Failure to Respond to a Coral Disease Outbreak: Potential Costs and Consequences

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Abstract

A coral disease with white plague-like signs was observed near Virginia Key, Florida, in September 2014. The disease outbreak directly followed a regional high temperature coral-bleaching event. Now called stony coral tissue loss disease (SCTLD), it has spread the length of the Florida Reef Tract from Key West to Martin County, a distance of about 450 km. Recently, the disease has also been observed at a number of sites throughout the Caribbean. The high prevalence of disease, the number of susceptible species, and the high mortality of corals affected suggests this outbreak is arguably one of the most lethal ever recorded. The initial response to this catastrophic disease by resource managers with purview over the ecosystem was slow. There is generally a very short window of opportunity to intervene in disease amelioration or eradication in the marine environment. This slow response enabled the disease to spread unchecked. Why was the response to the loss of our coral reefs to a coral disease epidemic, such a massive failure? This includes our failure as scientists, regulators, resource managers, the local media, and policy makers alike. This review encapsulates the numerous reasons for our failures during the first few years of the outbreak. Specifically, I show how the Port Miami dredging project that was ongoing at the time of the initial outbreak created a distraction as local NGO's, regulatory agencies, and resource managers initially blamed the project for observed large-scale coral losses. However, detailed analysis of 650 tagged corals that were part of a repeated measures monitoring program required for permit compliance associated with the Port Miami dredge project reveal that both disease susceptibility and coral mortality are invariant with the results collected by a number of scientific teams throughout the region. Finally, when the agencies responded to the outbreak the effort it was too little and much too late to make a meaningful difference. Because of the languid management response to this outbreak, we are now sadly faced with a situation where much of our management efforts are focused on the rescue of genetic material from coral species now at risk of regional extinction.

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Introduction

Imagine that you live in an apartment building and a dozen of your neighbors became sick, then died. You live on the top floor and those who initially fell sick first were on the first floor, then a week later a few people on the second floor went out the door in ambulances, and shortly after whatever was killing your friends jumped several floors to just below where you lived. At the same time, you noticed ambulances across the street and down the block. How would you feel knowing that whatever was killing your neighbors was coming for you? And no matter what you did, including calls to your doctor, to local government officials, and to all your friends, nothing happened. It was like you were in a bad dream. Where was the yellow tape to identify danger zones? Why wasn't this blowing up the Internet? Why was it not being covered by the media? Why no official government response? Where are the response teams from the Center for Disease Control? The thing is, this wasn't a bad dream. It exactly describes what happened to coral reefs in South Florida starting in 2014. And it wasn't the first time. We had three decades to prepare for this latest coral disease epidemic, with plenty of signs that it was coming (Cróquer et al. 2005, Miller et al. 2009, Hoegh-Guldberg and Bruno 2010, Miller and Precht 2013). Yet, nothing changed. By analogy, the death of chestnut trees in America and the resulting response by government and academics was immense (Ringling and Prospero 2018). That was for one species, iconic clearly, but just one species.. Why was the response to the loss of our coral reefs to a coral disease epidemic, an entire ecosystem, such a massive failure? That's the bigger question. The example of the 2014 – recent coral disease outbreak in Florida encapsulates our failures. Our failure as scientists, regulators, resource managers, and policy makers

The Outbreak

In the fall of 2014, while surveying corals at far-field control sites off Virginia Key for compliance monitoring associated with the Port Miami deepening project, scientific divers from my company identified the first signs of a coral disease similar to reports of white-plague disease that had been originally described in the mid-1990's by Richardson et al. (1998a, 1998b). This earlier disease raced through the reefs in the northern Florida Keys killing millions of corals (Sokolow et al. 2009). The new disease outbreak, now known as Stony Coral Tissue Loss Disease or SCTLD for short (FKNMS 2018) began just as corals were starting to regain their color (zooxanthellae) from a mass coral-bleaching event observed throughout the region during the summer of 2014 (Figure 1; NOAA 2014, Manzello 2015). Bleaching has been in the news a lot lately, largely related to its impacts on the Great Barrier Reef in Australia and its clear link with global warming (see Hughes et al. 2017).

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Figure 1. Close-up of initial observation of partial mortality (blue arrow) and first appearance of the white disease line (light yellow arrow) from tagged *Meandrina meandrites* coral located at one of our southern, inner-reef, far-field control permit compliance monitoring sites associated with the Port Miami deepening project (coral tag number R2SC2-LR-T2-C1) on September 26, 2014 (left) and again with well-defined white-plague disease line (light yellow arrow) and continued partial mortality from initial location of mortality (blue arrow) on October 8, 2014 (right) (from Precht et al. 2019). Note that in photo on right, that the bleached portion of the colony has regained color (zooxanthellae) in response to cooler water temperatures only 12 days later. Also note the rapid colonization of turf algae on the recently killed portions of the colony.

Continuing observations made throughout Miami-Dade County in the fall of 2014 and through the first half of 2015 by myself and my team, revealed the devastating and wide-spread impacts of this deadly epidemic (Precht et al. 2016). No one knew at the time of our original observations that we were about to witness the onset of one of the most contagious and deadly coral diseases ever recorded. Based on my personal observations, coupled with its rapid spread and extremely high levels of mortality, I sent an email to more than 20 local scientists, colleagues, regulators, and managers highlighting the potential impact of this disease on November 20, 2014 (see email attached below). That's when my reality started to resemble a bad dream.

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From: William Precht <william.precht@gmail.com>

Date: Thu, Nov 20, 2014 at 11:02 PM

Subject: White Plague Outbreak in Miami-Dade County

All,

Recently, while diving on our control monitoring sites south of Government Cut (off Virginia Key) we noticed a devastating outbreak of a disease with white-plague-like symptoms. It is still on-going, appears to be spreading, and is responsible for rapid mortality of the infected colonies. No work has been done to firmly establish etiology at this point. The outward symptoms strongly resemble previous descriptions of WPD from throughout Florida and the Caribbean. This disease is considered one of the most damaging to coral populations because of its frequent outbreaks, wide host range, and high virulence (Richardson et al. 1998a, 1998b; Richardson and Voss, 2005; Weil et al. 2006; Miller et al. 2003, 2006; Cróquer and Weil 2009). This outbreak started within the past month or so and followed on the heels of this summer's regional mass coral bleaching event. So far, the major species affected include MMEA, DSTO, SBOU and MCAV. The disease has not been noted on colonies of SINT, SSID, PAST.

Similar disease outbreaks have been observed following mass coral bleaching events. For instance, Weil et al. (2009) noted for the period following the 2005 mass coral bleaching event in the eastern Caribbean "Colonies were already stressed by a long period (14 degree heating weeks= # of weeks with water temperatures at least 1°C above average) of high water temperatures (and bleaching) which could have increased colony susceptibility and facilitated the WPD-like epizootic to develop. Contrary to the characteristic seasonality of this disease, the 2005 outbreak lasted longer, with many colonies showing disease signs until March-April of 2006 in La Parguera. Similar observations were reported for the Virgin Islands (Miller et al. 2006, 2009; Rogers et al. 2008, Rothenberger et al. 2008)."

If anyone else has seen or documented anything similar in their study sites, please share this information with me. Thanks!

Bill

I received little response to this email notice and request for additional observations. However, Dr. Diego Lirman replied stating that he, Dr. Laurie Richardson, and Dr. Mauricio Rodriguez-Lanetty had anticipated the possibility of disease outbreak(s) associated with warming and the 2014 bleaching event and had written a Rapid Grant proposal to NSF entitled “A hyper-thermal anomaly in the Florida Reef Tract: An opportunity to explore the mechanisms underpinning patterns of coral bleaching and disease” which was awarded to Mauricio Rodriguez-Lanetty from the Biological Oceanography section of NSF, Award #1503483. In addition, Ms. Karen Bohnsack

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from the Florida Department of Environmental Protection (FDEP) sent me periodic updates of disease reports from the Southeast Florida Action Network (SEAFAN) Bleach Watch program. Coordination with these scientists as well as conversations with local recreational dive operators helped us to track the spread of this disease outbreak region wide (Precht et al. 2016). The initial response was thus defined by an NSF study to determine relationships between coral bleaching and disease (Merselis et al. 2018) and the potential pathogens involved. In other words, some monitoring and sampling were being done, however, there was no management response to do anything about the spread of the emerging killer disease.

In 2015, as I followed the disease ravaging the coral populations in Miami-Dade County, I continued to send numerous emails (eight in total) including copies of photographs and the data I was collecting to inform other colleagues of my observations. Finally, to my great surprise, a few months later I received a trail of older emails that were attached to an earlier email I had sent about the disease epidemic. That's when I learned why there was little response to my numerous requests for information. Regulators who had received my initial emails were reluctant to respond because they thought the coral mortality I was reporting was caused and/or exacerbated by the on-going Port of Miami dredging operation, and that if it was a disease it was restricted to an area only surrounding Port Miami. Thus, the prevailing thought was it that it was a "local" issue that was caused by irresponsible environmental stewardship and everybody involved in the Port Miami project was somehow to blame (Staletovich 2015a). The evidence for this conclusion was based on assumptions and biases that are typical of environmental organizations that usually mean well but are not always based in reality (Silverstein 2015). Such assumptions, of course, have no place coming from government stewards who by default should base their conclusions on facts – not fake news. It had also become clear that because I was involved with the compliance monitoring of the Port Miami project, I had not been copied on any of their responses. In one specific case, the Southeast Regional Administrator for the Florida Coastal Office of FDEP stated the following in an email entitled "White Plague Coral Disease Outbreak in Miami" dated July 1, 2015: *"I am admittedly biased in my presumption that new(ish) sediment in the system is in part or wholly triggering this event. I would like to discuss what (if anything) we might be able to do to collect useful data that we can use to prove…my (biased) presumption*." The words highlighted in parentheses are her own. This is an astonishing admission. It's like if in my bad dream of disease ravaging my neighborhood, that the government official responsible for protecting our health and safety believed that the cause of the epidemic, without any evidence, was illegal immigration. Remember, it's my bad dream!

It wasn't until the summer of 2015 when other scientific monitoring teams who were collecting data at their sites throughout the region, including at sites far from the dredging project, detected that the levels of devastation wrought by this coral killer were significant (FRRP 2015, TNC 2015, Carsey et al. 2016, Gilliam et al. 2016). Finally, some nine-months after my initial email, the first interagency call to discuss the disease was organized and occurred on August 28, 2015. Does nine months seem like a long time? Is this amount of time typical for how government agencies respond to emergencies? I think not. For example, the Florida Reef Resilience Program, a consortium comprised of Florida scientists and resource managers from various universities, agencies and NGO's conducted a month-long survey of 76 reefs sites from Martin County to Key West, both

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during and shortly after an extreme winter cold front in January of 2010 that caused widespread coral mortality (Lirman et al. 2010). I was part of that massive response effort. A similar effort was mounted in the Florida Keys after the passage of Hurricane Irma in 2017. So, the answer to this question is not debatable. What is inexcusable, however, is that it wasn't for another year, until July 7, 2016 that the calls were expanded to include scientists, regulators, and resource managers from throughout the entire region (see Table 1 below). Two years passed and by then the conflagration had now moved south through Biscayne National Park and into the Florida Keys National Marine Sanctuary. If nine months is too long, then two years clearly crosses the line so whatever response might result is by default far too little and certainly too late. Importantly, at this point in time, the rate of progression of the disease could be predicted with relative certainty and each new reef impacted followed the same general pattern of disease prevalence, species susceptibility, and subsequent mortality (Precht et al. 2016).

Table 1. Disease Response Timeline

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- September 26, 2014 – Divers note first signs of disease outbreak off Port Miami southern control monitoring sites in Miami-Dade County off Virginia Key (adjacent to Central Miami Wastewater Plant Outfall)
- November 20, 2014 – Precht notifies numerous agencies and coral scientists via email about concerns regarding disease outbreak off Virginia Key and that it was spreading
- Precht submits numerous emails to FDEP-CRCP & Bleach-Watch Program providing regular updates of coral disease epidemic and regional spread between fall of 2014 and summer 2015. These emails contained photographic documentation and data from each site visited as well as observations by others.
- August 28, 2015 – First Inter-Agency Southeast Florida Coral Disease Conf. Call occurs 11 months after start of outbreak and after numerous regional scientists (both regulators and academicians) confirm it's NOT a Port Miami problem.
- July 7, 2016 – First Florida Reef Tract Coral Disease Outbreak Coordination Meeting and Call - almost two years after onset of disease.
- August 10, 2016 – Precht et al. (2016) Scientific Reports manuscript is published.
- August 27, 2016 – Precht sends email notice to "coral list" with an update on the status of the disease.
- July 11, 2017 – US Coral Reef Task Force declares disease emergency for south Florida almost three-years after disease onset and one-year after Scientific Reports manuscript was published (USCRTF meeting held in Ft. Lauderdale, FL)
- July 24, 2017 – First Emergency South Florida Coral Disease Workshop. Disease gets renamed "Stony Coral Tissue Loss Disease"
- February 18, 2018 - Sen. Bill Nelson of FL writes letter requesting Federal agencies to actively address disease crisis affecting Florida's Reefs (letter attached as an addendum to this editorial).
- July 2018, the Florida Department of Environmental Protection (FDEP), the Florida Keys National Marine Sanctuary (FKNMS) and the NOAA Coral Reef Conservation Program (CRCP) hosted a coral disease workshop to develop a response plan for the ongoing coral disease outbreak in Florida, with a focus on identifying interventions that could help slow the continued spread of disease and save priority corals.
- September 5, 2018 Sen. Marco Rubio (FL) writes op-ed piece in Miami Herald regarding Florida's dying coral reefs (Rubio and Crosby 2018).
- Winter/Spring 2019 disease observed at numerous locations throughout the Caribbean.
- April 29, 2019 disease has spread through most of Florida Reef Tract - still active and spreading off Key West.

So, why was there a failure to respond rapidly to this disease outbreak? And is there anything that could have been done that would have saved corals? The two questions are related because the delay impacted the ability to effectively respond to the disease event. Based on my involvement with the Port Miami deep dredge project, including following the lawsuits promulgated by local NGO's against the US Army Corps of Engineers (Solomon et al. 2011, Silverstein 2014, USDC 2016), as well as the extremely biased local media coverage of the project (Staletovitch 2014a,

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2014b), it was clear that there was tremendous opposition to the Port Miami dredging project even before it started (Alverez 2011). Then, when corals around Miami started to die from this disease outbreak these groups (including government employees from NOAA-NMFS and the State of Florida) immediately turned to the dredging project (Nelson 2015, Staletovich 2015a, 2015b) as the direct cause for the corals dying (see Miller et al. 2016).

There was a big problem, however, with the claim that the dredging project was the cause of the disease event. It turns out that the people who were talking about the dredge project killing the corals rarely, if ever, went in the water to see what was actually happening to the corals. Even worse, when they did go diving, they conducted single surveys often long after the corals had died and without baseline data or controls for comparison (NNMF 2015, 2016). These post hoc impact surveys are not analogous to doing an autopsy where you can run chemical tests or make observations that directly confirm the cause of death. Corals generally don't retain that kind of information and unless you are present, in real time, to observe what killed the corals. If not, you can only guess about the cause of death. In other words, you can't write a meaningful death certificate when all you have is a dead skeleton.

Writing coral death certificates is especially difficult these days because there are so many damaging things happening to our offshore waters, none of which are good for corals. This includes, but is not limited to, widespread warming that causes coral bleaching, chronic and low-level exposure too pollutants (Dubinsky and Stambler 1996) and wastewater (Wear and Thurber 2015, Staley et al. 2017), and yes, in some cases, coastal development including dredging projects (Foster et al. 2010, Erftemeijer et al. 2012). To emphasize why single surveys that observe corals only after they're dead can lead to incorrect conclusions, the following example is enlightening. The photo below (Figure 2) was taken by a contract employee of NOAA-NMFS while shadowing one of our project team divers during one of our site visits on May 19, 2015. The figure caption in their NMFS (2015) field report reads as follows "Figure 5a. Likely colonies of *Meandrina meandrites* smothered by fine sediment from the Port of Miami expansion dredging. Note that species identification after burial is complicated, however the morphology of the ridges and septa are distinct to *M. meandrites*."

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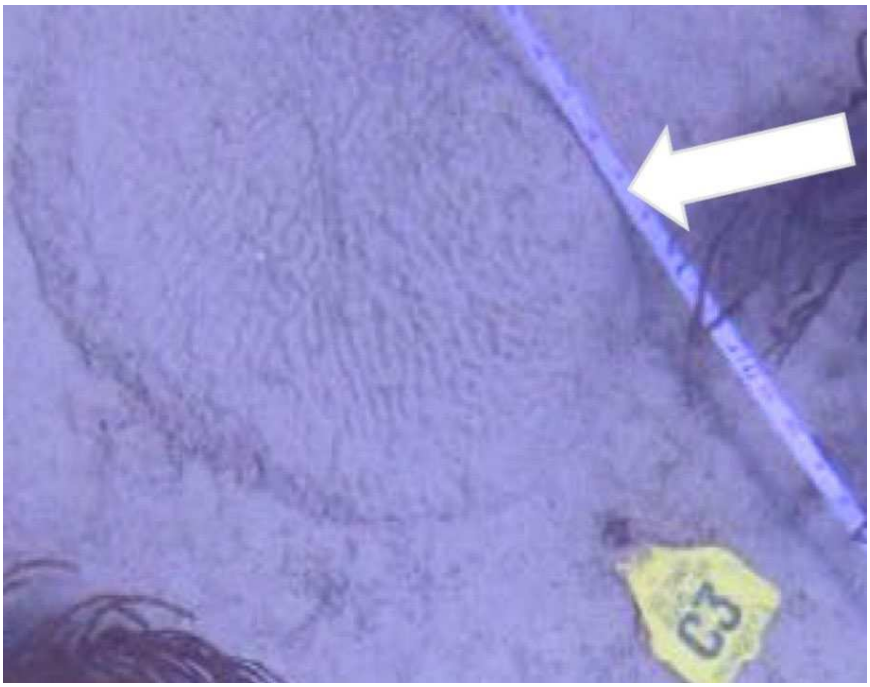

Figure 2. Image taken from Figure 5a in NMFS report (NMFS 2015). This tagged colony was coral number 3 on transect 1 at site R2N1-RR (located on an Inner Reef site and within 10 meters of the active dredge channel). Compare this photo with montage shown in our Figure 3 below of the same tagged coral. Diver from NMFS wafted sediment off top of colony by hand to reveal skeletal features prior to taking this photograph. Photo taken on May 19, 2015.

However, this was a tagged coral in our long-term compliance monitoring program. As a result, we could reconstruct the history of this colony by observing the sequence of photos taken in the weeks and months before the NMFS site visit. Dozens of dives were made to reconstruct the history of corals at the site, not just one after the coral had died as was done by the NOAA-NMFS team. First, the coral in the photograph is actually a colony of *Pseudodiploria strigosa* and not *M. meandrites*. I have enclosed a montage of this coral below that reveals the history of this colony during the dredging project that unambiguously documents the ultimate cause of its mortality (see Figure 3).

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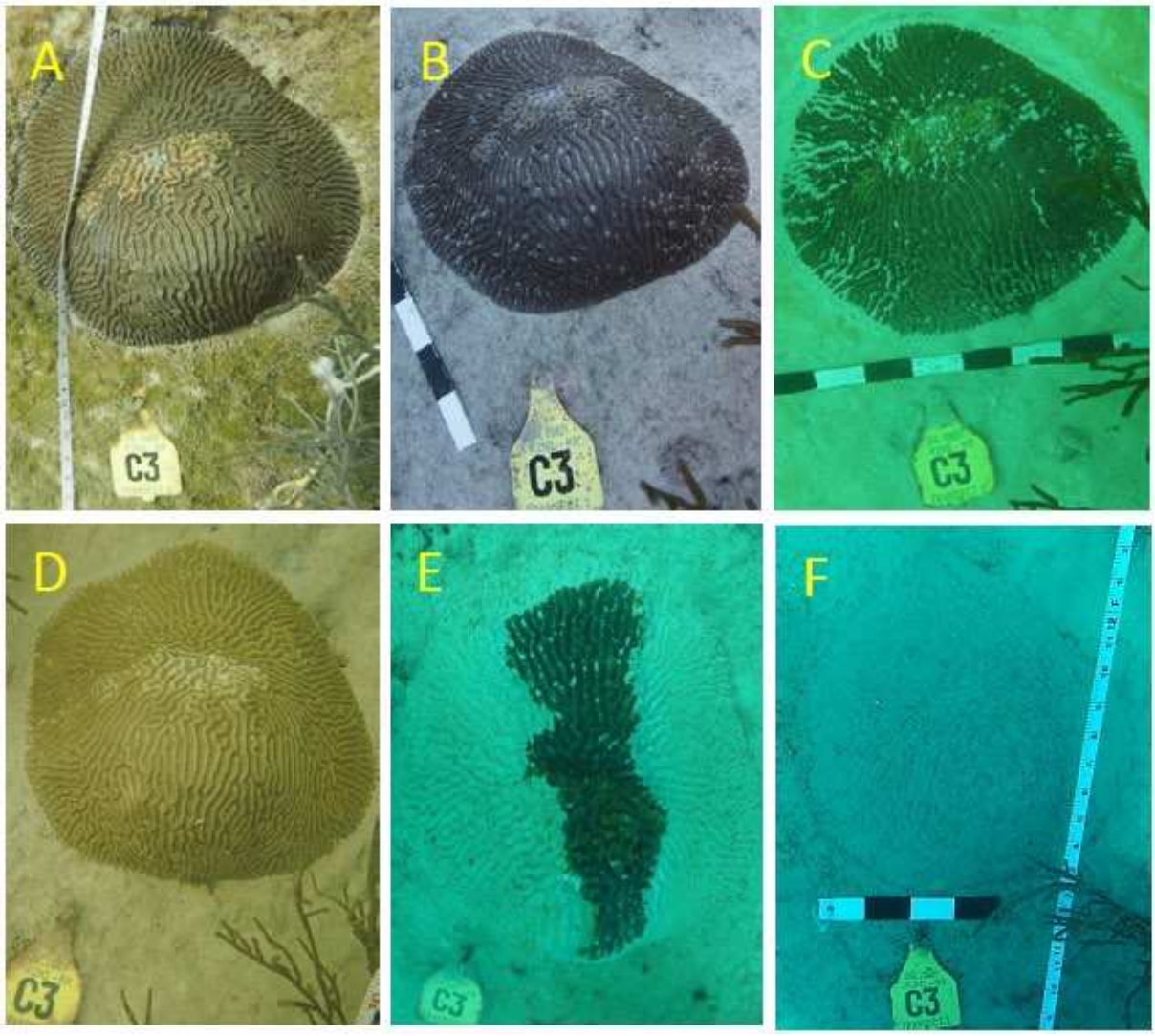

Figure 3. Temporal photographic montage of *Pseudodiploria strigosa* colony (R2N1-RR-T1-C3). This is the same channel-side coral as depicted in Figure 2 above. (A) Photograph of coral during initial baseline surveys on October 21, 2013; (B) coral during baseline week 4 on November 18, 2013 just prior to initiation of dredge activities. Note the green covering of turf algae visible in previous photo is now covered in fine-grained sediment as a result of the passage of the first winter storm of the season; (C) coral during compliance week 30 on June 14, 2014 showing sediment stress and partial burial from dredging activities with a berm of sediment around base of colony. This photo represents the week of maximum sediment stress to corals at this site during the peak of dredging operations; (D) coral showing signs of bleaching (paling) associated with warm-water thermal anomaly during compliance week 45 on September 28, 2014, note no apparent lesions or mortality related to earlier sediment stress event; (E) colony showing >60% mortality associated with progression of white-plague disease during compliance week 69, March 18, 2015; and (F) total colony mortality, note the coral is covered by fine-grained sediment, photo taken on May 19, 2015 following completion of dredging activities. This photo was taken on the same day as Figure 2 above. Note that the dead colony can no longer actively shed sediment.

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Note that the mortality of this coral was caused by white-plague disease that initiated following a regional thermal stress (bleaching) event and not sediment burial as proffered in the NMFS (2015) report. Unfortunately, the postmortem observations by NGO's, government officials, and regulators, like the one shown above in Figure 2 above are founded only on assumptions – not data and the facts that we accumulated over the course of careful and repeated monitoring. Their field reports and a publication that resulted (NMFS 2015, 2016, Miller et al. 2016) are riddled with similar egregious errors and assumptions that fail because correlation does not prove causation (see discussion in Precht et al. 2019). However, the assertions made in these NMFS reports further entrenched regulators, NGO's and the media, reinforcing their belief that coral mortality observed near Port Miami was dredge-related and not a result of a regional, highly virulent water-borne contagion (Staletovich 2015a, 2015b, 2016a, Alverez 2016).

In our monitoring program, our scientific divers performed over 10,000 dives over a three-year period (Precht et al. 2019). In addition, as part of the permit-compliance monitoring for the project (FDEP 2012), we were required to tag approximately 650 corals both at impact sites and their far-field controls for repeated measures monitoring. Each of these corals was observed and photographed approximately 40 times throughout the project. That is about 25,000 in situ coral observations. This level of coral monitoring had previously been unprecedented in South Florida to evaluate coral condition from a dredging project, or for that matter, any impact assessment program. Indeed, the longest running coral monitoring program in the Florida Keys, run by FWC, takes pictures and video once per year (Ruzicka et al. 2013). The coral condition data from our program were additionally compared in the lab with corresponding still photographs from each coral for cross-verification and validation. Combining these in situ coral data with other biotic (video functional assessments) and abiotic metrics (sediment, temperature, etc.) allowed us to differentiate between chronic and acute stressors and whether or not they were natural or anthropogenic in origin. More specifically, we were able to calculate the percentage of corals impacted by sedimentation, predation, competition, coral bleaching, and disease. Most importantly, in cases where our tagged corals had died, we were able to discern the exact cause of mortality by carefully evaluating the sequence of events recorded (and photographed) prior to their death (see Figure 3 above). Not surprisingly, coral morbidity (partial mortality) associated with sedimentation was highest at sites immediately adjacent to the dredge operations and some corals actually died (seven of the dredge-adjacent tagged colonies, ~2%) from project related impacts (Precht et al. 2019). Recently, we have been misquoted – specifically, Dr. Andrew Baker of the University of Miami stated the following in a radio interview "*The notion that only six corals died as a result of dredging is actually sort of absurd.*" Clearly, that not what we said. What we said was that was the numbers of tagged channel-side corals that died in our surveys. That number is ~2% of those corals. Two percent of all channel-side corals (those within 150 meters of the dredge) is still a significant number of dead corals. However, even if it was only one coral that is one too many! That is why repeated measures monitoring programs are so important to understanding the specific cause of mortality when corals die. Only then can appropriate lessons learned from these monitoring programs be applied to future projects to further reduce or eliminate dredge-related impacts. But what of Dr. Baker's (a tenured scientist) misquote of our work? Was it on purpose or

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accidental? If the former, then it should be viewed as a tactic to get headlines and is outside the realm of science and could undermine anything he says about the project in the future. If the latter, then he needs to be more careful to avoid misunderstanding and misquoting the scientific papers and data that are relevant to this project. Regardless, Dr. Baker crossed a line that scientists are faced with when they speak out on environmental issues - the truth matters, and scientists should not be contributing to fake news.

The combined losses from sediment burial, bleaching, competitive mortality, and other factors accounted for the mortality of only 4.1% of all monitored corals, yet 31.7% of all tagged corals died as a direct result of this disease outbreak (Precht et al. 2019). Thus, while project related impacts were real, they were trumped by the overwhelming impacts of the regional coral disease (Gintert et al. submitted). Essentially equivalent levels of disease related mortality were documented at both far-field control (29.4%) and dredge-adjacent locations (33.6%). This loss of around 30% of the coral population has been recorded by other scientists throughout the region. For instance, Walton et al. (2018) stated "*the 2014 to 2016 disease outbreak was arguably the most devastating disturbance event yet documented in the Southeast Florida coral reef tract (SEFCRT) and has altered ecosystem function to a point where recovery is greatly challenged. Our data estimates that regionally as much as 30% of coral colony density and 60% of live tissue area was lost*." Dr. Dave Gilliam from Nova Southeastern University was also quoted in the Sun Sentinel stating "*since appearing in South Florida in late 2014, as corals were weakened by bleaching, the disease epidemic has spread quickly. A 35 percent loss of stony coral has taken place off the South Florida coast north of the Keys, judging from the losses seen at sites monitored*" (Fleshler 2017).

It's easy to point the finger at dredging because it matches with our intuition that dredging can be bad and that it's something specific, a concrete thing that can be started and stopped, unlike global warming that causes coral bleaching that then makes corals more susceptible to disease (Harvell et al. 2002, Bruno et al. 2007, Altizer et al. 2013, Burge et al. 2014, Maynard et al. 2015, Zvuloini et al. 2015). Thus, prevent bleaching and you get less disease. What do you need to do to prevent bleaching? Address global climate change. This was especially relevant during the Port Miami project because this all happened at a time when FDEP employees could not utter the phrase 'climate change' (Korten 2015). So, it's perhaps understandable that they pointed their fingers at an easy – but wrong - target, like the Port Miami dredging project. So, when the story of corals dying appeared in the media it had a good hook, with a villain (Port Miami dredging and US Army Corps of Engineers) and a hero (the small NGO's standing up to Goliath). This narrative, however, was incorrect. Unfortunately, this misguided blame-game, while it has strong emotional appeal, retards scientific discovery and plays right into the hands of climate change deniers (Oreskes and Conway 2011). If facts don't matter, then the public and policy makers are truly abandoned to a world of fake news or at least highly exaggerated claims.

As a result of this misdirection and fake news, when the regulators and resource managers finally concluded that the disease was for real, that it was devastating corals not just around the Port Miami area but on reefs throughout the region, and that they needed to pay closer attention, the disease had already spread a significant distance (over 100 km) and was racing both north and south from its point of origin. By the time the decision makers finally got serious about what was

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happening, approximately two-years had already passed. Precious time was lost because of bias and presumption about the Port Miami dredge project being responsible for the mass coral mortality.

It is also ironic that the first media coverage of the devastation wrought by this disease was not covered by the local press (the Miami Herald or the South Florida Sun Sentinel) but by the Washington Post on October 26, 2015 (Harvey 2015). It wasn't until April 24, 2016 that the disease finally made headlines in South Florida (Fleshler 2016). Based on the timeline and history of the response to this coral disease outbreak, what I find even more ironic and disturbing are recent articles that are discussing the "race of Florida's agencies, NGO's, and scientists to find a cure to this coral killer." These articles were written more than three-years after onset of the disease (Fleshler 2017, Urry 2018). Racing – is three years really considered racing? I must still be dreaming! However, for those dealing with the reality of this coral disease it is no dream. Imagine being Sarah Fangman, the Sanctuary Superintendent of the Florida Keys National Marine Sanctuary who took her position in the Summer of 2017. At that time, the disease was rapidly advancing through the Florida Keys laying waste to iconic reefs such as Sombrero Reef and Looe Key. To Sarah, this reality must have been, and continues to be, her worst nightmare.

Now, here we are some 4 ½ years later and essentially the entire Florida Reef tract has been devastated from Key West in the south and Martin County to the north (Figure 4). Even more upsetting, the disease is now killing corals throughout the Caribbean (Alverez-Filip 2018, The Daily Herald 2018, DPNR 2019, Lubofsky 2019, Martin 2019; Figure 5), and again the same general suite of species are implicated. As the disease has progressed through time and space, it went from being a local issue (Precht et al. 2016), to suddenly becoming a regional/national emergency (Nelson 2018), and now has become an international crisis (AGRRA 2019).

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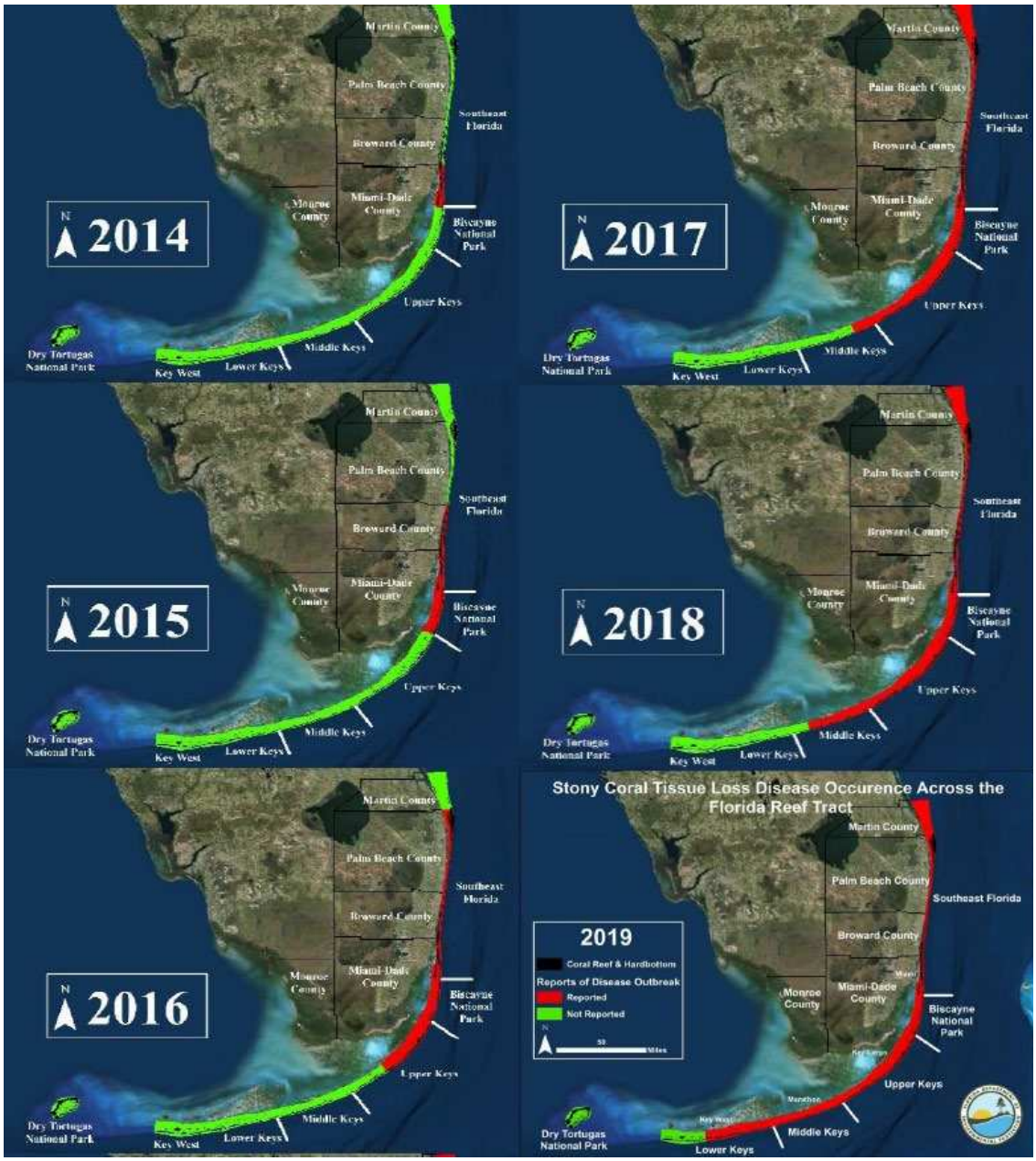

Figure 4. Progressive spread of SCTLD outbreak throughout Southeast Florida from 2014 – present (FDEP 2019).

Sadly, even to this day, there are some scientists who are diminishing the actual impacts of this disease (Miller et al. 2016, Cunning et al. 2019) with results that are in stark contrast to the regional data (Carsey et al. 2016, Precht et al. 2016, 2019, Aeby et al. 2017, Hayes et al. 2017, Lunz et al. 2017, Gilliam et al. 2018, Neely 2018, Ruzicka 2018, Walker 2018, Walton et al. 2018, FDEP 2019).

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I encourage everyone to watch carefully as various stake holders position themselves for or against the future expansion of Port Everglades off Ft. Lauderdale, Florida that is currently in its final planning stages (Swanson 2015, 2016, CBD 2016, Staletovich 2016b, Miami Waterkeeper 2019). Will there be a good-faith effort to apply lessons learned from the Port Miami dredging project? (see Precht et al. 2019). Or, will facts and data be undermined to advance agendas and fake news? Will my nightmare continue as a scientist constrained by the truth and the data?

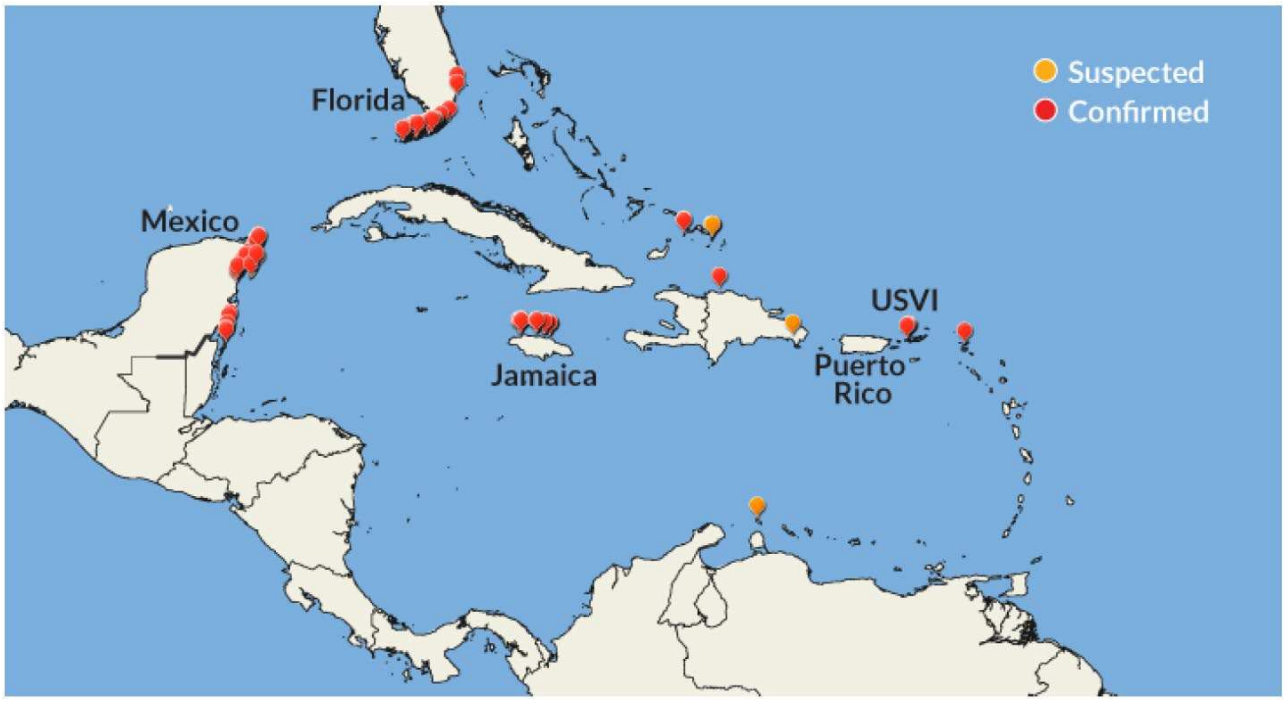

Figure 5. Originally spotted off Florida in 2014 the disease is now spreading across the Caribbean. Cases of the disease have been confirmed (red) on reefs off Mexico, Jamaica, St. Maarten, the Dominican Republic and St.Thomas in the U.S. Virgin Islands. Suspected cases are shown in orange (AGRRA 2019).

Management Responsibility

So, what could we have done differently, and would it have made any difference?

The first thing that you need to know about coral disease, or for that matter, any disease that occurs in the ocean, is that they can spread quickly and whatever causes the disease is usually carried from one place to another by currents in the water (e.g. Lessios et al. 1984). On land, that's why diseases that spread through the air are highly contagious. But on land, you can isolate the coughers and sneezers, or protect yourself with a vaccine or get treated by an antibiotic. Corals are not so lucky. There are no vaccines to protect them from disease or broad-scale antibiotics to treat them. And even if there were, how do you treat millions of corals that are located underwater

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over vast stretches of the seascape? Or, how do you stop the spread of disease when ocean currents are involved? It's a daunting challenge. A bad dream that's come to life.

During the early spread of this coral disease outbreak, some species losses, specifically *Meandrina meandrites, Dichocoenia stokesi*, and *Eusmilia fastigiata* may have been unavoidable due to the rapid spread and mortality of these highly susceptible species. However, less susceptible species may have benefitted from local removal (culling) of infected corals, especially during the initial outbreak or during winter periods when infections slowed within coral communities. This is the one thing that offers an opportunity to do something in the first moment when disease is first discovered. It's a similar response that is widely accepted as the only way to address the spread of invasive species – remove them before they have a chance to spread (Simberloff 2003). Examples of invasive species in Florida that spread quickly and unchecked that today have become a nuisance include Melaleuca, Australian Pine and Brazilian Pepper trees as well as animals such as pythons, iguanas and lionfish to name just a few. There are now eradication plans and protocols for each of these species including bounties and incentives on some (Kline and Duquesnel 1996, Serbesoff-King 2003, Macaluso 2016, Weekman 2017).

The manipulative action of removing infected coral colonies is clearly a drastic management response with numerous challenges that include ethical considerations and regulatory permit complications, yet the rapid and near total collapse of local coral populations during this multi-year outbreak requires that drastic actions are needed to slow the spread of this and future diseases that threaten what remains of our already endangered coral reefs. Similar management policies have been implemented where large swaths of vegetation are commonly eradicated in terrestrial systems with varying degrees of success (Gottwald et al. 2001, Sosnowski et al. 2009, Centner and Ferreira 2012). This is a common practice, especially when valuable cash crops such as citrus groves are at risk from disease (Hall and Gottwald 2011). Experimental work will help identify how many corals need to be removed and how fast. Monitoring work to evaluate the effectiveness of this dramatic recommendation will be also be needed to document its effectiveness (Smith and Cheeseman 2002). This is not to suggest that we need to know more about disease progress before acting. Instead, this is an example of the need to act fast in an emergency, because to not act ultimately dooms you to failure (Balzoni et al. 2014). Unfortunately, examples of such failure are found in the Florida response to SCTLD.

A result of this disease is that in South Florida, the iconic pillar coral *Dendrogyra cylindrus*, an ESA listed species, was ecologically eradicated from our regional seascape because we essentially monitored the impacts of the disease on the infected colonies (Kabay et al. 2017, Lewis et al. 2017) instead of actively intervening to save them until it was too late (Lewis 2016, O'Neil et al. 2018). In contrast, when pillar corals were impacted in Grand Cayman, the Cayman Islands Department of the Environment responded rapidly with a multi-pronged approach that resulted in high survivorship of the affected colonies (Warrender et al. 2018). While time intensive, the lessons learned from the Cayman experience shows that early intervention can have a positive impact. Not every coral can be saved, but the largest and most iconic species are clearly potential targets for intervention.

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At present, there are few other options available to stop or ameliorate a disease once an outbreak has occurred (Teplitski and Ritchie 2009). For instance, while the use of biocides, disinfectants, antimicrobial agents, and chemical treatments are commonly used to treat diseases in aquaculture and the aquarium trade, these are not viable methods for use in the open ocean due to their undesirable environmental toxicological consequences (Rodgers and Furones 2009, Sheridan et al. 2013). In a few cases, coral diseases caused by bacterial infections have been successfully treated using antibiotics in laboratory settings (Kline and Vollmer 2011, Sweet et al. 2014) while in others there appears to be multi-drug resistance to commercial antibiotics (Vizcaino et al. 2010). However, in-water treatment with antibiotics is generally not considered a viable option because of the general effect of antibiotics on all bacteria including probiotics responsible for regulation of the coral microbiome as well as ecosystem health (Reshef et al. 2006, Ritchie 2006). In addition, there are potential dangers of selection for antibiotic-resistant strains of diseases that could ultimately make matters worse (Parisien et al. 2007). In a last-ditch effort to save some of the larger diseased colonies in the Florida Keys, researchers have been field testing the use of an antibiotic putty being placed around diseased lesions creating a 'pharmaceutical barrier' to prevent its spread. To date, the results of these field trials have met with mixed results (Neely et al. 2018, Urry 2019).

One emerging remedial method for coral disease that shows some potential is phage therapy (Parisien et al. 2007, Doss et al. 2017). Lytic bacteriophages (phages) can be isolated from bacterial pathogens that are known to be directly responsible for coral diseases. By using these phages in experimental settings, it has been demonstrated that coral diseases can be controlled by the pathogen-specific phage (Efrony et al. 2009, Atad et al. 2012, Cohen et al. 2013). The initial data from these studies, indicate that the phages bind to the pathogen in seawater and are then brought to the coral surface where they multiply and lyse the pathogen. These phages multiply as long as their bacterial hosts are present and thus could also prevent subsequent infections. These studies suggest that phage therapy has the potential to control the spread of infectious coral diseases (Soffer et al. 2015). Unfortunately, in the case of the recent coral disease outbreak in southeastern Florida there has been no specific pathogen identified to-date that has be isolated (Meyer et al. 2019) and could be used in phage therapy treatments. This is an important point to emphasize.

There is another failure to talk about, which is the fact that 40 years after the first coral disease epidemic (white-band disease) killed billions of corals throughout the Caribbean and Florida (Gladfelter 1982, Aronson and Precht 2001a), little advancement occurred in the identification (Pollock et al. 2011) and our knowledge of coral diseases (Peters 1984, 2015,Harvell et al. 2004). Indeed, there remain only a handful of marine biologists with formal training in the study and treatment of coral diseases. Why is that the case? Why haven't marine biologists been effective about bringing resources to bear on this as compared to their terrestrial counterparts? Is it a failure to communicate or something larger about our society that is resistant to caring about ecosystem losses that are in the marine realm? Is out of sight, out of mind?

Beeden et al. (2012) stated many of these various remedial response actions proposed for coral disease abatement are highly experimental and likely to be prohibitively expensive on all but the smallest of spatial scales. However, are those justifiable reasons for not responding? Knowing

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what we know now about the catastrophic nature of the 2014-present coral disease outbreak, it would be disingenuous to argue that intervening is not a viable management option. No matter how large the expense, these costs will dwarf the potential financial losses associated with disease-related coral ecosystem collapse presently being observed throughout the Caribbean. The loss of eco-tourism and commercial and recreational fisheries alone that can be tied directly to this disease could potentially be in the billions of US dollars.

In a few short years, the ecological extirpation of many key charismatic species has fundamentally changed the way reefs throughout south Florida look and function, resulting in a depauperate community of small, ephemeral, stress-tolerant species (Burman et al. 2012, Precht et al. 2016, 2018, Toth et al. 2019). In addition, the conservation of species-specific disease susceptibility traits, region-wide, suggests that local management efforts aimed at improving reef resilience to-date have been ineffective at preventing and minimizing the impacts of coral disease outbreaks. For instance, a recent effort to map reef areas of high and low resilience to climate change in south Florida (Maynard et al. 2017), showed no difference in coral mortality patterns from the current thermally driven disease outbreak no matter the mapped resilience score. Plain and simple, if you were a highly susceptible species you got whacked and if you weren't, you didn't.

Whatever actions are taken, they must be implemented swiftly before the pathogen has a chance to spread and cover large areas, diminishing the effectiveness of in-water treatment options. In the case of the 2014-recent disease event in Southeast Florida the leisurely and misdirected management response to this outbreak (Table 1) have left no real viable options available for its eradication or amelioration. As a result, we are now sadly faced with a situation where much of our management efforts are focused on the rescue of genetic material from coral species at risk of regional extinction instead of disease abatement measures (Lewis 2016, Kimel 2018, O'Neil et al. 2018, Klingener 2019, Newborn, 2019, Brasileiro 2019a, 2019b). Accordingly, the level of coordination and speed of response to potential disease outbreaks must be increased if we have any chance of preserving what remains of our coral populations.

Finally, there is a need for all stakeholders to petition government agencies for "State of Emergency" designations when marine species, especially those that are under immediate threat of rapid local extinction, are at risk from acute disturbances. These designations could help bring visibility and funds to these regional-scale disturbances that will help support more comprehensive response efforts in the future. Waiting some two years to tap into these resources or request these designations is unacceptable and we need to demand more from our state and federal agencies with purview over these fragile marine ecosystems. However, the question remains – where would we be now had the responsible agencies responded immediately to the outbreak? While we will never know the answer, one thing is for sure, we would be at a minimum two years ahead of where we are now regarding our present level of knowledge and research on this devastating coral killer. Those two years lost can never be recovered.

As Aldo Cróquer prophetically stated more than a decade ago, "Due to its high virulence and wide host range; the cumulative impact (coral tissue mortality) of frequent white-plague disease events in many reef localities throughout the Caribbean over the years might end up having a more significant ecological impact than the white band event in the early 1980s" (Cróquer et al. 2005).

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Certainly, if this on-going coral disease continues to spread throughout the Caribbean at its current pace, the white-band disease outbreak that devastated the Caribbean *Acropora* species (Gladfelter 1982, Precht and Aronson 2001a) will ultimately pale in comparison. Then we may, in-fact, be looking at the regional loss of numerous key reef-building species that may result in the ecological collapse of what remains of our coral reefs. I have spent my much of career documenting the decline of reefs in Caribbean due to disease and bleaching (Aronson and Precht 1997, 2001a, Aronson et al. 2000, 2002, Precht et al. 2016, 2018), and it has taken an emotional toll (Aronson and Precht 2001b; see also Young 2017). Indeed, the spectacularly beautiful and biologically rich coral reefs that some of us experienced early in our careers, and our parents enjoyed without fear of their loss, will resemble flat concrete parking lots that our children will inherit. That's my bad dream come to life.

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Appendix – Letter by Sen. Bill Nelson (FL) ranking member of the US Senate Committee on Commerce, Science, and Transportation regarding the "urgency" in solving coral disease crisis in Florida dated February 28, 2018.

United States Senate
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
WASHINGTON, DC 20510–6125
WEBSITE: http://commerce.senate.gov

February 28, 2018

The Honorable Alex Azar
Secretary
Department of Health and Human Services
200 Independence Ave., SW
Washington, DC 20201

The Honorable Sonny Perdue
Secretary
Department of Agriculture
1400 Independence Ave., SW
Washington, DC 20250

The Honorable Wilbur Ross
Secretary
Department of Commerce
1401 Constitution Ave., NW
Washington, DC 20230

Dear Secretary Ross, Secretary Azar, and Secretary Perdue,

I am writing because your departments have the combined expertise necessary to help address an environmental crisis in the Florida Reef Tract, where an unprecedented disease outbreak – the most serious coral disease epidemic on record globally – is ravaging reefs.

The outbreak began in 2014, when isolated diseased coral colonies were reported near Key Biscayne off the coast of Miami-Dade County. It has since spread north and south without interruption. To date, over half of the Florida Reef Tract – the only living coral barrier reef in the continental United States – has been affected. The disease has been shown to affect at least 23 species of reef-building corals. Once infected, coral colonies typically die within weeks to months. Despite efforts from Florida scientists and regional managers, the disease remains yet to be identified.

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To adequately address the outbreak, we must have a correct diagnosis as soon as possible. And this is more than just an environmental concern. Florida's coral reefs attract over 16 million visitors each year, are estimated to bring in over $6 billion of revenues to the state, and provide over 71,000 local jobs. The 360-mile-long Florida Reef Tract is the third largest barrier reef in the world. These ecosystems are referred to as the rainforests of the sea for their biodiversity. They serve as the base of the food web for economically valuable fish stocks and a tourism draw for divers and snorkelers. That's why it is so important to figure out what's threatening the viability of these corals.

Hurricane Irma further damaged this invaluable natural resource. After the storm, divers surveyed more than 50 sites and reported significant shifting of sand and sediment accumulation, as well as structural damage to individual corals. This can cause serious harm to healthy coral reefs, but for vulnerable coral already exposed to disease, this type of damage can be catastrophic.

I believe that the agencies within your departments – specifically the National Oceanic and Atmospheric Administration, the Centers for Disease Control and Prevention and the Animal and Plant Health Inspection Service – have the expertise and tools to diagnose this disease and mitigate the outbreak. I urge you to establish an interagency epidemiological strike team to quickly deploy experts to the Florida Reef Tract to assist ongoing local efforts, to sample the corals to determine the mechanism of the disease and to perform field trials of intervention techniques to identify the most effective treatments for saving the remaining colonies.

Time is of the essence for Florida's coral reefs. Thank you in advance for your consideration. I look forward to your response.

Sincerely,

Bill Nelson

BILL NELSON
Ranking Member

cc: The Honorable John Thune, Chairman