- A damaged or diseased coral will allocate considerable energy to maintenance at the expense of growth and reproduction
- Corals either do: high recruitment rates, rapid growth rates, and low adult survival, or low recruitment rates, slow growth rates, and high adult survival
- Aging is less common in clonal organisms than it is in clonal reef organisms
- **Colony morphology:** important role in environmental susceptibility: certain corals more susceptible to thermal stress than corals with massive growth forms
- Difficult to compare thick and think-skinned corals
- **Mortality:** can occur at any stage of coral life. Factors affecting mortality rates: predation, water quality, and water motion, and UV radiation
- Can reef resilience be increased by local conservation efforts? Yes. For example, Wagner et al. (2010) recently showed that reefs in the Florida Keys that consistently suffered high loads of dissolved inorganic nitrogen were also more susceptible to coral bleaching under regional temperature stress. Such information is useful to reef management because it may lead to laws that reduce local discharge of nitrogen from local septic systems. In other words by improving water quality, local reef resilience may be increased in the face of climate change induced thermal stress.
    - Local management can alleviate fishing pressure on reefs that play a vital role in controlling fish densities.
    - Local recruitment of corals: will benefit the local environment, but if the local environment becomes degraded, the loss of suitable habitat and low probability of dispersal could lead to loss of sensitive species

Quotes: "Such strong selective pressure will favor certain species, while removing others from the gene pool. Quantitative studies are necessary to understand the complex mechanisms that govern micro- and macroprocesses on coral reefs and to understand which coral species will be most vulnerable"

"But success will depend on a number of conditions, including the nature of the regional gene pool, the life-history characteristics of the organisms involved, the frequency and strength of the disturbances, the local and regional oceanography, and the nature of the local and regionalmanagement strategies. In that sense, local and regional management strategies have the potential to buffer the expected negative changes to coral populations."

Vargas-Angel. Severe, Widespread El Niño-Associated Coral Bleaching in the US Phoenix Islands.

Abstract: The present study provides an assessment of the bleaching response of corals at

Baker and Howland Islands (central Pacific) following the 2009-2010 El Niño-Southern Oscillation event. Nearly 35% of colonies belonging to 17 coral genera surveyed within belt transects exhibited bleaching, predominantly along east Howland Island and east and northeast Baker Island, and within the 10-18 m isobaths. Bleaching conditions differed among coral taxa, with *Pocillopora*, *Acropora*, and *Fungia* exhibiting the greatest percentage of affected colonies, followed by *Pavona*, *Porites*, and *Psammocora*; *Montipora* appeared to be the most resistant to bleaching with < 2.5% of colonies affected. Colony size had direct effects on bleaching responses for *Acropora*, *Pavona*, and *Pocillopora*, with bleached colonies exhibiting greater mean diameters than unbleached corals; mixed effects were observed for *Fungia*, *Porites*, and *Psammocora*. Bleaching extent was also affected by colony size, but only in *Acropora*; the lack of differences in the other study corals is probably due to the high variability in the extent of bleaching within taxa. In situ subsurface loggers indicated that seawater temperatures increased steadily throughout 2009, peaking at 31.2 °c in early November, and remaining above the coral bleaching threshold (29.7 °c) beyond the time when instruments were recovered on 7 February, 2010. This is the first documented mass bleaching episode at baker and Howland Islands; however, anecdotal evidence suggests recurrent, widespread bleaching may be a principal source of disturbance, affecting coral reef species composition and structural dynamics at Howland and Baker over multi-year timescales.

Venera-Ponton, D. E., Diaz-Pulido, G., McCook, L. J., & et al. (2011). Macroalgae reduce growth of juvenile corals but protect them from parrotfish damage. ***Marine Ecology Progress Series, 421*****, 109-115.**

Abstract: Inhibition of early life stages of corals by benthic algae is a critical bottleneck to the recovery and resilience of corals. Increasingly frequent and severe disturbances are causing largescale coral mortality, usually followed by colonisation and dominance by benthic algae. The capacity of corals to re-establish in such algal-dominated habitats will depend on the effects of the algae on growth and survivorship of juvenile corals. We experimentally evaluated the competition between juvenile corals *Porites astreoides* and algae and the effects of algae on the exposure of juvenile corals to damage by parrotfishes (family Scaridae) in a Colombian Caribbean reef. We also explored whether those effects were consistent among climatic seasons (upwelling and non-upwelling). Benthic algae had negative and positive effects on the juvenile corals. The removal of algal turfs and fleshy macroalgae enhanced coral growth. Unexpectedly, removal of algae from around the juvenile corals increased predation upon the corals by parrotfishes. When algae were removed, at least 50% of the corals were grazed by parrotfishes, but no bites were observed on corals with intact algae. Coral growth and parrotfish damage were not affected by season. However, damage by parrotfishes neither lessened survivorship nor resulted in negative growth for any of the grazed coral colonies. The beneficial effects of algae in protecting the juvenile corals from parrotfish damage seem to be outweighed by the negative effects of the algae on coral–algal competition. Understanding such complexities in the interactions between algae and early life stages of corals can provide insight into the roles of algae in coral reef resilience.

Questions this article answers: What is the competition between juvenile corals and algae? What are the effects of algae on the exposure of juvenile corals to damage by parrotfishes?

Methodology: We experimentally evaluated the competition between juvenile corals *Porites astreoides* and algae and the effects of algae on the exposure of juvenile corals to damage by parrotfishes (family Scaridae) in a Colombian Caribbean reef.

Findings:

- Competition between corals and benthic algae in coral reefs is a critical ecological process driving the dynamics of both the algae and the corals
- Benthic algae had negative and positive effects on the juvenile corals. The removal of algal turfs and fleshy macroalgae enhanced coral growth
- Importantly, the negative effects of benthic algae on the juvenile corals did not vary among the 2 main climatic seasons, despite large variability in the type of algal communities occurring in the upwelling and rainy (nonupwelling) seasons.
- The presence of algae around the juvenile corals may to some extent also benefit coral populations by reducing the risk of predation by parrotfishes.
- When algae were removed, at least 50% of the corals were grazed by parrotfishes, but no bites were observed on corals with intact algae
- Coral growth and parrotfish damage were not affected by season. However, damage by parrotfishes neither lessened survivorship nor resulted in negative growth for any of the grazed coral colonies
- It is possible, for instance, that the long-term consequences of algal suppression on juvenile corals are even more complex than predicted by this short-term study.

Quotes:
"The protection against parrotfish predation provided by algae on corals may be explained by 2 mechanisms: (1) algae camouflage corals from the view of parrotfishes and (2) associational defences. The latter mechanism has been widely documented in marine and terrestrial ecosystems and refers to the protection gained from the association with low-palatability species, which create microhabitats of lowered grazing."

Villanueva, R. D., Edwards, A. J., & Bell, J. D. (2010). Enhancement of grazing gastropod populations as a coral reef restoration tool: Predation effects and related applied implications. ***Restoration Ecology, 18*****(6), 803-809**

Abstract: We aimed to evaluate the efficacy of the gastropod grazer *Trochus niloticus* in controlling epilithic algae and enhancing coral recruitment on artificial substrata on coral reefs where the biomass of herbivorous fishes was low due to heavy fishing pressure. Hatchery-reared, subadult trochus were stocked onto pallet balls (small artificial reefs composed of concrete and limestone aggregate) at a density of approximately four individuals per square meter (external surface area). This density was re-established with releases of new trochus each month for 6 months. At the end of the experiment, there were no significant differences in algal biomass, cover and community composition, or the density of coral recruits on substrata with and without trochus. High monthly attrition of stocked trochus on the pallet balls, apparently due mainly to predation by octopus, did not allow the evaluation of the efficiency of the trochus enhancement, at the desired density, as a restoration tool. However, at the lower trochus densities (circa 1 m^{-2}*)*, which occurred as a result of predation in this study, no apparent enhancement of algal grazing or coral recruitment were observed. The surprisingly high predation of stocked trochus in a heavily fished and gleaned reef site stresses the importance of understanding all the factors affecting the survival of stocked animals. To help mitigate predation of trochus, artificial habitat with refuge spaces that allow the grazers to escape predation could be provided and individuals of a larger size could be released.

Questions this article answers: what is the efficacy of the gastropod grazer *Trochus niloticus* in controlling epilithic algae and enhancing coral recruitment on artificial substrata on coral reefs?

Methodology: Hatchery-reared, subadult trochus were stocked onto pallet balls (small artificial reefs composed of concrete and limestone aggregate) at a density of approximately four individuals per square meter (external surface area). This density was re-established with releases of new trochus each month for 6 months

Findings:

- The algal community that developed on the pallet balls after the end of the 6-month experiment was mainly crustose and low profile.
- Tall, corticated macrophytes failed to develop, hence shading and abrasive effects to coral transplants did not occur.
- Crustose coralline algae, which also comprised about half of the algal community, can promote coral recruitment by acting as settlement cues for coral larvae
- The increase in algal cover with increasing transplant density could be due to the development of algal zones near the transplants (especially the branching forms).
- No apparent decrease in algal biomass and cover or change in algal community functional group composition was observed.
- On natural reefs, released subadult trochus have been recaptured mainly in habitats with these refuge structures, which can confer high survivorship, that is, at least 40% over 6 months

Webster, N. S. (2011). The larval sponge holobiont exhibits high thermal tolerance. *Environmental Microbiology Reports, 3*(6), 756-762.

Abstract: Marine sponges are critical components of benthic environments; however,

their sessile habit, requirement to filter large volumes of water and complex symbiotic partnerships make them particularly vulnerable to the effects of global climate change. We assessed the effect of elevated seawater temperature on bacterial communities in larvae of the Great Barrier Reef sponge, *Rhopaloeides odorabile*. In contrast to the strict thermal threshold of 32°C previously identified in adult *R. odorabile*, larvae exhibit a markedly higher thermal tolerance, with no adverse health effects detected at temperatures below 36°C. Similarly, larval microbial communities were conserved at temperatures up to 34°C with a highly significant shift occurring after 24 h at 36°C. This shift involved the loss of previously described symbionts (in particular the *Nitrospira*, *Chloroflexi* and a *Roseobacter* lineage) and the appearance of new *Gammaproteobacteria* not detected at lower temperatures. Here, we demonstrated that sponge larvae maintain highly stable symbioses at seawater temperatures exceeding those that are predicted under current climate change scenarios. In addition, by revealing that the shift in microbial composition occurs in conjunction with necrosis and mortality of larvae at 36°C we have provided additional evidence of the strong link between host health and the stability of symbiont communities.

Questions this article answers: What is the effect of elevated seawater termperature on bacterial communities in larvae of the Great Barrier Reef sponge, *Rhopaloeides odorabile*?

Methodology: case study of larval sponge in Great Barrier Reef and their symbiont relationship with microbial communities

Findings:

- Associated with global climate change (GCC), the projected increases in air and sea surface temperatures (SST) of up to 4°C by 2100 will have a direct and significant impact on coral reefs (IPCC, 2007).
- Sponges are a major component of coral reef macrofauna and play key ecological roles including: provision of habitat for other invertebrates, calcification, bioconsolidation, bioerosion, primary production and nitrification via complex microbial symbioses- but there are knowledge gaps in understanding the vulnerability of sponges to global climate change
    - -Probably have strict temperature thresholds- mass sponge mortality is correlated with high temps
- Sponges (both adults and larvae) host incredibly dense and diverse microbial communities- often specific to sponge hosts
    - Many of these symbiotic microbes are vertically transmitted from adults to larvae in the mesohyl tissue, providing additional support for their role in sponge biology and health
- Specifically, a strict thermal threshold between 31°C and 33°C was described for symbiosis in adult *R. odorabile* and the microbial shift included the loss of stable symbionts and the establishment of alien bacterial populations including potential pathogens.
- This research investigated the temperature tolerance of symbiotic partnerships in

the larvae of *R. odorabile* in an attempt to compare the thermal thresholds for the different life history phases of this model sponge species.

- Larvae of the GBR sponge *R. odorabile* have an extremely high thermal tolerance, surviving and functioning at 4–6°C above ambient temperatures at the time of larval release
    - After 48 h at 36°C sponge larvae showed signs of cellular lysis and mortality, which is consistent with an activation of the heat shock response at this temperature

  In adults- the same species exhibit high levels of necrosis and mortality after only 24–72 h at 32°C
- It is possible that larvae exhibit a different pattern of gene expression to adults, which allows them to physiologically cope with short-term exposures to high temperature

Weeks, S. J., Bakun, A., Steinberg, C. R., & et al. (2010). The capricorn eddy: A

prominent driver of the ecology and future of the southern great barrier reef. ***Coral Reefs, 29*****(4), 975-985.**

Abstract: This study focuses on a mesoscale eddy feature, the 'Capricorn Eddy' that typically forms within an indentation of the continental shelf in the southern GBR system. Satellite data at moderate resolution (1 km) are used to examine relevant mesoscale and sub-mesoscale sea surface dynamics. Available in situ measurements and model data are used to validate the satellite observations and to specify the nature of the processes occurring within the water column itself. The characteristic features are identified and physical theory employed to develop an understanding of associated processes. In particular, the effect of the eddy in raising cooler, nutrient-enriched oceanic subsurface water and transporting it to the reef zone, and eventually into the lagoon, is shown. This study demonstrates that the linkages between large-scale oceanography and the meso- and sub-mesoscale patterns are crucial to determining biologic responses on the scale of reef communities and may be key to understanding climate change impacts at the relevant spatial scales.

Questions this article answers: What are the examine relevant mesoscale and sub-mesoscale sea surface dynamics in the Capricorn Eddy?

Methodology: Satellite data at moderate resolution (1 km) are used to examine relevant mesoscale and sub-mesoscale sea surface dynamics. Available in situ measurements and model data are used to validate the satellite observations and to specify the nature of the processes occurring within the water column itself.

Findings:
The low chlorophyll concentrations that are typical of oceanic waters are likewise seen as intruding onto the shelf to the south of the Capricorn Bunker group,

It is known that the Capricorn-Bunker reefs, located on the shelf edge, are flushed by frequent intrusions of oceanic water

The resultant mixing of relatively cooler deeper water is clearly evident even in the long-term mean temperature distribution, which composites the summer months (December–February) over a number of years.

> This offers a clear indication of tidal mixing/shelf edge upwelling, evidently leading to generally lower levels of bleaching relative to the shallow coastal Keppel Islands' location inshore

Understanding the patterns of change that drive stress within coral reef ecosystems is critical to designing effective marine management outcomes

> Efforts to locate reserves in less stressful physical environments, such as relatively cool environments that experience high levels of mixing with cooler, deeper water, are critical issues within reserve design

Effects on local ecosystems are expected to be influenced in two potentially opposing ways by an intensification of EAC flow adjacent to the Capricorn Eddy:

(1) The complex of eddy mechanisms would tend to operate even more energetically (greater cooling effects, counteracting thermal stress and

bleaching efforts on reefs)

(2) Increased intensity of the local EAC flow might tend to increase the tendency for the Capricorn Eddy to be episodically shed from its quasi-stable position on the Capricorn Wedge, and perhaps to propagate southward along the Australian coast
    a. Might deprive the local system of the favorable eddy-related effects elaborated earlier, and likely affect those organisms that are highly dependent on the proximity of oceanic productive areas to nesting colonies or beaches

Wild, C., Hoegh-Guldberg, O., Naumann, M. S., & et al. (2011). Climate change impedes scleractinian corals as primary reef ecosystem engineers. *Marine and*

***Freshwater Research, 62*(2), 205-215.**

Abstract: Coral reefs are among the most diverse and productive ecosystems on our planet. Scleractinian corals function as the primary reef ecosystem engineers, constructing the framework that serves as a habitat for all other coral reef associated organisms. However, the coral's engineering role is particularly susceptible to global climate change. Ocean warming can cause extensive mass coral bleaching, which triggers dysfunction of major engineering processes. Sub-lethal bleaching results in the reduction of both primary productivity and coral calcification. This may lead to changes in the release of organic and inorganic products, thereby altering critical biogeochemical and recycling processes in reef ecosystems. Thermal stress-induced bleaching and subsequent coral mortality, along with ocean acidification, further lead to long-term shifts in benthic community structure, changes in topographic reef complexity, and the modification of reef functioning. Such shifts may cause negative feedback loops and further modification of coral-derived inorganic and organic products. This review emphasises the critical role of scleractinian corals as reef ecosystem engineers and highlights the control of corals over key reef ecosystem goods and services, including high biodiversity, coastal protection, fishing, and tourism. Thus, climate change by impeding coral ecosystem engineers will impair the ecosystem functioning of entire reefs.

Questions this article answers: How does climate change affect scleractinian corals (the primary reef ecosystem engineers)?

Methodology: literature review

Findings:
- Scleractinian corals act as key reef ecosystem engineers by:
- Autogenic engineering: because through their calcification and ensuing reef accretion, they change the physical, chemical, and biological environment and thereby **provide habitats** for associated reef organisms
- Corals also act as allogenic ecosystem engineers because they **intensively generate and transform inorganic and organic materials**.
- Ocean acidification can also affect coral reproduction by reducing sperm motility: ocean acidification may significantly affect recruitment rates and the competitive capacity of coral populations, and may consequently lead to a shift in coral community structure.
- Spawning female corals of the temperate species *Astrangia poculata* are more susceptible to the negative effects of ocean acidification than spawning male corals – gender discrimination- limited resources to compensate for the effects of acidification on calcification
- Thermal stress-induced bleaching and subsequent coral mortality, along with ocean acidification, further lead to long-term shifts in benthic community structure, changes in topographic reef complexity, and the modification of reef functioning.
- Scleractinian corals are eef ecosystem engineers; the control of corals over key reef ecosystem goods and services, including high biodiversity, coastal protection, fishing, and tourism will be affected by bleaching and high SST

- Bleaching-induced death of the coral engineers includes the generation of bare skeletons that are particularly sensitive to physical, chemical and biological erosion processes
- Production of calcareous reef sands will probably increase immediately after bleaching-induced mass coral mortality as a result of increased erosion.
- Will only last until carbonate supply is gone

Quotes:
The impacts of global climate change on fundamental physiological processes such as scleractinian coral growth, calcification, defence, maintenance and reproduction result in broad-scale consequences for ecosystem functions and services provided by the reef-building coral engineers. Reduced growth and reproduction translate directly to a reduced resilience of coral-dominated reef communities.

Wilkinson, Clive and Bernard Salvat. (2012). Coastal Resource degradation in the topics: Does the Tragedy and the Commons apply for coral reefs, mangrove forests and seagrass beds. *Marine Pollution Bulletin*.

Abstract: Tropical cyclones occur relatively frequently throughout the South Pacific with resultant changes to coral reefs and low lying coral islands. Cyclones can result in both accumulation of coral rock, rubble and sand to parts of coral reefs, whereas there can be severe damage and erosion to other parts of reefs and islands. Many coral reef islands owe their existence to the accumulation of material during tropical storms. The location of cyclones is strongly influenced by the El Nino Southern Oscillation, with more in the Eastern Pacific during El Nino events. The frequency of cyclones is unlikely to alter significantly in the future, however the strength of these cyclones will be strongly influenced by increasing global climate change and rising sea surface temperatures. The result is that there will probably be more large category 4 and 5 storms, which will result in even more localized damage to coral reefs and associated islands. While these cyclones will not be devastating for reefs at ocean scales, the synergy between their localized damage and more widespread effects of increasing sea surface temperatures, ocean acidification and rising sea levels, pose major threats for the long term existence of coral reefs as they occur today. Coral reef resource managers have no mechanisms to combat cyclones other than by joining global campaigns against climate change and the release of greenhouse gases; however they can assist in making reefs more resistant and resilient to cyclone damage by taking serious action to reduce direct and localized anthropogenic damage.

Questions this article answers: What is the potential impact of tropical cyclones on low lying coral islands?

Methodology: literature review

Findings:

- Cyclones can result in both accumulation of coral rock, rubble and sand to parts of coral reefs, whereas there can be severe damage and erosion to other parts of reefs and islands.
- The location of cyclones is strongly influenced by the El Nino Southern Oscillation, with more in the Eastern Pacific during El Nino events.
- The frequency of cyclones is unlikely to alter significantly in the future, however the strength of these cyclones will be strongly influenced by increasing global climate change and rising sea surface temperatures.
- The result is that there will probably be more large category 4 and 5 storms, which will result in even more localized damage to coral reefs and associated islands.
- While these cyclones will not be devastating for reefs at ocean scales, the synergy between their localized damage and more widespread effects of increasing sea surface temperatures, ocean acidification and rising sea levels, pose major threats for the long term existence of coral reefs as they occur today.
- Coral reef resource managers have no mechanisms to combat cyclones other than by joining global campaigns against climate change and the release of greenhouse gases

Wilson, S. K., Depczynski, M., Fisher, R., & et al. (2010). Habitat associations of juvenile fish at ningaloo reef, western australia: The importance of coral and algae. *PLoS One,* 5(12)

Abstract: Habitat specificity plays a pivotal role in forming community patterns in coral reef fishes, yet considerable uncertainty remains as to the extent of this selectivity, particularly among newly settled recruits. Here we quantified habitat specificity of juvenile coral reef fish at three ecological levels; algal meadows vs. coral reefs, live vs. dead coral and among different coral morphologies. In total, 6979 individuals from 11 families and 56 species were censused along Ningaloo Reef, Western Australia. Juvenile fishes exhibited divergence in habitat use and specialization among species and at all study scales. Despite the close proximity of coral reef and algal meadows (10's of metres) 25 species were unique to coral reef habitats, and seven to algal meadows. Of the seven unique to algal meadows, several species are known to occupy coral reef habitat as adults, suggesting possible ontogenetic shifts in habitat use. Selectivity between live and dead coral was found to be species-specific. In particular, juvenile scarids were found predominantly on the skeletons of dead coral whereas many damsel and butterfly fishes were closely associated with live coral habitat. Among the coral dependent species, coral morphology played a key role in juvenile distribution. Corymbose corals supported a disproportionate number of coral species and individuals relative to their availability, whereas less complex shapes (i.e. massive & encrusting) were rarely used by juvenile fish. Habitat specialisation by juvenile species of ecological and fisheries importance, for a variety of habitat types, argues strongly for the careful conservation and management of multiple habitat types within marine parks, and
indicates that the current emphasis on planning conservation using representative habitat areas is warranted. Furthermore, the close association of many juvenile fish with corals susceptible to climate change related disturbances suggests that identifying and protecting reefs resilient to this should be a conservation priority.

Questions this article answers: What is the extent os habitat specificity in forming community patterns in coral reef fishes? How does this relate to climate change related disturbances?

Methodology: quantified habitat specificity of juvenile coral reef fish at three ecological levels; algal meadows vs. coral reefs, live vs. dead coral and among different coral morphologies.

Findings:

- The composition of juvenile fish communities on coral reefs and macroalgal meadows are distinctly different, with the majority of fish species observed predominantly within one of these habitats
- Coral and macroalgal areas can be considered essential juvenile habitat and high fish diversity is likely to be dependant on the presence of both habitats
- Adults of juveniles observed exclusively in algal meadows were frequently observed on coral reefs, suggesting some connectivity between the two habitats
- Among the species found predominantly on coral reefs 14 were closely associated

with live coral, including several species that do not feed or associate with live corals as adults

- Massive and encrusting corals may not provide structural complexity at a spatial scale relevant to small-bodied juvenile fish
- Prevalence of corymbose corals may decline on reefs and the loss of this essential habitat could have a detrimental affect on the juvenile fish that rely on them for food and shelter
- The skeletons of dead corals may also act as important habitat for fish, providing refuge for a broad suite of species.
- The recruitment and survival of these fish is therefore intrinsically linked to resilience and recovery of reefs following extensive coral mortality- prevent the overgrowth of macroalgae

Yahya, S. A. S., Gullstrom, M., Ohman, M. C., Jiddawi, N. S., Andersson, M. H., Mgaya, Y. D., & Lindahl, U. (2011). Coral bleaching and habitat effect on colonisation of reef fish assemblages: An experimental study. *Estuarine, Coastal, and Shelf Science, 94*, 16-23.

Abstract: Degradation and mortality of corals is increasing worldwide and is expected to have significant effects on coral reef fish; hence studies on these effects are essential. In the present study, a field experiment was set up within Mafia Island Marine Park in Tanzania (East Africa) to examine the effects of bleaching and habitat structure on colonisation of coral reef fish assemblages. Live and bleached staghorn coral Acropora formosa was transplanted onto plots in a site dominated by sand and rubble, and the experimental design comprised of three treatments: live coral, bleached coral and eroded coral rubble. There was an immediate increase (within 24 h) in fish abundance and diversity in the two treatments with standing corals. Overall, live and bleached coral plots showed similar effects, but differed from the eroded coral plots which had a much lower abundance and diversity of fish. In general, fish species diversity changed with time over the study period while fish abundance did not. Multivariate analyses showed that while there were differences in fish assemblage structure between standing corals and the eroded coral treatment, there was neither a difference between live and bleached coral treatments nor any temporal effects on fish assemblage structure. Our findings suggest that physical structure and complexity of habitat have stronger effects on colonisation of reef fish assemblages than changes in coral health (such as bleaching) which do not affect coral structure. This may have important implications for appropriate coral reef management.

Questions this article answers: What is the effect of coral bleaching and habitat structure on the colonization of reef fish assemblages?

Methodology: field experiment was set up within Mafia Island Marine Park in Tanzania (East Africa) to examine the effects of bleaching and habitat structure on colonisation of coral reef fish assemblages.

Findings:

- The effect of transplanting the corals to an area with no standing corals was immediate as fish appeared on the plots shortly after they were set up.
- The rapidity of recruitment suggests that these fishes were migrants from nearby coral reefs, situated about half a kilometer away from the study area.
- The differences in abundance of fish between eroded and coral plots were likely due to a combined effect of structural complexity and relief, two important aspects of habitat that have been reported to influence fish community composition
- Disturbance may cause increased variability in marine assemblages and, in addition, tropical reef communities are typically seasonal and hence heterogeneity of fish assemblage composition between seasons is not unexpected

- The assemblage composition changed with time, most likely influenced by seasonality, predation and competition for food and space.
- Fish diversity was lower in the eroded plots than in the plots of live and bleached coral, indicating a positive relationship with habitat complexity
- Live and bleached coral plots attracted comparable numbers of fish species, but bleached corals take months to die

- The distributions of various fish species seemed to be defined by a combination of feeding preferences and habitat dependence/attachment
- This study supported the ecological theory that specialist species will have smaller home ranges than generalist species and highlight the need for consideration of both feeding and habitat dependency behaviour when analysing fish-habitat relationships
- Larger patch reefs tend to have higher total numbers and lower densities of fish compared to smaller patch reefs
- Small patch reefs, which are perhaps more vulnerable to physical processes than larger continous reefs, can serve as habitat for fish even after bleaching has occurred. In particular, there is an indication that juvenile fish used the plots as transitory 'safe'stations, to reside in until they were bigger and better able to survive in nearby continuous reefs.
- Coral reef fish display rapid responses to physical habitat alteration, but are less affected by distinct coral health phases (such as bleached corals) as long as the physical structure of the coral is intact.

Yakob, L., & Mumby, P. J. (2011). Climate change induces demographic resistence to disease in novel coral assemblages. *Proceedings of the National Academy of Sciences of the United States of America, 108*(5), 1967-1969.

Abstract: Climate change is reshaping biological communities and has already generated novel ecosystems. The functioning of novel ecosystems could depart markedly from that of existing systems and therefore obscure the impacts of climate change. We illustrate this possibility for coral reefs, which are at the forefront of climatic stress. Disease has been a principal cause of reef degradation and is expected to worsen with increased future thermal stress. However, using a field-tested epizoological model, we show that high population turnover within novel ecosystems enhances coral resistance to epizootics. Thus, disease could become a less important driver of change in the future. We emphasize the need to move away from projections based on historic trends toward predictions that account for novel behavior of ecosystems under climate change.

Questions this article answers: Is it possible the novel ecosystems could be obscuring the impacts of climate change? How do coral reefs show that this might be the case?

Methodology: field-tested epizoological model

Findings:

- Coral mortality from the first disease outbreak reduces the average size of a colony in the post-outbreak population.
- Because smaller colonies have a higher rate of mortality, the average turnover of the postoutbreak population is higher than that before the outbreak.
  - Makes is more difficult for a second epizootic to occur
- For an outbreak to occur, a colony must survive long enough to become infected and then infect, on average, more than one additional colony. This outcome becomes decreasingly likely for a population consisting of small, ephemeral colonies
- Whereas coral might exhibit adaptive immunological responses, we show that higher demographic rates naturally reduce the ability of the disease to spread within a population consisting of diminutive colonies under high flux.

Yamano, H., Sugihara, K., & Nomura, K. (2011). Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters, 38*

Abstract: Rising temperatures caused by climatic warming may cause poleward range

shifts and/or expansions in species distribution. Tropical reef corals (hereafter corals) are some of the world's most important species, being not only primary producers, but also habitat-forming species, and thus fundamental ecosystem modification is expected according to changes in their distribution. Although most studies of climate change effects on corals have focused on temperature-induced coral bleaching in tropical areas, poleward range shifts and/or expansions may also occur in temperate areas. We show the first large-scale evidence of the poleward range expansion of modern corals, based on 80 years of national records from the temperate areas of Japan, where century-long measurements of in situ sea-surface temperatures have shown statistically significant rises. Four major coral species categories, including two key species for reef formation in tropical areas, showed poleward range expansions since the 1930s, whereas no species demonstrated southward range shrinkage or local extinction. The speed of these expansions reached up to 14 km/year, which is far greater than that for other species. Our results, in combination with recent findings suggesting range expansions of tropical coral-reef associated organisms, strongly suggest that rapid, fundamental modifications of temperate coastal ecosystems could be in progress.

Questions this article answers: What is the evidence os large-scale poleward range expansion of modern corals?

Methodology: 80 years of national records from the termperate areas of Japan; where century-long measurements of in situ sea-surface temperatures have shown statistically significant rises

Findings:

- Four major coral species categories of the nine selected, including two key species for reef formation in tropical areas, showed poleward range expansions since the 1930s
    - No species demonstrated southward range shrinkage or local extinction
- The speed of these expansions reached up to 14 km/year
- Adult colonies in these regions exhibited spawning, indicating that corals newly settled as a result of expansion have the potential to reproduce and expand farther northward.
- Temperate areas may serve as refugia for tropical corals in an era of global warming, while corals in tropical areas suffer declines because of rising SSTs
- These expansions could have major effects on temperate ecosystems
- As the expanding A. hyacinthus and A. muricata have higher growth rates than other species, several species around mainland Japan, including five endemic species [Veron, 1992a], could suffer declines as a result of competition caused by the invasion of the tropical species.
- Recent findings in Japan, although not based on systematic surveys, suggest that such organisms (Acanthaster planci, reef fish and toxic microalgae that cause ciguatera) may also be expanding their ranges

Quotes:

"Our results not only provide evidence to serve as a baseline for the rapid range expansions of tropical reef corals but they also have strong implications for the potential range expansions of tropical species associated with coral reefs, which would contribute to changes in coastal marine biodiversity and ecosystems in temperate areas.”

Ziskin, D., Aubrecht, C., Elvidge, C., & et al. (2011). Describing coral reef bleaching using very high spatial resolution satellite imagery: Experimental methodology. *Journal of Applied Remote Sensing, 5*

Abstract: This paper proposes an experimental methodology toward describing and quantifying coral reef bleaching using very high spatial resolution optical satellite imagery. Sea surface temperature-based bleaching alerts issued by NOAA’s Coral Reef

Watch triggered image acquisition and served as an indication for high bleaching probability. Images of suspected coral reef bleaching events and reference images of the same reefs during previous unbleached conditions were coregistered and radiometrically normalized for change detection. An experimental methodology was developed to describe the severity and extent of the bleaching. The methodology hinges on the creation of the Coral Bleaching Index (CBI), constructed from change detected in the green, blue, and red wavelength bands. Results are provided in the form of colorized difference images showing areas of observed bleaching in gold, as well as CBI images, visualizing varying bleaching intensities. Comparison of the CBI with available field validation data yielded a correlation, however additional reference data would be needed for more detailed quality assessment. This technique is seen as a step toward the routine detection and long-term monitoring of coral reef bleaching from space and serves as a proposed tool for detecting bleaching in remote areas where observers cannot be deployed.

Questions this article answers: How can coral reef bleaching be desribed using high spatial resolution satellite imagery?

Methodology: experimental methodology toward describing and quantifying coral reef bleaching using very high spatial resolution optical satellite imagery

Findings:

- The satellite images used in these types of analyses typically contain coral reef systems, vegetated
- islands, oceans, clouds, cloud shadows, and surf, among other features.
- Satellite analysis of Buck Island bleaching indicates bleaching there should be widespread but of low-intensity. This was confirmed in the field
- Another possible cause of the attained results could be the early image acquisition date (September 18), well before the maximum thermal stress
- If there is substantially more vegetation in the event image than the reference image, the
- island will appear darker to the eye.
    - But, since the CBI enhances brightening in the G band, more vegetation will have a similar CBI as coral reef bleaching
- However, the CBI process was able to distinguish bleaching from cloud shadows

Quotes:

"This paper is seen as a step toward the routine detection and long-term monitoring of coral reef systems from space. The presented technique serves as a valuable tool for detecting bleaching in remote areas where observers cannot be deployed."