COASTAL POLLUTION, CROSS-SECTOR COLLABORATION AND A NEW WAY FORWARD FOR CORAL REEF CONSERVATION

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Marine Sciences.

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ABSTRACT

STEPHANIE LEAH WEAR: Coastal Pollution, Cross-Sector Collaboration and a New Way Forward for Coral Reef Conservation
(Under the direction of Charles Peterson)

Coral reefs are critically important habitats that provide structure and food to millions of marine flora and fauna, as well as food, jobs, and coastal protection to hundreds of millions of people. Despite their value, coral reefs have experienced a global decline due to overfishing, pollution, and warming oceans that are becoming increasingly acidic. To help halt and reverse this decline, we must evaluate our current efforts, address major gaps, increase return on investment, and engage new partners. My dissertation identifies a chronic threat to coral reefs, coastal pollution, that has been relatively underappreciated for its potential impact and largely neglected by the conservation community. I also show that coral reefs and people in tropical coastal areas face many of the same threats, and using sewage pollution as an example, propose a new collaboration between the human health and coral reef conservation sectors to address this ignored threat. From reef practitioner surveys (Ch. 1), I found that coral reef practitioners consistently rank overfishing and coastal development as the two top threats locally, but are investing at least twice as many resources in addressing overfishing relative to coastal development. This mismatch in allocation of resources was consistent across geographies and present in all organization types surveyed. In my literature review of sewage pollution impacts on coral reefs (Ch. 2), I found the impacts of sewage pollution to be generally assumed to be negative but with no experimental investigations or rigorous comparisons support this assumption. Consequently, I focused on the most common

components of sewage and found a wide range of negative impacts on corals associated flora and fauna, leading me to conclude that sewage should be considered a multi- rather than single stressor in conservation threat frameworks. Additionally, I found that 104 of the 112 coral reef geographies are impacted by some degree of sewage pollution, emphasizing the global extent of the threat. In my literature review on threats to human and coral reef health (Ch. 3), I demonstrate that people and coral reefs share at least 9 serious threats, with at least half being related to pollution. I then highlight that sewage pollution presents an opportunity to galvanize the coral reef conservation and human health sectors to join forces in battling this deadly problem. Recent marine conservation and management practice has emphasized marine protected areas (MPAs) as a primary management tool. However, MPAs do not address key threats to the marine environment (e.g., coastal development and associated pollution). As a whole, this dissertation provides a starting point for natural resource managers and conservationists that are pushing beyond MPAs as a management tool, to begin addressing neglected critical threats that impact both coral reefs and people.

To Brian, Parker, and Leah. You are my inspiration and without you,
I am pretty sure I would be baking cupcakes by now.

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I must start off by first thanking my advisor, Pete Peterson. Pete has played an important role in my graduate career. First as a committee member for my master's thesis 15 years ago, then as a cheerleader as my career evolved, and finally as my advisor for my PhD. Pete enthusiastically welcomed me back into the mix at IMS and worked to pave the way for a most unusual dissertation, ensuring that I would be able to pursue a highly relevant topic in applied marine conservation in a department that has historically focused on natural and physical sciences. He understood the importance of me returning to school both for me personally and for my career. I couldn't have asked for a better champion. Peter Kareiva has played a similar role from his position at The Nature Conservancy. He started a new professional development program that changed my life and my career trajectory. He encouraged me to pursue my passions, reminded me that I was more than a good science communicator, and found a way for me to step away from my demanding work (without ever losing touch) and pursue a PhD. A quick check in with Peter was often all I needed to give me the boost to push forward when I was losing confidence. When I first asked Peter if he thought I should return for my PhD, he wasn't sure so he did some research, asking various colleagues of ours that had not received a PhD, but were in senior leadership positions. They quickly returned with a resounding YES! and confirmed my understanding of the importance of it. So for that, I thank Brian Richter and Craig Groves for their quick response, candor, and encouragement. I have tremendous gratitude to my other committee members, Rachel Noble, Mike Piehler, and Xavier Basurto. Each was willing to join my team despite my different approach and each provided invaluable council throughout this process. I feel fortunate to be staying in this community and look forward to interactions of a more social nature in the future with this great crew! Speaking of fantastic local scientists, I owe a huge thanks to Lisa Campbell, who was my stealth committee member, helping me sort out the best way to approach my manager surveys and pointing me in the right direction when I was learning my way. I am confident this trend will continue, along with her encouraging me to maintain a healthy work life balance complete with yoga sessions and porch parties. While each of these folks provided inspiration and guidance through this process, Roy Vagelos, sponsor of the NatureNet Science Fellows Program, made it all possible with his generous support, encouragement, and belief in my vision. Roy's generosity is making a difference on so many fronts, and I am grateful that he chose to invest in me. I look forward to making him proud as I continue to further develop this work. I also owe a thank you to the lovely program officer at the Roddenberry Foundation, whose name I cannot seem to conjure; he shared a story with me about reinventing the toilet that set me on this journey. What a way to begin! I have so many colleagues at The Nature Conservancy that I owe some serious thanks to both in my journey prior to pursuit of my PhD and during it. To Bob Lalasz, one of my favorite colleagues, your laser sharp insights into how to best communicate via the written and spoken word have served me well. Bob challenged me repeatedly to clarify, focus, sharpen—to get to the point. I am still learning, but I have come a long way since he asked me to start blogging way back when. The constant cheerleading from Lizzie McCleod has meant so much to me. Her contagious energy, boundless enthusiasm, and eternal optimism have been a great reminder to me that what I am doing is important. I owe a major shout out to Rod Salm, who has been bugging me to get my PhD since 2004. It took me a long time to hear him on

this one, and I am so glad I finally came to my senses. Rod has been one of my favorite supervisors and mentors while at the Conservancy. He always reminded me of how important it was to prioritize my personal life first, then work. That one has also taken me a long time to hear, but I finally did—right about the same time as the PhD advice came through loud and clear! My master's thesis was dedicated to my parents who "reminded me to always do what I love", something I was reminded of by Pete on the day of my dissertation defense. I am still grateful for this advice as it has served me well and am also filled with gratitude for the role they continue to play both in my life and the lives of my children. Their enthusiasm for my love of nature, which ultimately turned into a career focused on protecting it, encouraged me as a young girl and still does today. The future—my children—Parker and Leah—who have been pretty awesome through this entire process. They motivate me every single day. Their enthusiasm for the natural world, learning new things, love of the ocean, and willingness to dance at the drop of a hat have kept me going and reminded me of why I am doing this. I hope my work and commitment to ensuring a healthy planet for their children and grandchildren will inspire them to be good stewards and teach others as they have taught me. Now for the grande finale—Brian Silliman. Somehow 20 years have past since he came into my life. His everlasting contagious enthusiasm for science and nature inspired me on the day I first met him. I actually changed my major from biology to environmental science after one conversation with him on The Lawn at the University of Virginia. He continues to be a source of inspiration, happiness, and wonder in my life. He might perhaps be best described as the ultimate stealth advisor. During the last couple of years, Brian was a constant source of stellar advice, encouragement, and reminders that 'this is normal for a PhD student'. He was also a willing editor, cook of almost all dinners during the past two years, soccer coach, school board member, rock star scientist, and my favorite human of all time. I am so lucky to have him as my partner in life and can’t wait to see what adventure comes next.

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CHAPTER I

INTRODUCTION

The loss of essential marine habitats has been extensive across the globe over the past 2-3 centuries — including a 80% loss of oyster reefs,[1, 2] a 29-65% decline in seagrass coverage,[2, 3] (a 19% loss of coral reefs,[4] and a ~ 50% loss of salt marsh habitat.[5, 6] These habitat declines have been driven by variety of human impacts including overfishing, eutrophication, pollution, invasive species, warming, acidification, and development. Over the next decades, the impact of most of these threats will increase in intensity and extent, with many synergistic effects predicted.[2, 7]

For many marine ecosystems, there has been substantial allocation of conservation efforts aimed at curtailing these losses. Despite these efforts, we continue to see negligible improvement and often-significant decline in the health and general condition of most marine ecosystems. Coral reefs are no exception. While hundreds of millions of dollars have been spent on coral reef conservation over the last decade, the threat has increased by 30% and coral cover continues to decline.[8, 9] These trends highlight that although marine conservation has been well-funded, protection efforts have not been able to keep pace with ever-increasing threats to these ecosystems.[8, 10, 11]

More resources to implement more of the same conservation strategies—while necessary—will not alone be sufficient to meet the increasing threats facing marine ecosystems. One critical step forward is ensuring that we spend our conservation resources efficiently and distribute them in relation to the intensity and urgency of severe threats. To do this, we must determine whether resources are being spent on the highest priority threats in proportion to threat intensity. Such assessments will highlight areas in which there are mismatches between funding level and threat intensity, for example, where resources are focused on a narrow suite of strategies and therefore ignore significant threats.

In addition to increasing efficiencies in resource allocation, we also need novel approaches that generate synergisms at all levels of conservation effort. For example, the expertise to solve an engineering problem may reside outside of conservation organizations and without involvement of engineers, effective solutions may never be developed.[12] Likewise, building partnerships with non-traditional partners that are working to abate threats that also have a negative impact on the environment is a potentially productive, but largely ignored, interaction. Such collaborations could lead to greater return on investment and advances in solution-based technologies.

A promising example of such a potential synergism is the collaboration that could occur between the human health and conservation sector. This partnership has great potential to maximize synergistic benefits and have more enduring results. The premise of such collaboration would be that promotion of healthy ecosystems promotes not only increased biodiversity but enhanced human health and well being. Improving human health has substantial appeal to policymakers and the global philanthropic community.[13] Yet what is often missing from their spending patterns and priorities, however, are policy actions that are designed to increase the health of ecosystems with the primary goal of increasing the health of local human populations. Without such actions, there is less recognition and realization that the public and environmental health movements can and should combine forces when appropriate, to reach shared goals more rapidly and efficiently.

There are powerful examples of where human health organizations recognize that healthy ecosystems help improve human health. The World Health Organization, for example, states that eliminating environmental hazards to health can prevent up to one-quarter of the global burden of disease.[14] Despite this recognition, WHO's focus is still overwhelmingly on using human-generated activities and remedies (e.g., water treatment plants, more toilets) to improve water quality[14] with comparatively little worked focused on collaborating with conservation organizations to improve health of humans by increasing ecosystem health. This rarely occurs even though nature can increase public health in many ways, such as healthy watersheds protecting water supplies,[15] intact wetlands and forests filtering toxic pollutants out of our air and water, [15] and intact predator assemblages suppressing rodent populations and associated human disease driven by rodent outbreaks and their parasites.[16]

For my dissertation, I use coral reef ecosystems as both a real and model system to begin to address these key voids in marine conservation understanding, i.e., are we addressing intense threats, are we being efficient, and where are untapped synergisms. Specifically, in my research I asked: (1) Whether the allocation of resources to abate severe threats facing coral reefs occurs in proportion to their perceived intensity level of that threat; (2) How a key component of the major threat that I found to be underfunded (i.e., sewage pollution) is known to impact coral reef health; and (3) How collaborations between the public health and coral reef conservation communities can lead to synergistic and increased success for both sectors. I employ surveys of the literature as well as coral reef practitioners to assess these questions. My results have broad implications for coral reef and marine conservation and suggest important and new steps forward in strategy that will likely improve our chances for saving coral reefs and turning the tide on their global decline.

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CHAPTER II

MISSING THE BOAT: CRITICAL THREATS TO CORAL REEFS ARE NEGLECTED AT GLOBAL SCALE

Abstract

Coral reefs have experienced a global decline due to overfishing, pollution, and warming oceans that are becoming increasingly acidic. To help halt and reverse this decline, interventions should be aimed at those threats reef experts and managers identify as most severe. I surveyed 170 managers, representing organizations from 50 countries and territories, and found that respondents generally agreed on the two major threats: overfishing and coastal development. However, resource allocation did not match this consensus on major threats. In particular, while overfishing receives much attention, coastal development and its attendant pollution are largely neglected and underfunded. These results call for a re-examination of how resources are allocated in coral reef conservation, with more attention given to aligning how money is spent with what are perceived to be the primary threats.

Introduction

Despite their well-documented importance to humans, coral reefs continue to decline at a steady pace.[1,2,3] *Reefs at Risk Revisited* (RRR) cited six primary stressors leading to the majority of decline in coral reefs: overfishing & destructive fishing, watershed-based pollution, marine-based pollution & damage, coastal development, thermal stress, and ocean acidification.[2] This report consolidated input from the world's leading experts on coral reefs and highlighted that these stressors are increasing in step with rising human population and activities (e.g., coastal development). Despite the collective efforts of many conservation organizations and governments to protect reefs, conservationists have been unable to keep pace with these anthropogenic threats. The authors of RRR conclude that the threat level increased by 30% between 1998 and 2011[2] while coral coverage on reefs continued to decline.[1]

It is clear that current reef conservation efforts are not sufficient. There are concurrent needs for both innovative approaches and a calibration of current reef conservation efforts with the magnitude of threats to these systems.[4,5,6,7] It is important to ask if resources are being put to best use.[4,6,8] To begin this process, reef conservationists must first assess if their resources (i.e., time and money) are being strategically allocated to address the major threats they face locally. This type of self-evaluation is critical to undertake, as threats change over time and conservationists and natural resource managers must continually track shifts in conservation priorities to determine whether their actions match those shifts.[4] While several studies have mapped the global distribution of threats[2,9,10] no studies have addressed the question of whether local coral reef conservation has adequately allocated resources to match the perceived local intensity of various threats to coral reefs.

An examination of the match between perceived threats and resource allocation is especially critical for coral reefs, because it is common for reef managers to cite a lack of resources as a limiting factor in their ability to achieve success (author's observation from over 25 reef manager workshops; personal communication with P. MacGowan). Using a survey of 170 reef managers from 110 different institutions around the world, I conducted an assessment to test whether perceived levels of the top six threats to coral reefs in their jurisdiction matched the relative amount of time and money allocated within their institutions. Specifically, my survey was designed to answer three main questions: (1) What is the perceived relative strength of threats to coral reef health? (2) Does the allocation of conservation and management resources match the degree of the perceived threat?; and (3) If there are mismatches, why?

Methods

The experts surveyed for this study were comprised of practitioners with extensive experience (an average of 11.5 years) and knowledge of the coral reef conservation and management activities in their jurisdiction. I identified potential respondents through The Nature Conservancy's Reef Resilience Network, a global network of coral reef managers from government, NGO, academic, and community organizations. From this pool, I randomly chose 550 individuals to receive a SurveyMonkey® survey via email. The survey is available as an online supplement (Appendix A). The general goal of the study was provided in the introductory information and no incentive was provided to respondents to complete the survey. The survey data were collected between May and September of 2014. A total of 170 individuals responded to the survey. Of this group, 132 individuals completed the entire survey (47% NGOs, 11% academic, 33% government, and 8% private). These 132 respondents were representative of the geographic range of coral reefs as well as institutions involved in managing coral reef communities. Respondents were from 110 different institutions, 45 countries, and 5 territories (see Table 2.1 for geographies). Each of the respondents was asked to identify their job type (i.e., park manager, fisheries manager, natural/marine resource manager, research scientist, academic scientist, and program manager) and years of experience in coral reef conservation.

Table 2.1. List of geographies represented in the reef manager survey

Country or Territory	
American Samoa[a]	Maldives
Australia	Marshall Islands
Bahamas	Mexico
Belize	Mozambique
Bermuda	Myanmar
Bonaire	New Zealand
Brazil	Palau
Cayman Islands	Philippines
Commonwealth of Northern Mariana Islands[a]	Pohnpei
Colombia	Puerto Rico[a]
Curacao	Saudi Arabia
Dominican Republic	Seychelles
Egypt	Solomon Islands
Fiji	Somalia
Germany	South Africa
Grenada	St Eustatius
Guam[a]	St. Vincent and the Grenadines
Hawaii[a]	Tanzania
India	Thailand
Indonesia	Tonga
Jamaica	Trinidad and Tobago
Kenya	United Kingdom
Kosrae	Florida[a]
Lebanon	US Virgin Islands[a]
Madagascar	Venezuela
Malaysia	

[a] U.S. territories

Six threat categories were used in the survey: (1) Overfishing & Destructive Fishing, (2) Watershed-based Pollution, (3) Marine-based Pollution & Damage, (4) Coastal Development, (5) Thermal Stress, and (6) Ocean Acidification. These categories were selected because they were identified as the top threats to coral reefs in RRR (Burke *et al*. 2011). I used the same threat definitions provided by RRR (Table 2.2) to ensure consistency and clarity, and also allow my results to be placed in the context of RRR studies.

Table 2.2. Threat definitions provided to survey respondents

Threat type	Definition
Overfishing & destructive fishing	Includes unsustainable harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons
Coastal development	Includes coastal engineering, land filling, run-off from coastal construction, sewage discharge, and impacts from unsustainable tourism
Watershed-based pollution	Includes erosion and nutrient fertilizer runoff from agriculture delivered by rivers and coastal waters
Thermal Stress	Incudes warming sea temperatures, which can induce widespread or "mass" coral bleaching
Marine-based pollution & damage	Includes solid waste, nutrients, and toxins from oil and gas installations and shipping; and physical damage from anchors and ship groundings
Ocean acidification	Driven by increased carbon dioxide concentrations, which can reduce coral growth rates

Note. These are the same definitions used in Reefs at Risk Revisited (2011).

The perceived threat level of the six major threats was determined by asking respondents to rate the threats according to severity of threat to coral health in the respondent's jurisdiction. It is important to note the responses were not about global threats, but threats being experienced locally. To assess how time and money were being allocated to address each of the six major threats in those jurisdictions, I asked respondents to estimate the amount of time and money their institution spent on each threat. Whether severity of threat aligned with the resources being directed to that threat was determined by comparing the ratings of threat severity and resource allocation.

I pooled all responses for each threat and calculated the mean for each threat rating to estimate perceived threat ratings. In order to determine how much time was being spent to address each threat, I looked at all respondents combined. I pooled all of the time estimates and calculated a mean. In order to compare time or money spent to the perceived threat rating, I made sure that only respondents that answered the questions about time and money were included in the threat ratings analyses.

I reviewed demographic and job description information about each respondent to ensure my survey population was not biased towards a particular threat (i.e., overfishing) in terms of organizational or occupational mandate. Only three respondents identified themselves as a fisheries manager and only three institutions were identified as a fisheries agency or department. The vast majority of respondents represented organizations with broader natural resource or coral reef management purposes. The same steps were repeated in order to determine portion of budget dedicated to addressing each threat and how that compared to the perceived threat ratings.

To determine whether respondents currently perceived mismatches in threat severity and resource allocation to that threat, I asked the respondents whether resources allocated to addressing each particular threat were too little, too much, or just right for their jurisdiction. I summed the responses by threat category. To determine whether there was a strong opinion about a mismatch of allocations in general, I combined all responses in all threat categories. I also gave respondents an opportunity to explain their responses if they had answered “too much” or “too little.”

To understand what factors respondents perceived to be major influences on decision-making about resource allocation, I asked respondents to select up to three options from eleven pre-selected choices, allowing them to also write in other responses. The eleven choices were intended to be comprehensive and selected based on past experience of working with coral reef managers at more than 25 international reef management workshops over 10 years in which over 600 managers attended (S. Wear, pers. obs.). I summed the responses for each factor and calculated the percentage across all responses. I was able to categorize the six written responses that were provided into already existing factors.

Data analysis

Perceived threat level and resource allocation (time and money) data were analyzed using linear mixed-effects models with threat type as the fixed factor and respondent ID as the random effect factor. All analyses were conducted using R 3.1.2 (R Core Team 2015). The effect of threat type was tested by comparing the resulting deviance to F statistics (Type II sum of squares) using R car package. Tukey multiple comparisons were conducted using R multcomp package. Data from survey questions that assessed frequency of categorical responses, that is, whether there was too much or too little allocation to certain threats and factors that influence resource allocation decisions, were analyzed using chi-squared tests. Pairwise Fisher's test was used to test for differences between categories (P value adjustment method: holm).

Results

All threats were not viewed equally and a few threats emerged consistently as the most important. For respondents that answered time allocation questions, overfishing and coastal development were the most highly rated threats, and did not differ statistically from each other (Figure 2.1a; n=95). Watershed pollution and thermal stress did not differ statistically and were intermediate in rating and significantly lower than both overfishing and coastal development ($P < 0.03$ all contrasts). Marine pollution and ocean acidification did not differ from each other ($P > 0.98$) and were rated significantly lower than all other threats ($P < 0.01$ all cases). For respondents that answered budg*et al*location questions (Figure 2.2a;

n=110), the pattern of the effect of threat type on perceived threat rating was similar. Coastal development and overfishing continued to be the most highly rated threats, whereas marine pollution and ocean acidification continued to be the lowest rated threats.

Time allocation varied among threat types (Figure 2.1b). Managers by far allocated the most time to dealing with the threat of overfishing ($P < 0.01$ all contrasts). On average, this comprised nearly 30% of managers' time. Managers allocated significantly less time (~50% less) to coastal development and watershed pollution ($P > 0.01$ both contrasts), despite the fact coastal development had a similarly high threat rating as overfishing (Figures 2.1a and 2.2a). The least amount of time was allocated to marine pollution, thermal stress and ocean acidification, each of which comprised ~5% or less of managers' time. For budg*et al*location, the patterns in the effects of threat type were nearly identical to that of time allocation (Figures 2.1b and 2.2b), except that the pattern became even more pronounced. For example, managers spent ~66% less money on coastal development in comparison to overfishing ($P<0.001$), despite the fact that they rated these threats as equal (Figure 2.2b).

When managers were asked if they spent too little, just right, too much or don't know for all threats combined, 40% responded "too little" and 40% responded "just right", and fewer than 5% responded "too much" (X-squared = 40.36; df =3, $P < 0.05$ for Fishers contrasts) (Figure 2.3a). When broken down by threat, answers for each threat generally followed the same pattern as for all threats combined (Figure 2.3b). However, there was still some statistically significant variation in the pattern among different threats (X-squared = 29.34; df = 15, $P <0.02$). The number of managers that responded "just right" and that responded "don't know" did not differ significantly for acidification ($P = 0.58$), but this difference was significant for all other threats ($P < 0.004$).

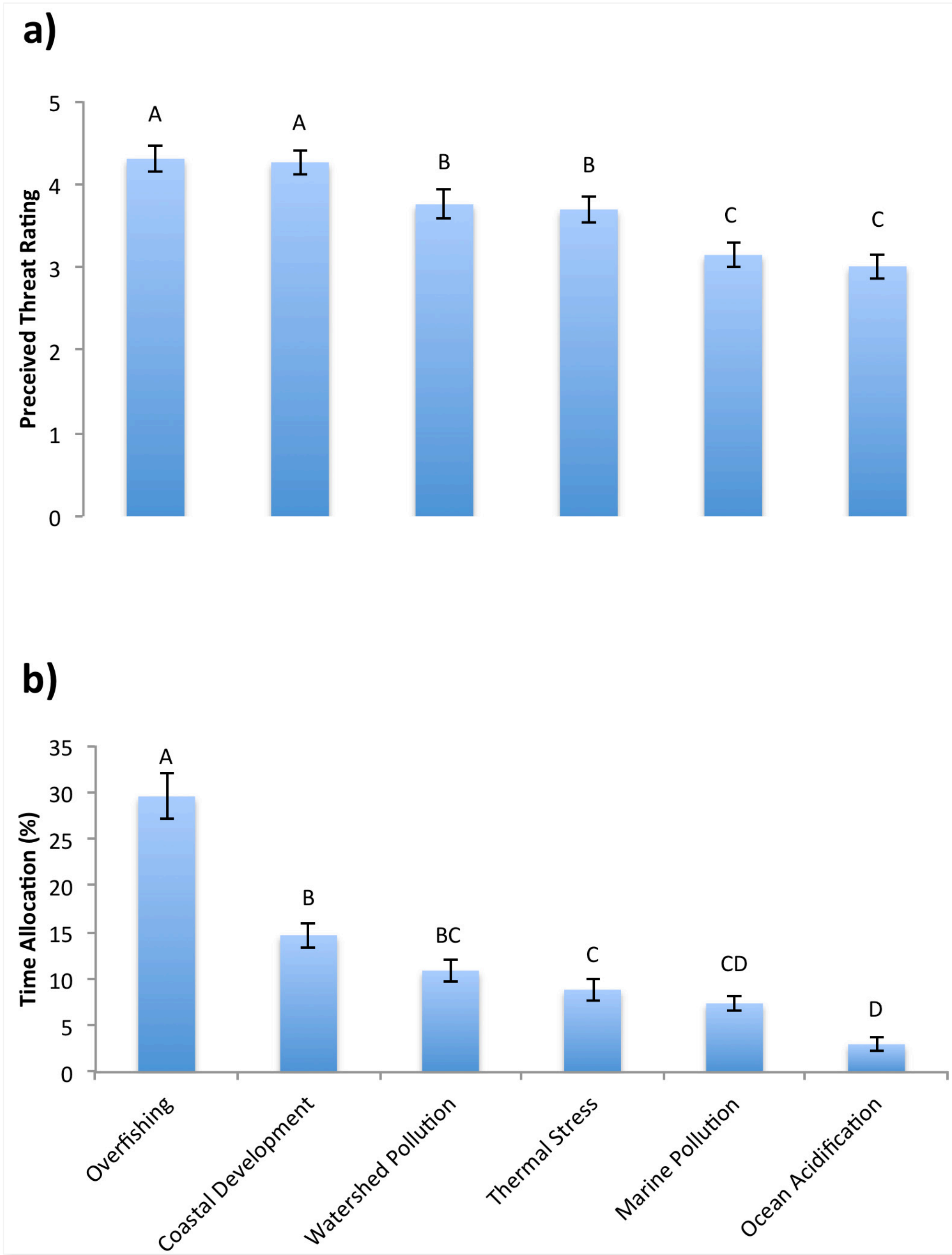


Figure 2.1. Results of survey looking at perceived threat of the top six threats to coral reefs (threat rating scale of 0-6, with 0 = no threat and 6 = extreme threat) (A) and resource (time) allocation to abate those threats (B). N= 95.

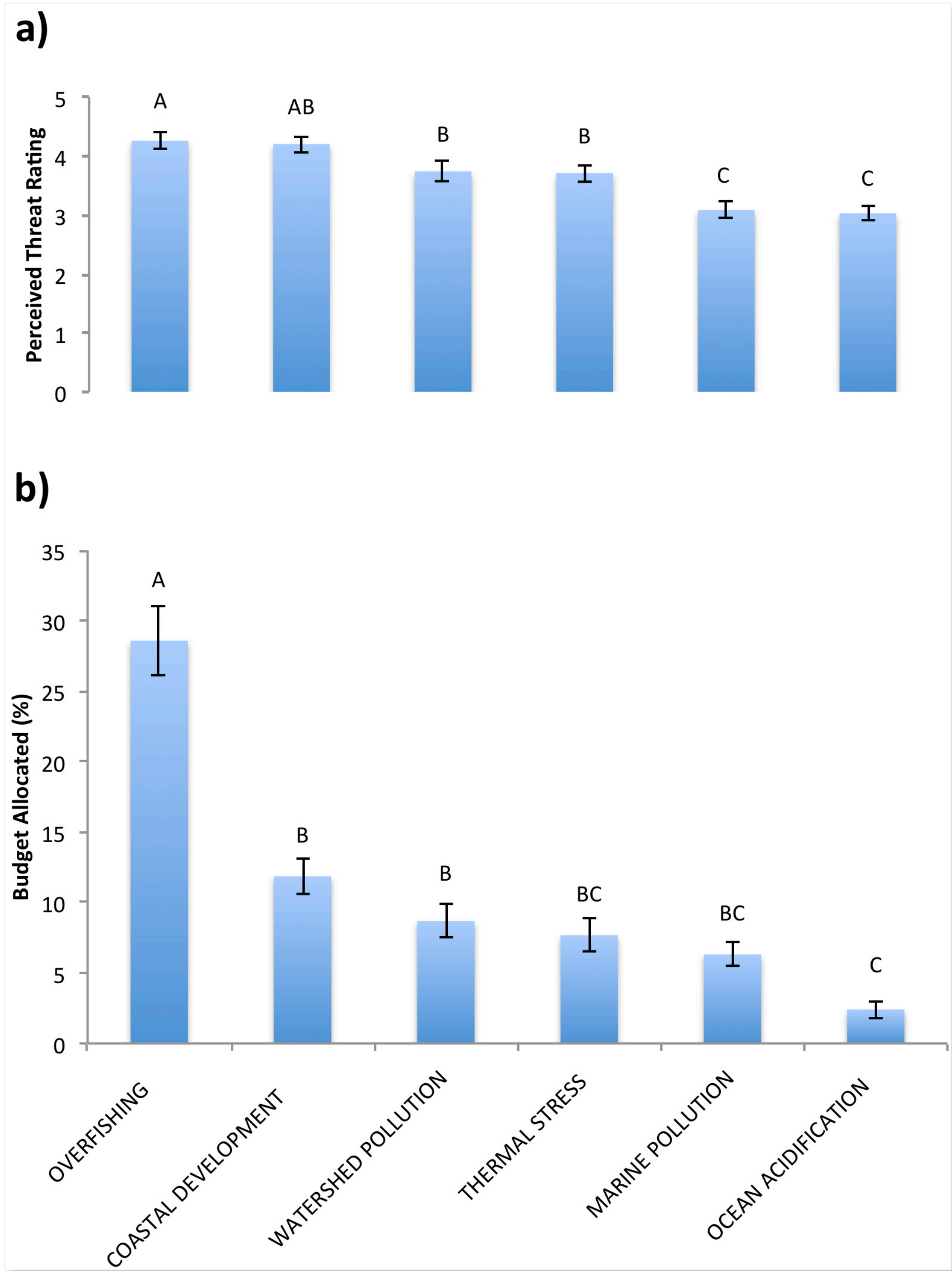
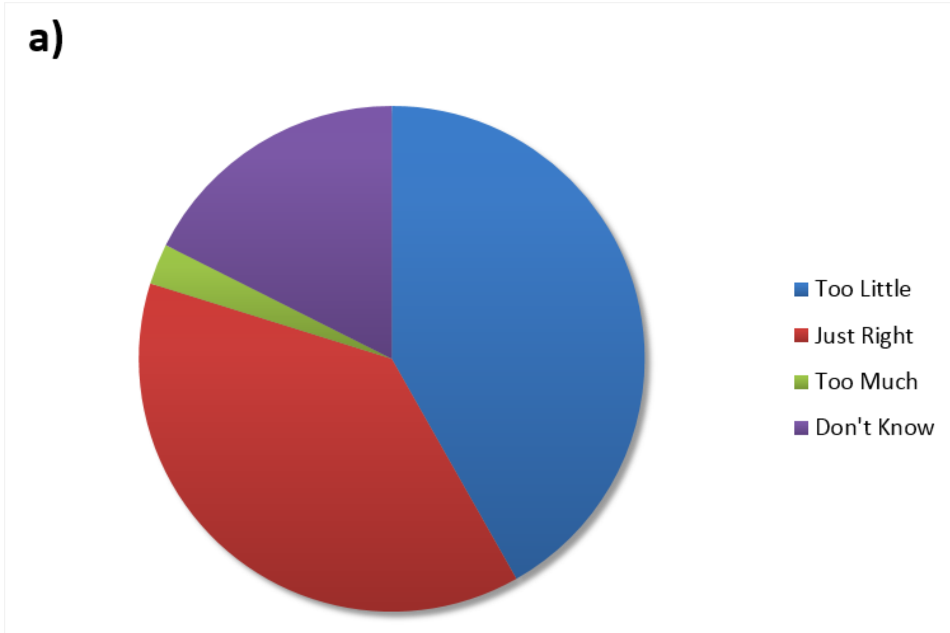


Figure 2.2. Results of survey looking at perceived threat of the top six threats to coral reefs (threat rating scale of 0-6, with 0 = no threat and 6 = extreme threat) (A) and resource (budget) allocation to abate those threats (B). N= 110.

Among different factors that may influence decisions about how resources were allocated (Figure 2.4), number of responses differed significantly (X-squared = 29.34; df =15, P <0.02). Government mandates, donor funding, and politics received the highest number of responses, followed by stakeholder/community and conservation organization agendas.

Discussion

The results of my global survey indicate that overfishing and coastal development stand out as the highest ranked threats (Figures 2.1a and 2.2a). Interestingly, this result differs from RRR[2] assessment of coral threat intensity, which used globally available proxy data as opposed to surveys of local experts and managers. The input data for the RRR "proxy analysis of threat" included human population density and infrastructure features such as location and size of cities, ports, and hotels, as well as more complex modeled estimates such as sediment inputs from rivers. For each of these mapped stressors, distance-based rules were developed, such that threat declines as distance from the stressor increases.[2] In the RRR threat ranking, overfishing was clearly identified as the biggest threat to coral reefs, with over 55% of coral reefs at risk from overfishing. The next highest ranked threat was coastal development, with about half as many reefs being at risk from this threat.



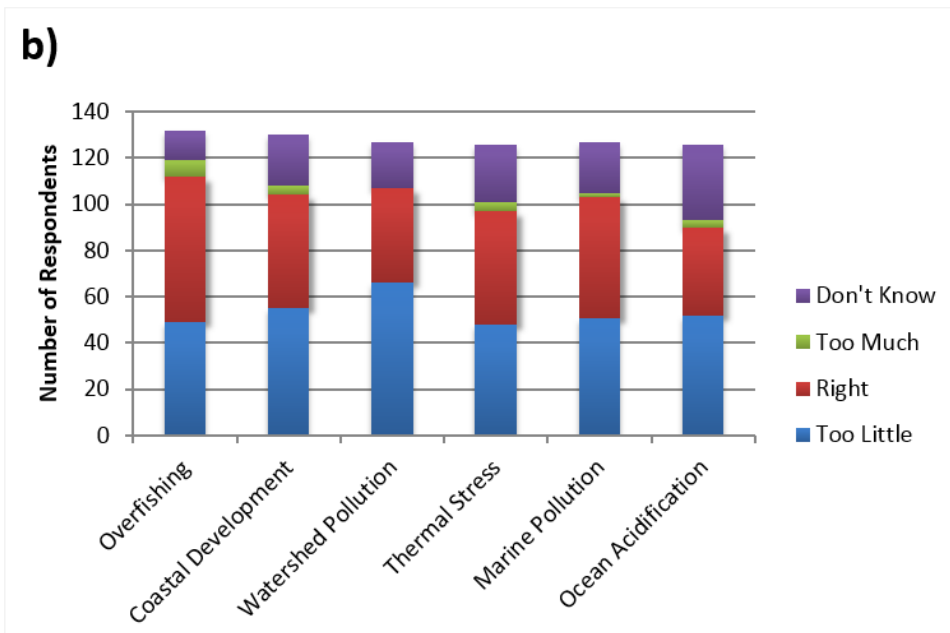


Figure 2.3. Survey responses to question about how resources are being allocated to address threat. A) All responses are combined in these data without regard to specific threat, to demonstrate general trends of allocation. B) Responses are shown by threat category. N= 134.

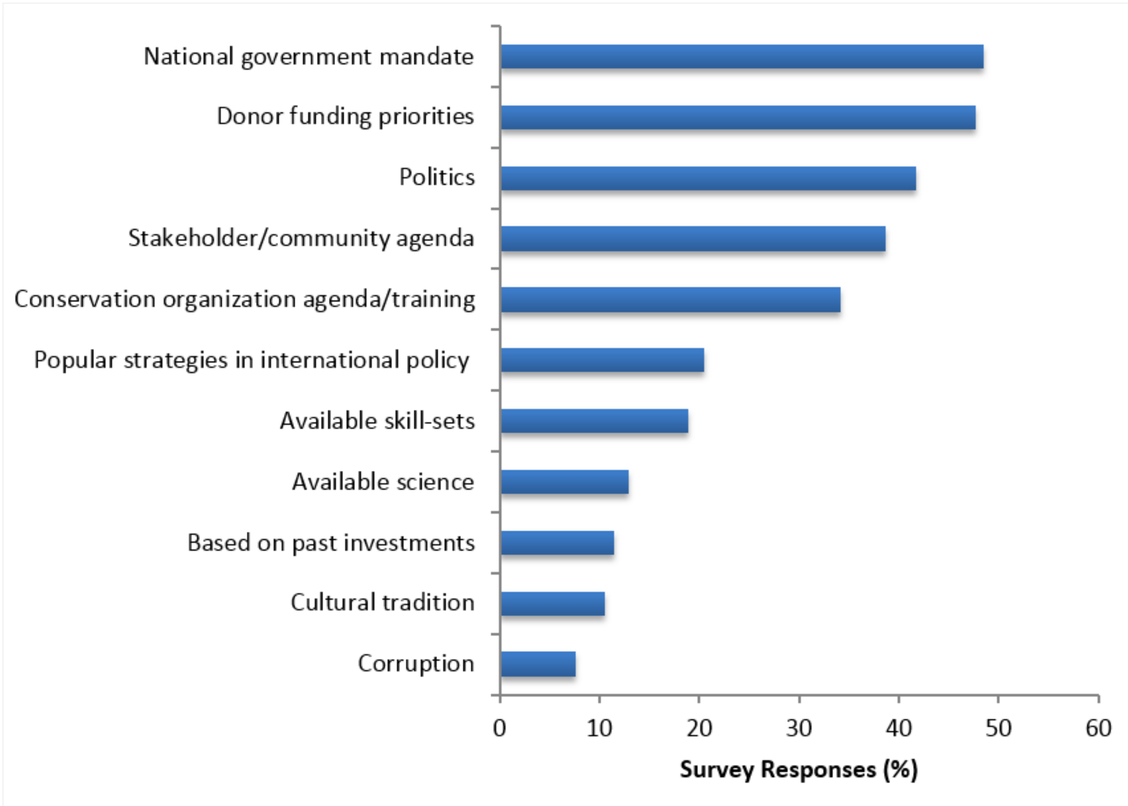


Figure 2.4. Survey responses to question asking respondents to identify which factors influence decisions about how resources are allocated. Respondents (N= 132) selected the top three factors from eleven pre-selected choices and were given the opportunity to write in additional factors.

My survey suggests a different reality for local managers. The biggest difference is the identification of coastal development and pollution as a major threat. While neither the survey approach, nor proxy mapping measure threat directly by documenting impact on corals, the survey approach does allow an examination of alignment between perceived threat and resource allocation. That examination uncovered a striking mismatch in the perceived severity of some threats and the amount of resources allocated to address those threats. Specifically, a disproportionate amount of resources are allocated towards addressing overfishing in comparison to other similarly, highly rated threats. Most notably this mismatch occurs with coastal development, but also for watershed-based pollution and thermal stress. For example, despite having similarly high threat level ratings, less than half the resources are allocated to coastal development relative to overfishing.

Why is there a mismatch?

There are numerous mechanisms that could be driving these observed mismatches. It is possible, for instance, faced with limited resources, managers are choosing to make a difference with at least one serious threat rather than spreading themselves thin across several serious threats. Alternatively, a threat could be neglected because the tools to address it may not be readily available or familiar to local managers. However, this would not explain the neglect of coastal development and pollution, because there are well-known approaches for reducing these threats.[11] Finally, the managers may not realize there is a mismatch. As it turns out, my survey results support this last hypothesis. The majority of respondents did *not* recognize there was a mismatch—and when they did acknowledge a mismatch, respondents commonly cited limited resources as the cause (Figure 2.3). Over 55% of respondents did not recognize that this large mismatch occurs, indicating that more agencies would benefit from evaluating how they are responding to the most serious threats. The limited awareness about the potential mismatch also suggests that the mismatch is not intentional; rather it is being caused by other factors not apparent to resource managers.

Managers face many pressures and demands that may intervene between what they think they should do and what they actually do. My survey uncovered five major factors that influence managers' decisions: (1) government mandate, (2) donor priorities, (3) stakeholder/community support, (4) political agenda, and (5) conservation organization agenda. Many respondents highlighted the lack of understanding of environmental problems and management priorities by politicians and community stakeholders, and pointed out that their support was critical in taking action. If these factors are indeed drivers of the mismatch in resource allocation, then it will be imperative that governments, NGOs, and the donor community begin to recognize that a more holistic approach is necessary to achieve natural resource management goals and evaluate their current funding strategies. Such an approach would be more balanced, incorporating the broader range of threats that impact coral reef ecosystems.

Does the mismatch matter?

Because conservation need far outweighs resources available to address those needs, making sure resources are efficiently allocated is key for maximizing success.[8] While this objective seems obvious, allocating resources for the greatest return on investment (ROI) is still a novel concept in conservation priority setting.[8] For coral reefs, survey results call into question the allocation of resources since investments are disproportionately focused on one threat, while neglecting other seemingly equally important threats. This mismatch matters because the threats that are getting less resource attention are real and substantial. Neglecting a major threat such as pollution, not only reduces our ability to mitigate the impact of multiple stressors on reefs but also puts our existing, massive investment in overfishing abatement at risk. For example, coral reef conservation most often occurs through MPAs and establishment of zoned areas that restrict fishing. While these boundaries can curtail overharvesting, they cannot stop incursion by coastal pollution or marine-based pollution. Thus, while a manager may succeed in addressing the threat of overfishing, their success may be undone by pollution.

What next?

The recent global declines documented for coral reefs demand that we reexamine what is being done to promote coral reef persistence into the future. Current efforts to develop tools and frameworks to improve cost-effectiveness and conservation outcomes will help managers[5,7,8] but until decision-makers embrace the importance of a holistic approach, priority setting at the site level will still be challenged by funding directives from above. While new strategies are needed, we must also look at how we are using the resources already in hand and consider whether they are being used efficiently. Taking a whole system approach in coral reef management is likely to produce better outcomes and greatly improve the conservation ROI. The results of this study illuminate a starting point to improve how limited resources are allocated and call for inclusion of a broader range of threats to coral reefs in future management activities. Governments and other funders of threat abatement activities must take the lead in ending our tendency toward myopic coral reef conservation. Coral reef conservationists should routinely evaluate whether their local interventions match the actual threats, and allocate resources accordingly. In order to reverse the decline, closer attention must be paid to ROI for conservation action and the overwhelming focus on a single threat at the cost of all other threats needs to come to an end.

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CHAPTER III

SEWAGE POLLUTION: MITIGATION IS KEY FOR CORAL REEF STEWARDSHIP

Abstract

Coral reefs are in decline worldwide, and land-derived sources of pollution, including sewage, are a major force driving that deterioration. This review presents evidence that sewage discharge occurs in waters surrounding at least 104 of 112 reef geographies. Studies often refer to sewage as a single stressor. However, we show that it is more accurately characterized as a multiple stressor. Many of the individual agents found within sewage, specifically freshwater, inorganic nutrients, pathogens, endocrine disrupters, suspended solids, sediments, and heavy metals, can severely impair coral growth and/or reproduction. These components of sewage may interact with each other to create as yet poorly understood synergisms (e.g., nutrients facilitate pathogen growth), and escalate impacts of other, non-sewage based stressors. Surprisingly few published studies (8) have examined impacts of sewage in the field—but those that have, suggest negative effects on coral reefs. Because sewage discharge proximal to sensitive coral reefs is widespread across the tropics, it is imperative for coral reef-focused institutions to increase investment in threat abatement strategies for mitigating sewage pollution.

Introduction

Coral reefs play a critical role in coastal ecosystem function in the tropics, providing food and habitat for 550,000 to 1,330,000 species.[1] Along with the inherent biodiversity these habitats support, reefs built by corals also provide many valuable services for humans including: shoreline protection, livelihoods from ecotourism, fisheries production, and a living synthesis engine of biomedical and industrially valuable compounds.[2, 3, 4, 5] The value of these services varies globally, but is estimated at over $31 billion (US$, 2014) annually for all reefs combined.[6] Unfortunately, reefs and the many benefits they provide are under severe threat, with evidence of a general pattern of habitat degradation.[7, 8]

Spatial variation and forces behind coral reef decline

Coral reefs are exposed to a multitude of stressors emanating from human activities[7, 8, 9, 10] and as a result, have experienced drastic declines in spatial coverage and diversity over the past fifty years.[7, 8] At a regional level in the Indo-Pacific, live coral cover has declined at an annual rate of 1% from the early 80's to 2003; while in the Caribbean, the annual rate of coral cover loss was 1.5% between 1977 and 2001.[11] Recent work cataloguing the status of reefs has estimated that we have functionally lost at least 25% of coral reefs globally and one third of all coral species are threatened with extinction.[12] Chief among threats identified in Reefs at Risk Revisited (RRR) are: overfishing, pollution, coastal development and climate change.[8] For example, increasing temperature of surface waters from climate change, has led to increased bleaching events and subsequent reef loss.[13] Bleaching due to elevated water temperatures is perhaps the most notable stress, with some reefs experiencing over 85%

[1] Wear, S., & Vega Thurber, R. (2015). Sewage pollution: mitigation is key for coral reef stewardship. Annals of the New York Academy of Sciences. http://doi.dx.org/10.1111/nyas.12785

mortality in the 1998 mass bleaching event.[14, 15, 16, 17] While the 1998 bleaching event resulted in significant losses, coral reefs were already in a state of decline when this event occurred.[10, 18] The additive and synergistic effects of long-term overfishing, chronic coastal pollution, and poorly regulated coastal development had already compromised coral reefs, making it difficult for reefs to withstand more stressful conditions associated with increasing frequency and intensity of bleaching events.[10, 18, 19]

Over the past two decades, the conservation community has generally considered overfishing as the threat to coral reefs that warrants the most attention.[8] For example, RRR emphasizes that more than 55% of the world's reefs are under immediate threat from overfishing[8] which can lead to phase shifts from coral-dominated reefs to algal-dominated reefs as the number of algae-eating fish decreases significantly.[20] Halpern *et al.* [21] also suggest that overfishing is one of the most severe causes of coral reef decline. The extensive scientific literature on overfishing has prompted coral reef management responses that include: limiting or banning fishing in some areas, regulations that prohibit the take of certain key fish species, and global efforts to influence consumer choice by limiting the demand for ecologically important species.

Notably, the threat to coral reefs from pollution and eutrophication, although potentially just as important as overfishing, as suggested by RRR[8] and Halpern *et al.*[21] assessments, has received much less attention from conservation organizations (S. Wear, pers. obs.). Reasons for this disparity may include the practical challenges of dealing with a large-scale diffuse threat, the diversity of pollutants involved, the high cost of water treatment facilities, and bureaucracy. The solutions to reducing and understanding the exact impacts of coastal pollution, where it is likely to be strong, have been lacking because of the inherent difficulties of monitoring and evaluating nonpoint sources of pollution along with jurisdictional issues such as agency and private land conflicts.

The largest component of coastally derived pollution is sewage.[22, 23, 24, 25] Most coral reefs are located along the shorelines of developing countries, where tertiary sewage treatment is rare. Most sewage enters tropical waters as either poorly or completely untreated discharge, or stormwater runoff.[25, 26] In fact, the United Nations Environmental Program (UNEP) estimated that 85% of the wastewater entering the sea in the Caribbean is untreated.[27] As our global population likely expands by 2 billion over the next 35 years,[28] the amount of sewage polluting reefs will also increase. It is thus critically important to understand the role of sewage discharge in coral reef declines and identify ways to minimize its impact on reef health. In this review, we synthesize what is known about the composition of sewage and how each component may impact coral reef health. We explore interactions between and among these components to evaluate synergisms. We also present a synthesis of previously conducted studies on the impacts of sewage discharge on coral reefs. Finally, we present a summation of the geographic extent of sewage pollution, in regions where coral reefs occur.

What is in sewage and how do those components impact corals?

Most reports addressing the impact of sewage on coral reefs cite high inorganic nutrient content as the primary reason for alarm—as those nutrients could lead to increased growth of algae and coral diseases. [29, 30] However, sewage in its raw form contains many more compounds than just inorganic nutrients (e.g., see Refs. 24, 25, 31). In particular, sewage discharged into tropical coastal seas contains hundreds of different compounds, the most common of which being freshwater, inorganic nutrients, pathogens, endocrine disrupters, suspended solids, sediments, heavy metals, and other toxins.[25, 31] Below we describe each of these constituents in detail and briefly summarize what is known about negative impacts on coral reefs and the mechanism(s) underlying the impact (Table 3.1). Importantly, this understanding does not come from studies on sewage itself, but rather from work investigating how explicit sewage components (e.g., freshwater, ammonium) impact corals.

Freshwater

The primary component of sewage is freshwater, a known stressor to corals. Although, there are surprisingly few studies examining impacts of freshwater on coral health, classic laboratory studies conducted over 80 years ago revealed most corals die after prolonged exposure to fresh or brackish water sources and that the lower salinity tolerance of corals is ~15-20ppt.[32] In the field, the effect of freshwater discharge onto coral reefs has been studied in a limited number of cases using correlational methods.[32, 33] In these studies, increased freshwater input into coastal waters associated with storm water runoff was correlated with rapid drops in near-shore salinity and in turn, significant loss of nearby corals. Reef mortality associated with these flood-related reductions in salinity has been documented around the world (e.g., see Ref. 32). Understanding the specific limits and tolerances of corals to freshwater exposure, however, is relatively underexplored.

Table 3.1. Examples of coral reef (corals and associated organisms) responses to common stressors found in sewage

Stressor	Response	Sources
Freshwater	Increased coral mortality (with lowered salinity for >24H).	Coles and Jokiel 1992; Jokiel *et al*. 1993
Dissolved inorganic nutrients (ammonium, nitrite+nitrate, & phosphate)	Increased coral bleaching, increased coral disease prevalence and severity, decreased coral fecundity, algal overgrowth, decreased coral skeletal integrity, decreased coral cover and biodiversity, and increased phytoplankton shading.	Vega-Thurber *et al*. 2014; Bruno *et al*. 2003; Koop *et al*. 2001; River and Edmonds 2001; Fabricius 2005; Wooldridge and Done 2009; Wagner *et al*. 2010; Voss and Richardson 200; Shantz and Burkepile 2014
Endocrine disrupters (e.g., steroidal estrogens)	Reduction in coral egg-sperm bundles, slowed coral growth rates, coral tissue thickening.	Tarrant *et al*. 2003, 2004; Tarrant 2005
Pathogens	Source of white pox disease pathogen for corals and associated mortality, and increased pathogenicity in corals.	Patterson *et al*. 2002; Sutherland *et al*. 2010, 2011
Solids	Reduced photosynthesis of coral symbionts, coral species richness, coral growth rates, coral calcification, coral cover, and coral reef accretion rates, and increased coral mortality.	Tomascik & Sander 1985; Rogers 1990; Lewis 1997; Fabricius & Wolanski 2000; Fabricius 2005; Pollock *et al*. 2014
Heavy metals	Coral mortality, coral bleaching, reduction of basic functions such as respiration and fertilization success; Fe2+ may increase growth of coral disease.	McAuliffe and Weiss 1980: Howard and Brown 1984; Griffiths 1991; Reichelt-Brushett and Harrison 1999

Stressor	Response	Sources
Toxins	Lethal and sub-lethal effects on corals—highly variable and dependent on specific toxin. Reduced photosynthesis of coral symbionts, coral bleaching, coral mortality, reduced coral lipid storage, reduced coral fecundity, death of coral symbionts, and decreased coral growth.	van Dam *et al*. 2011 and references therein

Nutrients

Sewage discharging into coastal tropical waters contains very high concentrations of inorganic nutrients, such as ammonium, nitrite, nitrate and phosphate. A number of studies have examined effects of these compounds on specific components of coral health. Impacts can be categorized as either direct, having effects on the coral animal or its symbionts, or indirect, whereby nutrients influence other aspects of the reef that in turn negatively impact coral health. One of the most influential single mechanisms is indirect, whereby nutrient enrichment enhances macroalgal overgrowth, killing corals and thereby removing a foundation species. A growing body of new literature has also examined direct impacts, such as how inorganic nutrients modify microbial communities found on and in corals, coral symbionts, and calcification rates. Here, we briefly review key findings related to each of these topics.

Nutrients and algae

Since tropical reefs are generally nutrient poor or oligotrophic, any significant input of limiting macronutrients into coastal waters could cause shifts in reef community composition.[34] Most research on nutrient impacts on reefs has focused on the direct effects of inorganic nutrients on primary producers, such as phytoplankton or macroalgae, both of which compete with corals for light and space. For example, increases in nutrient concentrations can facilitate large, often monospecific, blooms of algae.[35, 36, 37] It is also well documented that increasing inorganic nutrient levels increases macroalgal cover on reefs, to the detriment of coral cover.[20, 29, 38-43]

This reduction in coral cover is due to the increased proliferation of macroalgal biomass in the presence of elevated dissolved inorganic nitrogen, which translates to increased competitive ability for macroalgae as they interact with corals and compete for space.[44, 45] This increase in macroalgal competition, when combined with nutrient pollution, may further reinforce a coral-depauperate state by reducing the growth and survival of adult corals[46, 47, 48] and preventing the recruitment and establishment of juveniles. [45, 48] Increased macroalgal growth and competitive displacement of corals in response to increasing nutrients from human activities has been documented in enrichment studies in the Caribbean Sea, Indian, and Pacific Oceans.[29, 49]

Nutrients, coral disease and bleaching

Nutrient enrichment has also been hypothesized to be a driver of coral disease and bleaching. Recent studies on the Great Barrier Reef[50] and in the Florida Keys[51] found a positive correlation between bleaching prevalence and inorganic nitrogen (N) levels. Field surveys have also found that coral disease prevalence is often positively correlated with ambient seawater nutrient concentrations.[52, 53] For example, increasing nutrient availability is positively correlated with increased disease progression rates (i.e., the rate of movement of the disease over a coral's surface) of some coral diseases, such as yellow blotch and black band disease.[54, 55]

Recent experimental evidence has confirmed predictions from these observational studies and shown that nutrients can cause an increase in both the prevalence of coral disease and extent of bleaching on natural reefs.[30] Researchers have enriched replicate portions of a coral reef with inorganic N and phosphorus (P), to levels within the nutrient ranges experienced by contaminated reefs.[56] After three years of this nutrient enrichment, disease incidence in corals increased by more than two-fold and bleaching prevalence in one coral species increased by more than 3.5 fold.[30] Perhaps most importantly, after termination of nutrient additions, there was a return to pre-enrichment water quality, followed by rapid recovery (within 6 months) of the enriched reef sites, such that disease and bleaching levels returned to those in control reef sites lacking the enrichment treatment. These findings demonstrate that measures to reduce inorganic nutrient pollution through water quality mitigation efforts may successfully reduce coral disease and bleaching levels, perhaps even very rapidly.

Nutrients and coral growth

Nutrients have long been hypothesized to reduce coral growth rates. A recent meta-analysis showed that exposure to nitrate and ammonium over a wide range of concentrations (0.5-26 μM) generally had negative effects on corals, but increased P (0.11-26 μM) actually enhanced calcification. [57] Nevertheless, even though elevated P concentrations increased calcification rates, this response also involved losses of skeletal integrity. The effects were also context-dependent such that different morphologies (mounding vs. branching) and different species of corals exhibited varying calcification responses and varying impacts of N depending on type (nitrate or ammonium) and source (natural or anthropogenically-derived).[57] The variable effects of nutrient pollution across coral morphology and species carries implications for how different habitat types will uniquely respond to nutrient enrichment. In particular, mounding and Poritid corals were shown to be more susceptible to the negative effects of increased nutrients, and habitats or ecosystems dominated by these taxa are more likely to suffer impacts from increased inorganic nutrient concentrations that often accompany reduced water quality.

Nutrients can also decrease coral growth by acting on the autotrophic algal partner *Symbiodinium* that is a symbiont in corals. Nutrients have long been hypothesized to decrease coral growth rates via bleaching through elevating the abundance of algal symbionts.[58, 59] Increased symbiont density leads to corresponding increases in reactive oxygen species, which may result in damage to host cells and/or death and expulsion of the symbiont.[60] It is this loss of the pigmented *Symbiodinium* that causes coral bleaching, decreased growth rates, and even whole colony mortality. It should be noted, however, that recent research has revealed that increased nutrient levels do not always have a negative impact on coral growth but instead can have a unimodal relationship, where increasing nutrient levels first increase coral growth but then decrease coral growth as levels of nutrients rise.[61]

Nutrients and microbial communities

Coral associated microbes (i.e., eubacteria and archaea) have a multitude of context-dependent roles in health and physiological homeostasis of scleractinian corals.[62, 63] For example, mucus-associated bacteria are believed to regulate the settlement and/or growth of opportunist microbes by occupying space or producing effective antibiotics.[64, 65, 66] Alterations in ambient conditions, such as water temperature and nutrient concentrations, have been shown to induce shifts in the associated microbes or microbiome of a coral.[67, 68] These shifts can be the result of both direct and indirect effects of inorganic nutrients. For example, tank experiments suggest that addition of inorganic N can induce growth of potential bacterial pathogens.[68, 69] An increase in nutrients also can stimulate growth of macro- and turf algae,[70] which have been shown to have multiple negative effects on the coral microbiome, such as depletion of local oxygen concentrations,[37, 71, 72] transferal of allelotoxins,[73, 74, 75, 76] and transmission or vectoring of pathogens.[77, 78] Shifts in the microbiome can ultimately lead to coral health declines and sometimes death.[37, 62, 79]

Pathogens

Coral disease has increased in prevalence in the Caribbean, with as much as 20% of reefs impacted in some places.[80] While the Pacific has not yet experienced the devastating consequences of coral diseases, it is clear that many diseases are present, and the problem is expected to grow with environmental change (e.g., see Ref. 81-82). For example, at least seven diseases have been documented in Australia's Great Barrier Reef, including cyanobacterial, protozoan, and *Vibrio* spp. infections.[80] The impacts of disease on corals can be profound, ranging from minor tissue loss to entire colony mortality. For example, in the 1980's, the two dominant Acroporid species, *Acropora palmata* and *Acropora cervicornis*, experienced Caribbean-wide die-offs due to white band disease, with estimates reaching as high as 95% of colonies lost.[83, 84] Such losses are unprecedented and have led to dramatic management responses, including the listing of both taxa under the Endangered Species Act.

Recent work has started to link certain environmental conditions,[30, 54, 85] as well as a changing climate, to the emergence of disease.[86, 87] However, we understand very little about reservoirs for coral disease. One such likely reservoir for pathogens is sewage. In fact, sewage effluent has been identified as the source of the pathogen complex that causes white pox disease in Caribbean corals.[88, 89, 90] Using Koch's postulates, Patterson *et al*.[88] first identified *Serratia marcescens* as the disease-causing agent for white pox disease. At the time of this study the elkhorn coral, *A. palmata*, was experiencing a major die-off in the Florida Keys, with more than 70% of coral cover lost due to white pox disease.[88] During a subsequent outbreak of white pox disease in 2003, a unique strain of *S. marcescens* was identified (PDR60) from samples taken from live *A. palmata*, as well as two other species of non-Acroporid corals, reef water, and nearby sewage sources.[89]

In their most recent publication, Sutherland *et al*.[90] used experimental laboratory manipulations to demonstrate that sewage was indeed the source of the disease, and that a human strain of the pathogen was the causal agent. These findings marked the first time that a human pathogen has been demonstrably transmitted to a marine invertebrate, providing strong evidence for the linkage between sewage exposure and disease in the marine environment. While evidence showing that sewage is an important disease reservoir is limited to one type of disease and its associated causal agent, the potential for discovery of more examples is considerable, given the sheer numbers of microbes and viruses present in the average human gut and consequently in the average sewage effluent (e.g., see Refs. 91-93).

Endocrine disrupters

Endocrine disrupters are common pollutants in coastal waters. They include both natural and synthetic estrogens, polychlorinated biphenyls (PCBs), plasticizers, pharmaceuticals, parabens, phthalates, dioxins, petrochemicals, organochlorinated pesticides, microplastics and detergents.[94, 95, 96, 97, 98] Endocrine disrupters are chemicals with the ability to disrupt the endocrine or hormone system in living organisms. They can act on multiple processes in animals, including reproduction, immune response, and growth. [99] Endocrine disrupters are commonly identified in sewage effluent delivered by human excretion,[96] as well as through general household wastewater. They have also been detected in sediments adjacent to coral reefs.[95, 100, 101]

Both distance from the source of sewage and physical characteristics of an area impact the concentrations of endocrine disrupters.[96, 100, 102] As is the case for some other pollutants, well-flushed areas have lower concentrations of endocrine disrupters, whereas areas that are enclosed, or semi-enclosed, tend to have higher concentrations.[96] Studies on the effects of endocrine disrupters on corals have shown that impacts are similar to those they have on other organisms, i.e., suppressing growth and reproduction.[95, 103] Early work on understanding the role of endocrine disrupters, specifically steroidal estrogens, established the presence of estrogens in the water column and in the tissues and skeletons of corals.[96, 104, 105, 106] Subsequent studies demonstrated that corals take up estrogens, incorporate them into their tissues and skeletons, and metabolize them.[103] The metabolic mechanisms are poorly understood, but what has been shown is that certain estrogens affect coral reproductive abilities, growth rates, and morphological features. For example, Tarrant *et al*.[95] showed that additions of estradiol to *Montipora spp.* over three weeks resulted in a reduced number of egg-sperm bundles by 29%, whereas additions of estrone to *Porites* spp. over 2 to 8 weeks slowed growth rates by 13-24%. Tarrant *et al*.[95] also added estrone to *Montipora* spp. nubbins over several weeks, and found an increase in tissue thickness. Much more study is needed to better understand these dynamics, so that informed strategies for minimizing exposure to these and other endocrine disrupters can be developed.

Suspended solids and sedimentation

Both suspended solids and sediments accompany sewage discharge and are threats to coral health.[25, 107, 108, 109, 110] Sewage typically contains high concentrations of suspended solids, primarily organic. Suspended solids increase turbidity and block sunlight, which can reduce growth of coral symbionts.[108, 111, 112] Corals may survive for many days under severely reduced sunlight, but after a few weeks, excessive shading can result in reduced photosynthetic activity, growth, and ultimately coral cover.[113] When chronic shading due to increased suspended solids occurs, this can result in coral depth distribution shifts.[114] Thus, the impact of suspended solids on corals will depend on how long solids remain in the water column and how much sunlight they block.

High rates of sedimentation may also co-occur with sewage discharge, especially coinciding with storm events.[115] The range of impacts from prolonged sediment cover includes shading and thus suppression of food production by coral symbionts, smothering of corals,[108, 116, 117] energetic losses due to effort spent to reject sediments,[118] and disease.[110, 119] Corals differ in their susceptibility to sedimentation based on differences in morphology,[117, [120, 121] size,[122] and ability to reject sediments.[120] Regardless of any coping mechanisms that corals may have, sedimentation impacts are pervasive. Fabricius (2005) conducted an extensive review on field studies that provided evidence that sedimentation has negatively impacted reefs across all major coral reef geographies (See Table 1 in Fabricius 2005).[107] This work also highlighted specific stress responses of individual corals (e.g., reduced growth rates, reduced calcification, and increased mortality), communities (e.g., reduction in species richness and coral cover) and ecosystems (e.g., net productivity and accretion rates), to different levels of sedimentation.

Besides the physical stress that sedimentation and suspended solids can generate, there may also be chemical stress generated, especially from sewage-derived sediments because they contain a wide range of compounds. For instance, suspended solids associated with sewage that eventually settle on corals often have a different profile, both in chemical composition and toxicology from those originating from other sources, such as agricultural runoff and natural erosion flows.[24] Suspended solids may contain toxic compounds and high levels of nutrients, each of which can result in negative responses in corals, such as disease and mortality.[25, 123] The highly organic particles derived from sewage can chemically stress corals by greatly increasing biological oxygen demand in surrounding waters, as bacterial consumption of oxygen rises with increasing availability of organic material.[25, 123]

Heavy metals

Heavy metals are commonly present in sewage worldwide.[124] Metals routinely found in sewage include mercury, lead, cadmium, chromium, copper, nickel, zinc, cobalt, and iron.[124, 125] In general, increasing levels of heavy metals in the tissues of organisms interfere with metabolism and influence the activity of a wide range of enzymes, suppressing important physiological processes, such as respiration and nerve communication. Numerous studies have shown that exposure to elevated levels of metals can result in coral mortality, bleaching, and decreased fertilization success.[126, 127] Heavy metals also have the potential to damage corals by increasing success of certain microbes. For example, Fe^{2+}, which is common in raw sewage, is recognized as playing an important role in increasing both the virulence of pathogenic microbes (e.g., *Vibrio* spp.), and the growth rates of microalgae. This occurs because Fe^{2+} is a limiting nutrient for microbe reproduction and thus its addition leads to increased microbial growth.[128] When iron is in excess and freely available, it is taken up by pathogenic microbes, allowing them to further multiply and increase their success in attacking and infecting live corals.[128] Lastly, increases in this essential bacterial micronutrient have been implicated in altering reef community structure and function in extremely oligotrophic environments, such as isolated coral atolls.[129]

Other toxins

The range of other toxins potentially present in sewage is wide, but which toxins actually are present is dependent on local conditions, such as type and abundance of local industries and agriculture. Chemicals commonly found in sewage beyond the metals and endocrine disrupters discussed above include PCBs, chlorine, pesticides, herbicides, petroleum hydrocarbons, and pharmaceuticals.[24, 25, 130, 131, 132] Numerous laboratory studies and field studies have examined the impacts of these toxins on corals. This work was summarized by van Dam *et al*.[133] who reported that the response of corals depended both on type of toxin and its concentration, with responses varying from mortality, to bleaching, to reduced lipid concentrations (See Table 3.1 for examples of responses).

Field evidence linking sewage exposure and coral reef health

The section above reviews the impacts that individual components of sewage have on coral reef health and suggests that sewage as a whole has the potential to have strong negative impacts. However, this prediction is based on studies that did not experimentally expose corals in the field to sewage. To evaluate the findings of field experiments and observational studies assessing the effects of sewage and its constituents on coral reefs, we conducted a search of the literature (Web of Science with following search terms: TOPIC: “coral reef*” and TOPIC: “sewage” and TOPIC: “pollution”). Remarkably, we found not one experimental field study that investigated impacts of sewage on coral reef health. Most studies looking at linkages between sewage and coral reefs focused on identifying indicators of sewage presence and intensity, rather than on the actual impacts of sewage on coral reef constituents, the general untested assumption being that sewage had a negative impact, and so should be monitored and abated.[134, 135, 136, 137, 138, 139] We did, however, identify eight observational studies that surveyed coral reef areas with substantial sewage input and compared them to nearby, environmentally similar areas with little or no known suspected sewage input.[115, 140, 141, 142, 143, 144, 145, 146, 147]

In each of these correlational studies, scientists investigated how the condition of coral reef communities varied with decreased water quality (e.g., fecal coliform counts, turbidity, and inorganic nutrients) associated with sewage outflows. In seven out of the eight studies, a negative impact of sewage on reefs was implicated and, in one study, no effect was suggested. Below, I briefly review the findings of these studies. Caution should be taken in interpreting the results of these studies, as none used the most robust design (i.e., Before-After-Control-Impact)[148] for correlational testing of contaminant effects. Nonetheless, taken together, their quantitative results allow us to make informed hypothesis about the probable impacts of sewage on coral health.

Two of these observational studies focused on the incidence of coral disease in response to sewage exposure. In Kaczmarsky *et al*.,[141] the authors examined two different sites in St. Croix, USVI—a sewage-impacted site, and an ecologically and geologically similar site nearby, with no known sewage exposure. Water quality sampling by the Virgin Islands Department of Planning and Natural Resources showed high counts of fecal coliforms (1460/100ml) after a sewage overflow event at the sewage-impacted, site but no indication of fecal coliforms (0/100ml) at the non-impacted site (approximately 1.5 km from the sewage pipe). The authors conducted surveys to determine the prevalence of black-band disease and white plague type II at both sites, and found significantly ($p < 0.0001$) more disease cases at the sewage-impacted sites with seven of the ten species surveyed showing an increased incidence of disease. Redding *et al*.[147] reported similar trends of increasing coral disease with exposure to sewage. In this study on reefs in Guam, the authors found that increasing sewage (estimated from measurements of sewage-derived N) correlated significantly to increases in white syndrome disease on *Porites* spp. and that the level of $\delta^{15}N$ was a strong predictor of severity of this disease.[147]

Five other field studies implicated increased sewage exposure as the factor generating inferred changes in community structure on reefs, with the most common responses being an increase in macroalgae and a decrease in coral cover.[115, 144, 146] For example, a study examining two bays in Thailand, one sewage-impacted and the other not, found that the sewage-impacted bay had significant increases in turbidity and inorganic nutrients.[115, 143] The authors then correlated these differences to changes at multiple ecological levels of organization in the nearby coral reef community, including increased macroalgal density and diversity, reduced cover of reef-building corals, and reductions in fish abundance on the reef.[115, 143] Similarly, a study of reefs in Taiwan that examined the impacts of sewage found that higher levels of sewage (as estimated by measurements of nutrient and suspended sediment levels) were linked to algal blooms and sediment smothering of corals in shallow areas.[145] Finally, during a bleaching event in 1995, scientists examined the interactions between bleaching and sewage pollution in Curaçao and found that the highest levels of coral tissue mortality occurred on reefs chronically exposed to sewage.[142]

Our search yielded only one published field study purporting to find no detectable effect of sewage outflow on coral communities. Grigg used a control-impact design to investigate effects of sewage outflow coming from pipes deployed in the coastal waters of Hawaii.[140] Grigg stated that there were no statistically significant impacts of sewage outflow on coral species richness and cover,[140] a negative result that has been cited over 180 times in the literature. Close examination of the methods and results of Grigg,[140] however, call into question this inference and thus challenge the wisdom and rigor of the widespread use of the conclusions of this paper in the scientific literature. Specifically, for the case of coral cover, no statistical results were reported in the figures, tables or text. In addition, visual inspection of the differences in coral cover at shallow depths (Figure 2.1 in Grigg 1994)[140] next to outflow pipes vs. coral cover in control sites, suggest the opposite effect—i.e., significantly less coral cover around outflow pipes. These concerns, along with the fact that there were no before-after data, suggest that Grigg's strongly worded conclusions[140] that sewage does not impact coral reef ecosystems should be reevaluated.

In summary, seven out of eight of these observational field studies show positive correlations between increasing sewage concentration on reefs and increasing coral disease and degradation of coral reef communities. The eighth study reports no effect, however we have concerns about the analysis and interpretation of data provided. Future investigations should use both experimental manipulations of sewage presence in the field, and more rigorously designed Before-After-Control-Impact studies[148] to test for this putative causal relationship. Furthermore, new studies should: (1) employ varying degrees of sewage exposure, in order to produce a functional relationship between increasing sewage concentration and metrics of coral health and reef community condition; and (2) measure concentrations of as many sewage-associated toxins as possible to help begin to decipher which toxin(s) within sewage is most correlated with declines in coral health.

Synergistic impacts of sewage

When organisms experience multiple stressors, synergistic impacts can occur.[149] In particular, exposure to multiple stressors has been cited as a key factor in habitat loss in marine ecosystems[150, 151] and to decreasing growth rates in many marine species (e.g., see Refs. 149 & 152).

This is an important point, because sewage discharge is often mischaracterized as a single stressor in coral reef management. This review challenges that view and documents that sewage is a conglomerate of many potentially toxic and distinct coral and coral reef stressors, including freshwater, inorganic nutrients, pathogens, endocrine disrupters, suspended solids, sediments, heavy metals, and other toxins. Given the high number of individual stressors found in sewage and that the negative impacts of many of these pollutants are likely to combine at least additively because of positive feedbacks (see Figure 3.1 and discussion below), we argue that sewage should be viewed primarily as a multiple-, rather than single-stressor.

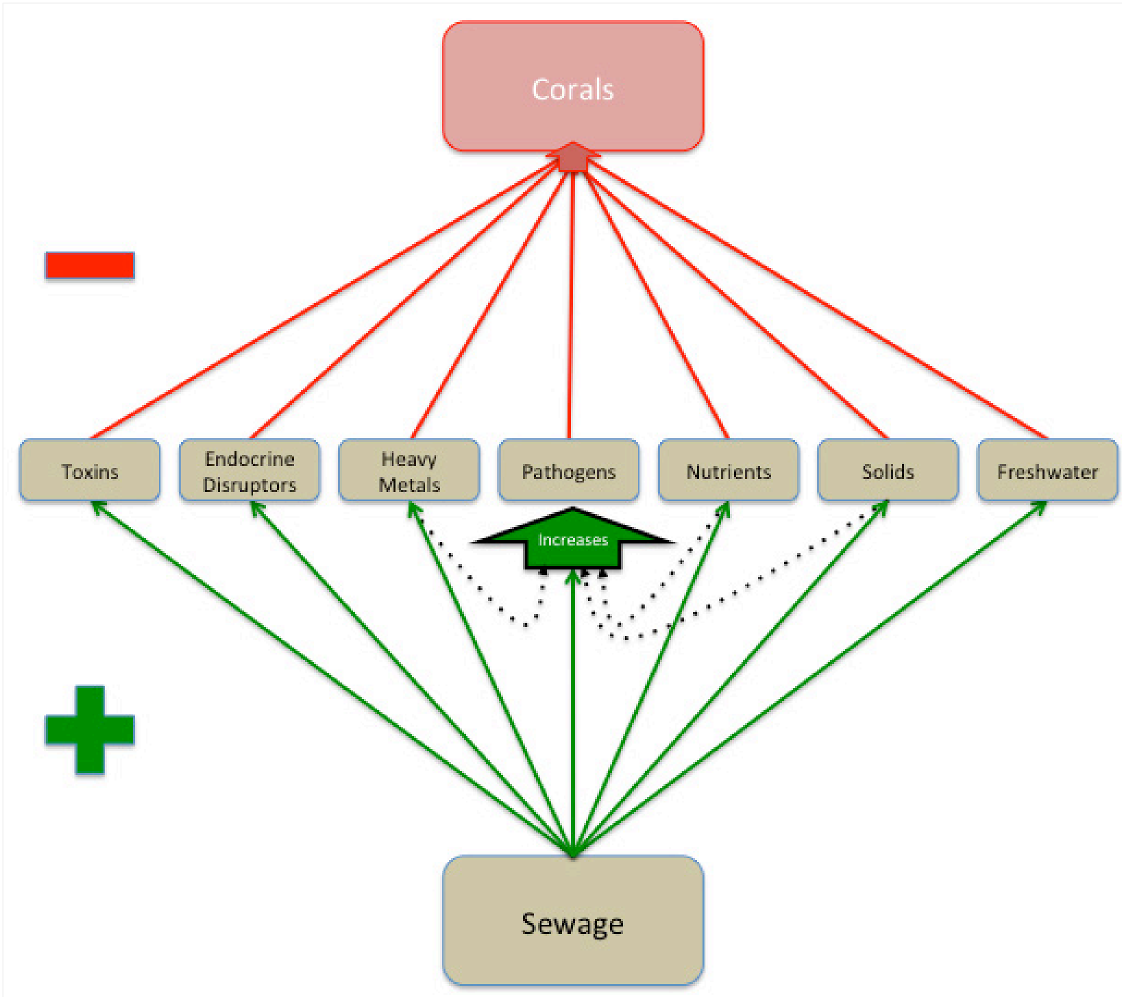

Figure 3.1. Interaction diamond illustrating impacts of sewage on concentrations of known stressors to corals and the positive feedbacks those stressors can have.

We propose a conceptual model to highlight common direct and indirect negative impacts that stressors found in sewage can have on corals (Figure 3.1). This model also highlights common directional interactions that those stressors may have with each other; and therefore additionally points out opportunities for positive feedbacks, additive effects, and subsequent multiple stressor effects. For example, sedimentation generated by sewage can stress corals and deplete their energy resources, resulting in increased susceptibility to pathogens that are found in high concentrations in sewage.[107, 153] Sediment-facilitated coral disease has the potential to be fueled to an even greater degree by increased nutrients[54] derived from sewage. The most important conclusion that can be taken away from this model is that the pathways for multiple-stressor effects generated by the multitude of component pollutants within sewage, are high both in diversity and abundance, making sewage a potentially lethal cocktail for coral reefs.

In addition to the synergistic effects that can occur *among* the component stressors found within sewage, there is also the strong possibility for synergistic interactions *between* sewage discharge and the many non-sewage stressors that impact coral reefs worldwide. For example, warming seas are hypothesized to play a role in facilitating disease outbreaks by increasing the susceptibility of coral to disease through temperature stress and increasing the virulence of pathogens.[80, 154] Evidence to support this hypothesis is present in recent work examining temperature anomalies and disease outbreaks.[86, 155] Furthermore, overfishing can lead to release of small corallivores from predatory control, such that they increase surface wounds on corals.[156] Increased wounding of corals is subsequently followed by greater disease susceptibility in these foundation species.[136, 157,158,159] Sewage discharge, through introduction of heavy metals and inorganic nutrients, could also interact with ocean warming and acidification to decrease coral growth and reproduction in an additive or synergistic way.[87, 160] These interactions with sewage are likely to lead to greater declines in coral cover and ultimately more disease, as stressed corals are more susceptible to disease.[87, 160] We would expect sewage impacts to be strongest in areas in close proximity to human populations, especially in areas with low flushing.[96]

A common mechanism leading to synergies between stressor impacts in both of these examples is that non-sewage stressors increase susceptibility to infection, while the addition of sewage renders disease delivery more likely and disease progression more rapid. The various effects that combined anthropogenic stressors have on the complex microbial community in the surface mucous layer of corals are not well explored. As we learn more about the role this mucous layer plays in coral health, we may learn that even small disturbances have the potential to tip the balance in favor of more harmful bacteria and viruses, ultimately leading to serious outbreaks of coral disease. Given the high potential for these synergistic interactions to occur when stress levels are high, future scientific studies and conservation efforts focused on sewage discharge should take their potential occurrence into careful consideration.

How extensive is the sewage discharge problem?

We conducted a literature review to determine how many coral reef geographies had a documented sewage pollution problem. Using the World Atlas of Coral Reefs[7] list of coral reef geographies, we conducted a Web of Science search with the following terms: TOPIC: "coral reef*" and TOPIC: "sewage" and TOPIC: "pollution" and TOPIC: "Location Name" (e.g., "Bahamas"). We identified the majority of our cases of sewage-impacted coral reef geographies in this way, with the remainder identified through a Google search using the same key words. In these cases, we typically found a local government report, but a few were noted only in newspaper articles. Our review revealed that, for almost every coral reef geography, raw or partially treated sewage is polluting the local environment. Figure 3.2 illustrates the spatial extent of the sewage contamination problem in the tropics, and clearly shows that no region is immune to this problem. Of the 112 coral reef geographies, including territories, states and countries, 104 have documented sewage contamination problems, with the majority having documentation of direct ocean discharge. Only 3 of those geographies are uninhabited, and therefore have no potential for sewage contamination. Although the amount of sewage discharged into the environment is difficult to quantify with accuracy, this survey reveals that the spatial extent of the problem is global in that it occurs in almost all coral reef geographies. However, the magnitude of the problem in a particular place is not represented in this assessment.

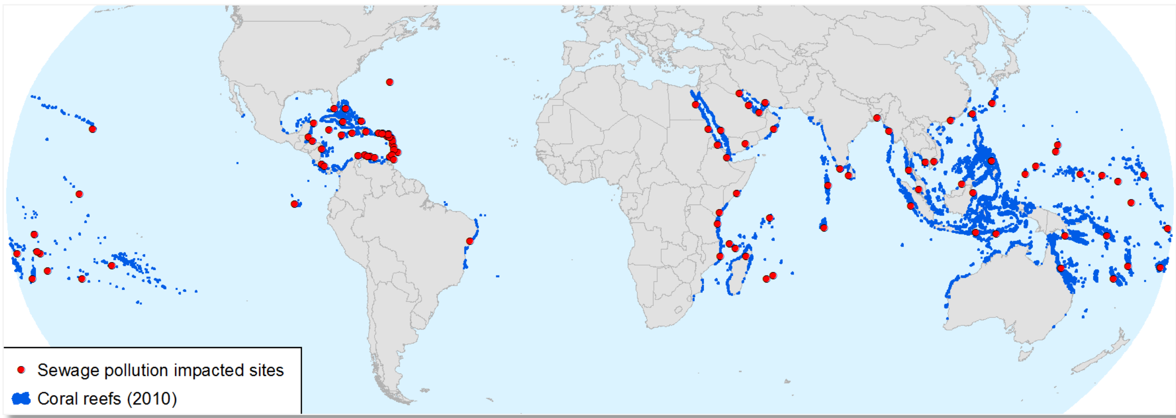

Figure 3.2. Global map showing 104 of 112 distinct coral reef geographies listed in the World Atlas of Coral Reefs[7](including 80 countries, 6 states, and 26 territories) with a documented coastal sewage pollution problem.

The ways by which sewage reaches waters bathing coral reefs are diverse, including intentional sewage contamination through direct-discharge outfall pipes (e.g., Hollywood, Florida sewage outfall),[161] and treatment systems that allow sewage overflows or bypasses during rain events or system failures (e.g., US Virgin Islands Frederiksted sewage bypass outfall).[141] Unintended sewage contamination also often occurs through faulty systems, attributable to engineering design flaws, especially inadequate capacity for flooding waters, a leaking infrastructure, shifts in soils and rock that surround the sewerage system, or lack of maintenance.[162] Even when state-of-the-art sewage treatment plants are installed, the governments of developing countries often do not have the staff or long-term funding to properly maintain the facility; thus, these facilities often fall into disrepair, leaving the communities to once again deal with a sewage problem.[162, 163]

Along with the faulty sewer and sewage treatment systems comes the issue of a widespread lack of proper sanitation. There are 2.4 billion people without access to sanitation, many in tropical, developing countries.[163] This lack of proper sanitation is linked to public health problems, including significant illness and death rates associated with diarrheal disease in developing countries.[164, 165] There are many geographies where the ocean is used as a toilet in common practice (open defecation), with this disposal method widely socially accepted.[163] While there is much progress being made on the Millennium Development Goals,[166] which are specifically working to address the lack of access to sanitation, there is still much work to be done to reduce overall sewage contamination in the environment. The World Health Organization expects to fall short of its sanitation goal in 2015 by half a billion people.[163] As human populations continue to grow and sea level continues to rise, the problem of sewage contamination in the environment will persist in the absence of truly significant interventions and likely grow as a function of human population growth.

Research and conservation recommendations

This review documents sewage discharge as a global and intense threat to coral reefs. Remarkably, despite the extent of this threat, both scientists and conservationists have paid relatively less attention, (in comparison to overfishing, for example), to understanding and abating sewage impacts on coral reefs. This is surprising because it is well documented that sewage contains a range of contaminants that individually are known stressors of coral reef ecosystems. Furthermore, the additive or synergistic impacts of these multiple contaminants have the potential to combine with one another and with other stressors beyond sewage, such as warming waters, to accelerate coral reef ecosystem declines. Mitigating this growing global threat will require future research that focuses on: (1) understanding tolerance thresholds that corals have to sewage exposure, evaluating individual contaminants as well as additive and synergistic combinations of contaminants; (2) quantifying the spatial extent and magnitude of the sewage discharge problems; and, most importantly, (3) testing both proactive and reactive strategies that can be employed to reduce the adverse impacts of the massive amounts of human sewage that enter tropical coastal waters. Pursuing only advanced treatment options for sewage systems is not an appropriate, viable solution to this problem. In many cases, this approach is not even feasible because of high costs. We must think creatively to solve this problem, by forging partnerships among human health organizations, sewage infrastructure and treatment experts, entrepreneurial groups, and development and environmental conservation organizations. Sewage pollution is a global threat that humans and coral reefs share. Combining forces across organizations in traditionally non-interacting sectors (e.g., conservation and economic development) is essential if we are to address the strain of human sewage in our reef systems, and their associated human communities.

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CHAPTER IV

BATTLING A COMMON ENEMY: MARINE CONSERVATION AND HUMAN HEALTH SECTORS SHOULD JOIN FORCES IN THE FIGHT AGAINST SEWAGE POLLUTION[2]

Abstract

The health of both coral reefs and people are imperiled by a common global threat -- sewage and the toxins and pathogens it carries. Despite this common enemy, those concerned with human health and those concerned with coral reef health have rarely joined forces. To jump-start an alliance between coral conservation and human health sectors, this paper: (1) documents the threats that humans and reefs share and; (2) identifies threat-abatement strategies that will benefit both people and reefs, highlighting mitigation of water pollution as a prime example. By joining forces, conservationists and human health practitioners can increase the overall resources they bring to bear against sewage, and can make more efficient use of those resources.

Introduction

Rarely do conservation and health sectors join forces. The irony of this is that in many cases these two sectors are fighting a common enemy. Nowhere is this more apparent than in coral reefs. In this paper I argue for establishment of a cross-sector, collaborative approach, by highlighting that there are many linkages between coral health and human health.

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[2] This chapter was submitted to *Frontiers in Ecology and Environment* on February 28, 2015 and is still under review at the time of this printing (April 26, 2015).

To map the "threat space" for coral reefs and human health, I surveyed the literature using a Web of Science search (Figure 4.1). Results of this survey uncovered significant overlap among multiple threats that affect both humans and coral reefs, as well as distinct threats that are unique to either reefs or to humans (Figure 4.1). For those threats held in common, six out of nine are related to water quality (sanitation, agricultural pollution, runoff from coastal development, etc.), while the remaining three deal with overfishing and greenhouse gas emissions. In almost every case of threat-overlap, conservation and human health sectors are already independently addressing these threats. This raises the possibility that by joining forces, positive outcomes would grow for both corals and people.

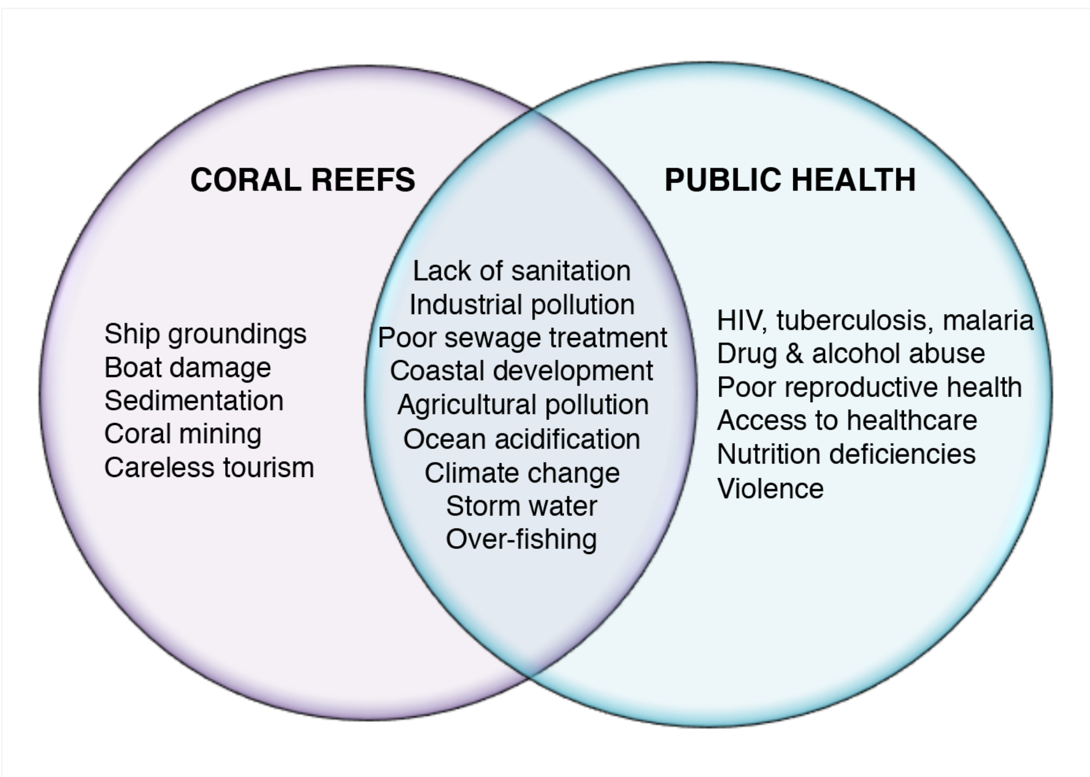

Figure 4.1. To assess the evidence of a common enemy for coral reefs and human health, I surveyed the literature using a Web of Science search, with the following search terms: TOPIC: "coral reef*" AND TOPIC: threat* OR stress* OR degrad*; and TOPIC: "human health" OR "public health" OR "community health" AND TOPIC: threat* OR disease* OR ill* OR sick* OR mort* AND TOPIC: coast* OR tropic*. This diagram illustrates the overlap between nine common and significant threats to both coral reefs and people.

Dirty water sickens corals and people

Water pollution is a prime example of a threat that is shared by both corals and humans.[1,2] The examples of how poor water quality leads to decreased human health are diverse and widespread. Poor water quality, for instance, leads to increased incidence of diseases such as cholera and hepatitis in human populations[3,4]. Likewise, over 180 million cases of upper respiratory disease and gastroenteritis occur each year due to humans bathing in polluted ocean waters.[5] Studies have found the incidence of these diseases among bathers increases with increasing levels of human sewage in coastal waters.[6] Summed across the globe, pathogenic microorganisms from wastewater pollution into the sea cause an estimated $15.4 billion (USD 2014) in economic losses annually because of their direct impacts on humans alone.[5]

At the same time, numerous ecological studies have demonstrated a clear linkage between increasing water pollution and declining coral health. Over the past 20 years, field studies have observed an increased incidence of disease in corals with exposure to sewage effluent.[7] More recently, a direct link was established between the human pathogen (*Serratia marcescens)* and white pox disease in Caribbean corals.[8] This bacterium comes from sewage that is being directly discharged into the ocean, either intentionally, or because of faulty sewage management systems.[8] Recent studies have also demonstrated that excess nutrients from land-derived pollution have negative impacts on reefs, causing increases in both disease and bleaching in Caribbean corals.[2] It is worth noting that excess nutrients, especially nitrates that find their way into drinking water, may cause methemoglobinemia, an illness found especially in infants.[9] Given that the health of both humans and coral reefs is commonly threatened by untreated human waste across the globe[2] (Figure 4.2), greatly enhanced treatment and management of sewage, before discharge into coastal waterways, would positively affect the health of both humans and coral reefs.

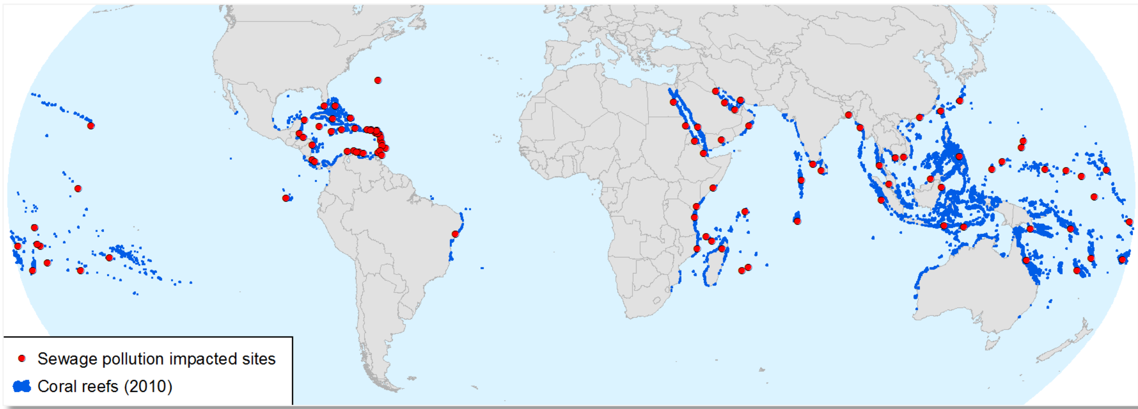

Figure 4.2. Global coral reef map showing 104 of 112 distinct coral reef geographies (including countries, states, territories) with a documented coastal sewage pollution problem (Wear & Vega Thurber in Press).

Ready to walk the talk

The idea that collaborations among the human health and environmental organizations are critical to successful outcomes for both sectors is not new. Most notably, in 2002, the World Health Organization and United Nations Environment Program launched Health and Environment Linkages Initiative (HELI), which was joined a year later by Health and Environment Alliance (HEAL), an initiative of the European Public Health Alliance. In addition, U.S. Agency for International Development (USAID) has been funding Population, Health, and Environment (PHE) projects for a couple of decades, which attempt to integrate conservation and development goals. While these examples represent far-reaching and substantial investment efforts in cross-sector collaborations, they do not go far enough and are still the exception rather than the rule. Given the ever-growing levels of threat, and increasing complexity of the problems facing the environment and human populations, it is time to build from these initial collaborative efforts, and push forward towards more concrete collaborations and substantive results. To provide a starting point, I reviewed 58 organizations that are either well-positioned to engage in such collaborations, based on their organizational mission and expertise, or have already made efforts to do so—whether testing the waters or going full bore. This analysis reveals that some of the largest and most influential health and conservation organizations are well positioned to engage in cross-sector work. Indeed, 21 of these organizations already list human and environmental health as shared goals of their organizations (Table 4.1). We can look to these organizations as a starting point to broaden cross-sector collaboration between human and environmental health, but there are likely hundreds more that could join in a movement towards integration, and foster even stronger alliances.

Table 4.1. Organizations that list both human and environmental and/or ocean health as shared goals

Organization
Conservational International
Global Coral Reef Alliance
Global Environment Facility
Harvard School of Public Health: Center for Health and the Global Environment
Health and Environment Alliance
Healthy Reefs for Healthy People
National Fish and Wildlife Foundation
National Oceanographic and Atmospheric Administration: Oceans and Human Health Initiative
Seaweb
The Nature Conservancy
U.S. Agency for International Development
U.S. Coral Reef Task Force
U.S. Environmental Protection Agency
United Nations Environmental Program
University of North Carolina at Chapel Hill: Water Institute
Wellcome Trust
Woods Hole Center for Oceans and Human Health
World Bank
World Health Organization: Health and Environment Linkages Initiative
World Resources Institute
World Wildlife Fund for Nature

Global health and global conservation organizations could form a powerful alliance

If health and conservation organizations continue to work in our traditional silos, we can expect more of the same: incremental results; occasional successes; and temporary fixes that rarely get to the root of the problem. By working together, the conservation and human health sectors will be more likely to find lasting solutions that do not get undermined by external forces. For example, there is a recent history of well-meaning water charities working to improve access to safe drinking water by digging wells in communities. These wells often end up being only a temporary solution because either local communities fail to maintain them or groundwater levels fall due to depletion by agricultural demands. Indeed, a 2009 International Institute for Environment and Development briefing reported that up to $360 million USD has been wasted because of the inability to maintain drinking wells once they fall into disrepair, which often happens in just a few years.[10] In many cases, clean water is scarce because of poor environmental stewardship. Long-term solutions should include considerations of watershed protection to help ensure access to safe drinking water. Bringing together epidemiologists, engineers, economists, and ecologists is likely to result in better-informed, and arguably better-designed, solutions to problems facing both people and nature. By pooling resources as well as expertise, a more systematic and efficient approach could emerge for planning or threat reduction, based on technological or scientific breakthroughs generated from interdisciplinary collaboration.

To begin to assess possibilities for cross-sector collaboration, I examined each shared threat identified in my literature survey (Figure 4.1), and highlighted examples of commonly employed strategies for each threat that could be used to improve the conditions for both coral and human populations. For every shared threat in Figure 4.1, I have identified multiple threat-abatement strategies (Table 4.2). Given the overlap in threats, and the possibility of shared strategies, it is evident much could be gained by focusing on interventions that benefit both human health and reef health.

An especially promising opportunity entails the Bill and Melinda Gates Foundation, which has recently set out to reinvent the toilet to provide toilets to those without adequate sanitation. This is no small endeavor—with approximately 2.4 billion people without access to adequate sanitation,[11] ultimately leading to both socioeconomic and health problems for these populations. One criterion for the new toilet is no discharge of pollutants. This design feature, if achieved, would also have significant environmental benefits. In tropical coastal areas, widespread use of these toilets could dramatically improve water quality for coral reefs and other important ocean habitats, such as seagrasses and mangroves. Remarkably, there is no conservation group poised to use their community networks to assist in the implementation of "clean toilets", even though such a program could have immediate benefits to corals. Ecologists could help identify the best locations for the units to maximize water quality enhancement within a watershed context, and thus improve human health and wellbeing to a greater degree with the same investment of resources—a common goal that conservation and human health organizations should share.

Table 4.2. Expected strategy outcomes

Threat	Strategies	Expected outcomes: Coral reefs	Expected outcomes: People
Lack of sanitation	Improve sewage treatment systems, install nonpolluting toilets, maintain septic systems	Decreased algal overgrowth, reduced disease occurrence, reduced coral bleaching	Reduced disease occurrence, positive social impacts (e.g., increased access to education, improved safety for women)
Industrial pollution	Industry regulations developed and/or enforced, corporate partnerships, technology innovations	Reduction in toxin-related stress to corals and reef-associated organisms	Reduction in exposure-related illnesses, improved quality of life, improved socio-economic status
Poor sewage treatment	Installation of modern sewage treatment facilities, tertiary treatment systems in place, staffing & maintenance standards implemented, improved on-site toilet systems	Decreased algal overgrowth, reduced disease occurrence, reduced coral bleaching	Reduced disease occurrence, positive impacts on tourism, industry (reduced tourist illness, better tourist experience)
Coastal development	Increase coastal habitat buffers, implement best management practices for road building and land clearing, minimizing vegetation loss	Reduction in suffocation-related stressors, decreased algal overgrowth, reduced disease occurrence, reduction in habitat loss	Reduction in exposure-related illnesses, stable income from reef-related activities (e.g., fishing, tourism)
Agricultural pollution	Increase riverine and watershed buffers, farm practices that reduce nutrient input including reductions in harmful fertilizers and pesticides	Decreased algal overgrowth, reduced disease occurrence, reduced coral bleaching, reduction in anoxia stress	Reduction in disease occurrence (e.g., red tide-related), improvement in fisheries/income
Ocean acidification	Reduce greenhouse gas emissions, adaptation planning, resilience-based strategies	Stable growth rates in corals and invertebrates with carbonate skeletons, structurally sound coral reefs	Sustainable food supply and job security for fishing industry, coastal security
Climate change	Reduce greenhouse gas emissions, adaptation planning, resilience-based strategies	Reduction in thermal stress/bleaching, reduced disease occurrence	Reduction in cholera outbreaks, reduction in projected health impacts: extreme heat, air pollution, natural

Threat	Strategies	Expected outcomes: Coral reefs	Expected outcomes: People
			disasters, allergens
Storm water	Implement building standards (i.e., pervious surfaces/roads, landscaping, etc.), constructed swales and rain gardens, enhancement of combined sewer systems	Decreased algal overgrowth, reduced disease occurrence, reduced coral bleaching, reduction in toxin-related stress to corals and reef-associated organism	Reduced disease occurrence, reduction in exposure-related illnesses (e.g., toxins), reduction in property damage (e.g., erosion, flooding)
Overfishing	Economic incentives for sustainable fishing, supply-chain improvements, aquaculture, fisheries closures, gear restrictions	Decreased algal overgrowth, increased space for coral settlement, improved ecological function	Sustainable food supply, improved tourism, sustainable livelihoods

Note. Taken together, this list of strategies and outcomes is extensive, but is not meant to be exhaustive. Rather, the list identifies many strategies that, when implemented, could benefit both people and reefs.

Another example of synergy stems from the growing use of habitat restoration in coastal watersheds (e.g., forests or oyster reefs) to increase the services natural communities provide humans. The goals of these environmental projects are to decrease erosion, and increase fisheries production and shoreline protection in surrounding waters, but also to enhance water quality so that other more sensitive sea life may thrive (e.g., seagrasses). The objectives of these conservation projects, if achieved, would also likely decrease public health hazards as well because forests and wetlands filter toxins and pollutants. Conservation organizations possess the technical expertise to restore these ecosystems; and by joining forces and aligning with conservation, human health organizations can begin to tackle high priority human health issues from a more holistic perspective.

Maximizing return on investment

To do this right, a conservation or human health organization cannot just hire a few experts in the parallel field, and have them consult on all projects with potential for conservation or health benefits. To be successful, the silos need to come down, and organizations need to come together, in more concrete and expansive ways. For example, engaging in joint strategy development, fundraising efforts, and outreach campaigns would be a good start. There is also the potential for substantial long-term savings by looking to root causes or taking a more holistic approach, which could be facilitated by the increased diversity of expertise and understanding that comes with a more united effort. For example, in 1997 it was estimated that it would take nearly $300 billion (USD 1997) to meet the entire developing world's needs for water and sanitation over a project period of 10 years[12]—yet making a $3 billion investment (just 1% of the project cost) to protect watersheds would be as effective as the alternative option of installing water piping, stand taps, sewer systems, and other complementary infrastructure.[12] Not only would this be an incredible cost savings, but protecting those watersheds would also have a significant impact on protecting or improving coastal water quality by decreasing pollution and erosion.

The World Health Organization (WHO) states that eliminating environmental hazards to health can prevent up to one-quarter of the global burden of disease.[13] However, a win-win outcome is not easy and requires quantitative planning, modeling, and monitoring to maximize the potential for mutualistic outcomes between conservation and human health.[14] Without concerted efforts involving co-planning on the part of environmental and health organizations, opportunities for maximizing returns on investment will be left unfulfilled.

What are the costs of collaboration?

Given the potential additive and synergistic benefits that may result from collaborative efforts, one must question why examples are so rare. There is always the potential for unintended costs, and collaborations are complicated—demanding more staff and meeting time than would be the case if each organization were left to work on its own. In addition, there will be times when conserving nature has the potential to negatively impact human health (e.g., protecting wetlands that may serve as breeding grounds for mosquitos that spread human disease). In addition some initial case studies of joint conservation and development projects drew pessimistic conclusions.[15] However, more recent quantitative meta-analyses revealed that for World Bank projects, there was no cost to including conservation or biodiversity goals in development projects.[16] That is, both conservation and development goals could be achieved with the same effort, without compromising the success of the project, or increasing the cost of the overall project. While this analysis considered development broadly and not human health, its results suggest that there may be ways of fruitfully combining health and conservation efforts without undue costs.

Human benefits beyond immediate health hazards?

In recent years, the case for conservation has evolved from one mostly focused on protecting nature for nature's sake to one that also highlights conserving nature because of the benefits it provides humans.[17,18] In the context of coral reefs, it is estimated that over half a billion people benefit from services provided by coral reefs: including food; jobs; and space to live.[19] Besides these indirect linkages, coral reefs also provide clear, direct health benefits to people, through the myriad of medicines derived from coral reef animals. These include treatments for cancer, Alzheimer's, and HIV. Summed across all provisioned services, coral reefs have been estimated to provide $31 billion (USD 2014) annually in net benefits to people.[20]

It is time to act

Despite the magnitude and importance of reef-generated benefits, coral reefs continue to degrade and disappear. Over the past 40 years, coral reef coverage has dropped steadily in the Caribbean and the Indo-Pacific.[21] As the world population increases by at least 2 billion over the next 50 years, both the human health and nature conservation sectors will face greater and greater challenges achieving their goals. To reverse the decline, coral reef conservationists must devise new strategies to do more with less, and form new partnerships that increase resource availability. Clearly, humans have intimate connections with nature: healthy nature increases human well-being, and humans and nature have many threats in common. Recognizing these linkages is the first step in fostering cross-sector collaboration. If we can find ample evidence to motivate and inspire decision-makers worldwide to initiate alliances between nature conservation and human health organizations, both ecosystem and human health stand to achieve dramatic improvements.

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CHAPTER V

CONCLUSION

This dissertation identifies lack of action towards addressing coastal pollution as a critical gap in conservation practice, provides a comprehensive review of the impacts of sewage pollution (the largest contributor to coastal pollution), and proposes new ways forward in conservation that will ignite new conservation and research initiatives to address sewage pollution, with the ultimate goal of generating benefits for both people and coral reefs.

In Chapter 1, I examine whether coral reef conservation and management organizations are allocating resources according to the severity of local threats and find that there is a significant mismatch that occurs globally. Initial inquiry as to why this mismatch is occurring, reveals that organizations face numerous external factors that influence resource allocation that have nothing to do with the most pressing threats. While this may be intuitive, it is important to note which factors seem to play a major role, as they could be considered in future strategies that address coastal pollution. Further study to better understand why these mismatches are occurring is essential to any effort working to influence how conservation resources are allocated, or to increase efficiency in conservation outcomes.

Although the findings of this study were significant, I was unable to draw clear comparisons about regional geographic and organizational differences. While it is likely that there is a difference in how resources are allocated between organizations—further study that attempts to answer this question would be helpful in refining management recommendations.

Follow-up studies that examine country-specific trends are needed to determine the nature of the mismatch as well as the drivers of those decisions. This type of work should be the next step for anyone interested in addressing the issue in a specific geography.

In Chapter 2, I reviewed the impacts of sewage pollution on corals and coral reef communities. Because there were so few studies that examined the impacts of sewage on coral reefs, the majority of my review focused on the main components of sewage and studies that examined their impacts. This review revealed the importance of viewing sewage pollution as a multi- rather than single-stressor, given the diversity of harmful components and the range of effects they can have on corals and associated flora and fauna. Additionally, this review demonstrated a need for well-designed experimental studies as well as more rigorous comparative studies to better understand the impacts of sewage. Given that exposure to sewage can vary widely and that not all sewage exposure is a concern for the marine environment, studies that examine dose-response would be helpful for managers looking to prioritize management action that mitigates sewage pollution. Studies that examine the fate of the various sewage components, that is, study of the factors that control the persistence and fate of these stressors, would help reef managers to make better decisions based on the unique characteristics of their site (e.g., well-flushed vs. poorly flushed). For example, a poorly flushed bay may face long term issues from re-suspension of sediments deposited in a single event that would differ from those faced by a well-flushed water body. Investigations that examine how sewage effluent interacts with other stressors such as ocean warming or overfishing have the potential to help managers' priorities when and where they mitigate sewage pollution.

I also mapped the presence of sewage pollution in coral reef geographies across the globe to demonstrate the extent of the threat. However, this map only provides information regarding documentation of sewage pollution and does not provide information about magnitude, frequency, or location of sewage pollution within those geographies. Such geospatial information would be very helpful in priority setting efforts both at the local and regional scale.

In Chapter 3, I examined the connections between human health and coral reef health. As a conservationist, I am interested in how humans relate to their environment and seek to identify clear connections to increase understanding of the role nature plays. In this case, I was interested in whether there were opportunities to connect human health and coral reef health that might build support for broader action. I conducted a literature review to determine the most common threats to both coral reefs and people, and found that they share nine serious threats, most of them associated with some pollution variant. Additionally, I reviewed studies that showed human pathogens in sewage to be the causal agent of a coral disease in the Caribbean.

To stem decline of coral reefs from a wide range of threats, we must find new strategies and resources to increase both the overall conservation effort and the efficiency of those efforts. One such strategy that has received relatively little attention but has high potential is collaboration between the environmental and human health sectors, especially when the stressors (e.g., pollution) that they are trying to mitigate overlap. This study provides both qualitative and quantitative arguments in favor of this collaboration by pointing out how working together can generate synergisms and thus increased protection of both humans and the environment per investment unit by each organization. In doing so, it is one of the first efforts to take a position calling for a united human and coral reef health initiative.

To further strengthen and support such an effort, it would be useful to collect geospatial information about sanitation access, sewage treatment and coral reef priority areas to identify the best opportunities for testing or addressing the shared threat. For example, it would be useful to know which coral reef geographies are lacking sanitation in or near their coastal areas or which geographies experience direct discharge of sewage into the ocean. Studies that test different technologies to reduce sewage pollution are also needed to demonstrate the potential for shared benefits as well as to simply identify best technologies to mitigate the threat. Experimental studies looking at the impacts of conservation projects on human health and vice versa will help to determine potential for shared benefits as well as expand the understanding of how humans depend on a healthy environment. Finally, further study of the linkages between human pathogens and marine organism disease is needed to clarify these links as well as identify additional pathogens that may play a role in coral disease.

Despite significant conservation investments over the past 30 years, marine ecosystems and the services they provide to humans are under increasing threat. For most ecosystems, conservation efforts have slowed rather than reversed decline. The future of coral reefs is uncertain given the array of threats they face. The tools applied to reduce threats to coral reefs have been limited and mostly focused on area-based strategies such as marine protected areas (MPAs). However, MPAs rarely address coastal pollution. While coral reef practitioners continue to refine MPA design and monitoring protocols, directing the majority of their limited resources to such activities, these same waters continue to be compromised by pollution. In order to effectively mitigate threats to coral reefs, we must consider a broader suite of threats and look beyond the impacts of overfishing. We must also break down the silos of conservation and natural resource management and begin to partner more closely with organizations working to improve the lives of people through development, infrastructure, and human health initiatives.

It is clear that conservationists will not achieve their goals without extending their reach beyond the traditional boundaries. Now, more than ever, large conservation organizations are making human well-being an explicit part of their mission. This dissertation provides the foundation for conservation organizations to take the next step toward addressing coastal pollution for the benefit of both ocean habitats and people.

APPENDIX A

REEF MANAGER SURVEY

The goal of this study is to understand how various threats to coral reefs are perceived and what actions are being taken to reduce them. We are also interested in how investments are being made in particular threat reduction strategies and how priorities are determined. Your responses and feedback are very important.

The information collected in this survey will be used to inform a doctoral research project at The University of North Carolina at Chapel Hill, sponsored by The Nature Conservancy. Please keep in mind that in some cases, we are asking about all known activities with regard to strategies - not just those carried out by your organization.

All of your responses are completely confidential and voluntary. Your name will not be associated with any of your answers and all information will be kept strictly confidential. The average time to take this survey is 20 minutes.

These questions are provided in online survey form to facilitate your responses. If you have any questions or concerns about this survey or would prefer to be interviewed by phone, please contact Stephanie Wear, Ph.D. student in the Department of Marine Sciences, at swear@live.unc.edu.

***1. Please provide the following information below to help us identify the geographic region and organization you represent.**

Name:

Organization Name:

State/Province (required):

Country (required):

Email Address:

2. If you work in more than one geography, please list here:

***3. Select the organization type for which you work:**

- ◯ Local Government
- ◯ State Government
- ◯ National Government
- ◯ Local NGO
- ◯ National NGO
- ◯ International NGO
- ◯ Academic
- ◯ Private

Other (please specify)

***4. Which category below best describes your current position?**

- ◯ Park Manager
- ◯ Fisheries Manager
- ◯ Natural/Marine Resource Manager
- ◯ Research Scientist
- ◯ Academic Scientist
- ◯ Program Manager

Other (please specify)

5. How many years of experience in conservation and/or resource management do you have?

- ◯ 1-5 years
- ◯ 6-10 years
- ◯ 11-15 years
- ◯ 16-20 years
- ◯ 21-25 years
- ◯ More than 25 years

***6. What are the main marine habitats you work with? (Please select all that apply)**

- ☐ Coral reefs
- ☐ Seagrasses
- ☐ Mangroves
- ☐ Beaches
- ☐ Estuaries
- ☐ Rocky Intertidal
- ☐ Other (please specify)

The next several questions will ask you to rank the threats to coral reefs in your geography. Both the threat categories listed and the descriptions provided directly below each threat category have been taken directly from "Reefs at Risk Revisited" (2011).

On a scale of 0 to 6, where 0 is not a threat and 6 is an extreme threat to the health of coral reefs in YOUR JURISDICTION, rate the following threats.

0 = NO THREAT
6 = EXTREME THREAT

PLEASE REVIEW all threat descriptions before rating.

***7. MARINE-BASED POLLUTION & DAMAGE**

Threat includes:

- Solid waste, nutrients, and toxins FROM oil and gas installations and shipping

- Physical damage FROM anchors and ship groundings.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***8. WATERSHED-BASED POLLUTION**

Threat includes erosion and nutrient fertilizer runoff from agriculture delivered by rivers and coastal waters.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***9. OVERFISHING & DESTRUCTIVE FISHING**

Threat includes unsustainable harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***10. THERMAL STRESS**

Threat includes warming sea temperatures, which can induce widespread or "mass" coral bleaching.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***11. OCEAN ACIDIFICATION**

Driven by increased carbon dioxide concentrations, which can reduce coral growth rates.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***12. COASTAL DEVELOPMENT**

Threat includes coastal engineering, land filling, run-off from coastal construction, sewage discharge, and impacts from unsustainable tourism.

0	1	2	3	4	5	6
○	○	○	○	○	○	○

***13. RANK THE FOLLOWING THREATS in order of the impact they have on the health of coral reefs in your jurisdiction, where 1 is most harmful and 6 is least harmful.**

PLEASE NOTE: The ranking is automatic and will reorder the list based on each ranking you make so be sure to CONFIRM THE RANKINGS ARE CORRECT before moving to next question.

- [ ] Marine-Based Pollution & Damage
- [ ] Watershed-Based Pollution
- [ ] Overfishing and Destructive Fishing
- [ ] Thermal Stress
- [ ] Ocean Acidification
- [ ] Coastal Development

***14. RANK THE FOLLOWING THREATS in order of how much time and money is allocated to addressing that threat by your organization, where 1 receives the most resources and 6 receives the least resources.**

PLEASE NOTE: The ranking is automatic and will reorder the list based on each ranking you make so be sure to CONFIRM THE RANKINGS ARE CORRECT before moving to next question.

- [ ] Marine-Based Pollution & Damage
- [ ] Watershed-Based Pollution
- [ ] Overfishing & Destructive Fishing
- [ ] Thermal Stress
- [ ] Ocean Acidification
- [ ] Coastal Development

***15. Does your organization implement strategies aimed at reducing the threat of Overfishing and Destructive Fishing on coral reef health?**

****Threat includes unsustainable harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons.**

○ Yes

○ No

16. Overfishing & Destructive Fishing: Please select all activities below that are currently issues your organization works on (e.g., policy, promoting activity, supporting publicly, programs, projects) to improve coral reef health.

- [ ] Planning for multi-objective marine areas
- [ ] Implementing area-based management (MPAs, No-take, FPAs, etc.) with fisheries-specific goals
- [ ] Regulating herbivore fisheries
- [ ] Restoring reefs damaged by fishing or boating activities
- [ ] Acquiring access rights for fisheries
- [ ] Implementing collective fishing arrangements/co-management with local communities or government agencies
- [ ] Collecting socio-economic or fisheries data on particular fisheries in your area
- [ ] Assessing fish stocks
- [ ] Assessing best fishing gear
- [ ] Improving/implementing fishing regulations (banning gear, reforming permits, developing fisheries management plans for specific stocks, etc).
- [ ] Alternative livelihoods

Other (please specify)

____

***17. Does your organization implement strategies aimed at reducing the threat of Coastal Development on coral reef health?**

****Threat includes coastal engineering, land filling, run-off from coastal construction, sewage discharge, and impacts from unsustainable tourism.**

- ◯ Yes
- ◯ No

18. Coastal Development: Please select all activities below that are currently being implemented by your organization to improve coral reef health.

- [ ] Improving waste water treatment systems
- [ ] Monitoring & maintenance of septic systems
- [ ] Reducing wastewater/sewage discharge
- [ ] Regulating marinas to reduce non-point source pollution
- [ ] Planning for multi-objective use of marine areas
- [ ] Implementing sustainable building guidelines
- [ ] Enforcing/implementing coastal habitat set-backs
- [ ] Prohibiting/limiting beach renourishment
- [ ] Prohibiting/limiting shoreline hardening/bulkheads/seawalls
- [ ] Implementing wetland buffer zones
- [ ] Restoring coastal habitat
- [ ] Mitigating coastal habitat loss
- [ ] Protecting terrestrial areas adjacent to coast
- [ ] Improving road building practices
- [ ] Implementing sediment retention practices
- [ ] Facilitating watershed planning

Other (please specify)

***19. For the strategies below, RANK EFFECTIVENESS in improving water quality to the best of your knowledge where 1 IS MOST EFFECTIVE and 5 IS LEAST EFFECTIVE.**

If you are unfamiliar with the strategy, please leave line blank. For additional strategies, please use the OTHER row and specify the strategy in the box below the final row.

	1	2	3	4	5
Improving waste water treatment systems	◯	◯	◯	◯	◯
Monitoring & maintenance of septic systems	◯	◯	◯	◯	◯
Reducing wastewater/sewage discharge	◯	◯	◯	◯	◯
Regulating marinas to reduce non-point source pollution	◯	◯	◯	◯	◯
Planning for multi-objective use of marine areas	◯	◯	◯	◯	◯
Implementing sustainable building guidelines	◯	◯	◯	◯	◯
Enforcing/implementing coastal habitat set-backs	◯	◯	◯	◯	◯
Prohibiting/limiting beach renourishment	◯	◯	◯	◯	◯
Prohibiting/limiting shoreline hardening/bulkheads/seawalls	◯	◯	◯	◯	◯
Implementing wetland buffer zones	◯	◯	◯	◯	◯
Restoring coastal habitat	◯	◯	◯	◯	◯
Mitigating coastal habitat loss	◯	◯	◯	◯	◯
Protecting terrestrial areas adjacent to coast	◯	◯	◯	◯	◯
Improving road building practices	◯	◯	◯	◯	◯
Implementing sediment retention practices	◯	◯	◯	◯	◯
Facilitating watershed planning	◯	◯	◯	◯	◯
Other (please list in box below)	◯	◯	◯	◯	◯

Other (please specify)

***20. Does your organization implement strategies aimed at reducing the threat of Watershed-based Pollution to coral reef health?**

****Threat includes erosion and nutrient fertilizer runoff from agriculture delivered by rivers and coastal waters.**

- ◯ Yes
- ◯ No

21. Watershed Management: Please select all activities below that are currently issues your organization works on (e.g., policy, promoting activity, supporting publicly, programs, projects) to improve coral reef health.

- ☐ Reducing erosion
- ☐ Reducing point-source pollution
- ☐ Restoring watersheds
- ☐ Reducing agricultural nutrient loading
- ☐ Improving agricultural practices to minimize run-off
- ☐ Facilitating watershed management planning
- ☐ Helping establish water funds
- ☐ Increasing sediment retention

Other (please specify)

***22. For the strategies below, RANK EFFECTIVENESS to the best of your knowledge in improving water quality where 1 IS MOST EFFECTIVE and 5 IS LEAST EFFECTIVE.**

If you are unfamiliar with the strategy, please leave line blank. For additional strategies, please use the OTHER row and specify the strategy in the box below the final row.

	1	2	3	4	5
Reducing erosion	○	○	○	○	○
Reducing point-source pollution	○	○	○	○	○
Restoring watersheds	○	○	○	○	○
Reducing agricultural nutrient loading	○	○	○	○	○
Improving agricultural practices to minimize run-off	○	○	○	○	○
Facilitating watershed management planning	○	○	○	○	○
Helping establish water funds	○	○	○	○	○
Increasing sediment retention	○	○	○	○	○
Other (please list in box below)	○	○	○	○	○

Other (please specify)

***23. Does your organization implement strategies aimed at reducing the threat of Marine-based Pollution & Damage to coral reef health?**

****Threat includes:**
- Solid waste, nutrients, and toxins FROM oil and gas installations and shipping
- Physical damage FROM anchors and ship groundings.

○ Yes

○ No

24. Marine-Based Pollution & Damage: Please select all activities below that are currently issues your organization works on (e.g., policy, promoting activity, supporting publicly, programs, projects) to improve coral reef health.

- [ ] Promoting best practices via boating programs
- [ ] Implementing inspection and maintenance program for sanitary waste receptacles
- [ ] Making pump-out stations easily accessible
- [ ] Regulating ballast water
- [ ] Preventing groundings via navigational markers & current navigational maps
- [ ] Preventing anchor damage via mooring systems

Other (please specify)

***25. Does your organization implement strategies aimed at reducing the threat of Thermal Stress on coral reef health?**

****Threat includes warming sea temperatures, which can induce widespread or "mass" coral bleaching.**

- ○ Yes
- ○ No

26. Thermal Stress: Please select all activities below that are currently issues your organization works on (e.g., policy, promoting activity, supporting publicly, programs, projects) to improve coral reef health.

- [ ] Monitoring for resilience
- [ ] Designing resilient MPAs/Networks w/coral bleaching-specific goals
- [ ] Implementing bleaching response programs
- [ ] Implementing bleaching monitoring programs
- [ ] Implementing herbivore enhancement programs
- [ ] Reducing local threats to increase resilience
- [ ] Communicating with stakeholders about climate change adaptation and planning
- [ ] Implementing community-driven ecosystem-based adaptation
- [ ] Implementing national-driven ecosystem-based adaptation
- [ ] Implementing disaster risk reduction initiatives
- [ ] Restoring reefs to defend shorelines
- [ ] Maintaining coral nurseries and restoring coral reefs

Other (please specify)

***27. Does your organization implement strategies aimed at reducing the threat of Ocean Acidification?**

****Driven by increased carbon dioxide concentrations, which can reduce coral growth rates.**

- ◯ Yes
- ◯ No

28. Ocean Acidification: Please select all activities below that are currently issues your organization works on (e.g., policy, promoting activity, supporting publicly, programs, projects) to improve coral reef health.

- ☐ Monitoring ocean acidification
- ☐ Designing resilient MPAs/Networks w/ocean acidification-specific goals
- ☐ Implementing herbivore enhancement programs
- ☐ Communicating with stakeholders about climate change adaptation and planning
- ☐ Implementing community-driven ecosystem-based adaptation
- ☐ Implementing national-driven ecosystem-based adaptation
- ☐ Implementing disaster risk reduction initiatives
- ☐ Restoring reefs to defend shorelines
- ☐ Maintaining coral nurseries and restoring coral reefs
- ☐ Reducing land-based sources of pollution

Other (please specify)

____

Below you will be asked to identify the percentage of time or money that is being allocated to address each of the threats listed. Your total allotment can be less than 100%, but it cannot exceed 100%.

***29. Approximately what percentage of your organization's time is allocated/spent on reducing the threats listed below?**

"Organization time" incorporates all time being spent by staff in your organization. If you are part of an international NGO and are unfamiliar with total budgets, please respond for your operating unit or department.

	Marine-Based Pollution & Damage	Watershed-Based Pollution	Overfishing & Destructive Fishing	Thermal Stress	Ocean Acidification	Coastal Development
Less than 5%	☐	☐	☐	☐	☐	☐
5%	☐	☐	☐	☐	☐	☐
10%	☐	☐	☐	☐	☐	☐
15%	☐	☐	☐	☐	☐	☐
20%	☐	☐	☐	☐	☐	☐
25%	☐	☐	☐	☐	☐	☐
30%	☐	☐	☐	☐	☐	☐
35%	☐	☐	☐	☐	☐	☐
40%	☐	☐	☐	☐	☐	☐
45%	☐	☐	☐	☐	☐	☐
50%	☐	☐	☐	☐	☐	☐
55%	☐	☐	☐	☐	☐	☐
60%	☐	☐	☐	☐	☐	☐
65%	☐	☐	☐	☐	☐	☐
70%	☐	☐	☐	☐	☐	☐
75%	☐	☐	☐	☐	☐	☐
80%	☐	☐	☐	☐	☐	☐
85%	☐	☐	☐	☐	☐	☐
90%	☐	☐	☐	☐	☐	☐
95%	☐	☐	☐	☐	☐	☐
100%	☐	☐	☐	☐	☐	☐

***30. Approximately what percentage of your organization's budgetary resources are allocated/spent on reducing the threats listed below?**

"Organization budgetary resources" incorporates all funds being spent in your organization. If you are part of an international NGO and are unfamiliar with total budgets, please respond for your operating unit or department.

	Marine-Based Pollution & Damage	Watershed-Based Pollution	Overfishing & Destructive Fishing	Thermal Stress	Ocean Acidification	Coastal Development
Less than 5%	☐	☐	☐	☐	☐	☐
5%	☐	☐	☐	☐	☐	☐
10%	☐	☐	☐	☐	☐	☐
15%	☐	☐	☐	☐	☐	☐
20%	☐	☐	☐	☐	☐	☐
25%	☐	☐	☐	☐	☐	☐
30%	☐	☐	☐	☐	☐	☐
35%	☐	☐	☐	☐	☐	☐
40%	☐	☐	☐	☐	☐	☐
45%	☐	☐	☐	☐	☐	☐
50%	☐	☐	☐	☐	☐	☐
55%	☐	☐	☐	☐	☐	☐
60%	☐	☐	☐	☐	☐	☐
65%	☐	☐	☐	☐	☐	☐
70%	☐	☐	☐	☐	☐	☐
75%	☐	☐	☐	☐	☐	☐
80%	☐	☐	☐	☐	☐	☐
85%	☐	☐	☐	☐	☐	☐
90%	☐	☐	☐	☐	☐	☐
95%	☐	☐	☐	☐	☐	☐
100%	☐	☐	☐	☐	☐	☐

The next question is about how your resources are allocated within your institution - specifically resources intended for marine conservation or management. WE ARE NOT asking if you have adequate funding, rather we are asking about HOW you allocate the resources you have.

***31. Given the total resources available in your organization, the amount allocated to each of the following is:**

	Too Little Allocated	Right Amount Allocated	Too Much Allocated	Don't Know
Overfishing and Destructive Fishing	○	○	○	○
Thermal Stress	○	○	○	○
Watershed-based Pollution	○	○	○	○
Marine-based Pollution & Damage	○	○	○	○
Ocean Acidification	○	○	○	○
Coastal Development	○	○	○	○

32. If you answered too little or too much for any of the threats above, why do you think there is a mismatch between level of threat and allocation of resources?

33. Which of the following factors do you think influences decisions about resource allocation the most? PLEASE CHOOSE UP TO THREE FACTORS.

- ☐ Stakeholder/community agenda
- ☐ National/Federal government mandate
- ☐ Conservation organization agenda/training
- ☐ Donor funding priorities
- ☐ Available skill-sets
- ☐ Available science
- ☐ Popular strategies in international policy (e.g., MPAs)
- ☐ Politics
- ☐ Corruption
- ☐ Cultural tradition
- ☐ Based on past investments

Other (please specify)

34. Please use this space to provide additional comments about this survey.

35. Would you be willing to speak with us to follow up on your responses? If so, please leave the best contact information for you in the comment box (skype name, email, etc.).

Thank you for taking the time to complete this survey. Please feel free to contact us with any questions or concerns about this survey by emailing Stephanie Wear at swear@live.unc.edu.