Title

Environmental Stressors to Coral in the Florida Keys: Supplemental Information

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ABSTRACT

Coral decline has been observed worldwide including in the Florida Reef Tract. Several global and local stressors have been implicated as contributors to the decline of coral populations. Coral reefs face multiple stresses; however, the most pervasive and deleterious stressors are global sea temperature change and acidification caused by rising atmospheric CO_2 levels. These global warming changes cause coral bleaching and ultimately coral death. Stony Coral Tissue Loss Diseases (SCTLD) is causing widespread devastation in the Florida Reef Tract. Some localized stressors also contribute to the decline of coral, including invasive species, unsustainable fishing practices, coastal development, untreated or poorly treated wastewater, urban and agricultural run-off, and tourism-related damage. Expert coral biologists have identified the most important stressors to coral reefs in Florida and worldwide, but recently, a few scientists have hypothesized about the potential for certain sunscreen active ingredients to contribute significantly to the decline in coral health. However, weight-of-evidence has not verified sunscreen active ingredients as a contributor to coral decline.

Improving the ecological status, or health, of coral in the Florida Reef Tract requires prioritizing efforts on the most significant stressors. Mitigation efforts to restore damaged coral have been successful to some extent but are labor and time intensive. Conservation efforts should continue on recreational practices such as educational efforts on boaters, divers, and other activities in and around the coral reef to reduce the spread of SCTLD disease and minimize structural damage to the reefs.

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1.0 EXECUTIVE SUMMARY

Coral decline has been observed worldwide including in the Florida Reef Tract. Several global and local stressors have been implicated as contributors to the decline of coral populations. The most pervasive and deleterious stressors are global sea temperature change and acidification caused by rising atmospheric CO_2 levels. These global warming changes cause coral bleaching and ultimately coral death. Some localized stressors also contribute to the decline of coral including coral diseases, invasive species, unsustainable fishing practices, coastal development, urban and agricultural run-off, and tourism-related damage. Expert coral biologists have identified the most important stressors to reefs in Florida and worldwide, but recently, a few scientists have raised questions about the potential for certain sunscreen active ingredients to contribute significantly to the decline in coral health. This "sunscreen active ingredients hypothesis" is discussed in comparison to each stressor identified by coral experts to evaluate its plausibility and relative importance compared to widely scientifically recognized stressors. An investigation was conducted to evaluate environmental stressors to coral in the Florida Reef Tract with a focus on the Florida Keys through the lens of accepted global and local factors. Environmental stressors impacting or having the potential to have significant impact on coral ecosystems in the Keys, and specifically Key West, are listed below in order of magnitude and severity of impact.

- <u>Sea surface water temperature</u>: Increases or decreases in sea surface temperature beyond coral's temperature range (coral growth is optimized around 26–27°C) causes a stress response of bleaching. Sea temperature changes beyond the narrow optimal coral growth range can ruin the symbiosis between coral and its main food, the microalgae that live on and inside its tissue. In warming water, microalgae can overproduce sugars and toxins. This leads coral polyps to expel the algae. Since coral polyps need these microalgae in order to survive, without them they turn white, a process known as bleaching. Soon after, if this symbiosis is not returned, the coral die. Since the beginning of the 20th century, sea surface temperatures have increased. Not able to cope with the unusually warm temperatures, coral reefs have experienced mass bleaching events at increasingly short intervals. This temperature stressor phenomenon has been well documented and studied over the world. High temperature events are increasing in severity, duration, and frequency. Recorded mass bleaching along the Florida Reef Tract by the National Oceanic Atmospheric Administration's (NOAA)'s Coral Reef Watch have increased since 1980s. Scientists from the University of Miami, Florida Institute of Technology, and other marine research organizations have found that coral bleaching and disease outbreaks are often inter-related phenomena. Many coral diseases are opportunistic pathogens that further compromise thermally stressed colonies. An increase in climate-related hurricanes and other storms also negatively affect the Caribbean reefs.

- <u>Stony Coral Tissue Loss Disease (SCTLD)</u>: SCTLD is causing widespread devastation along the Florida Reef Tract. The disease causes the coral's colorful tissue to slough off a colony, exposing its bright white skeleton, and results in the death of coral tissue itself. This appears as coral bleaching; however, SCTLD creates lesions on the edge of the coral colony and spread upward rather than a generalized paling and bleaching of coral tissue. Since first reported in 2014 in Biscayne Bay, SCTLD has spread approximately 205 linear miles north and south along the Florida Reef Tract infecting half of the stony coral species. This infectious disease does not slow down during cooler months as observed with coral bleaching. Other coral diseases identified in Florida are white plague and yellow, red, or black band diseases. At present, the causal agents for SCTLD are unknown. Prospective agents, however, include: bacteria, virus, natural toxins, human-made toxicants, and metabolic dysfunction.

- Land-based pollutants: Examples include urban-, construction-, agricultural-runoff, wastewater treatment effluent, chemical spills, and improper disposal of chemicals. Agriculture is not a significant land use in Key West but is more significant in the southeastern Florida mainland where many agricultural areas drain to Biscayne Bay and are in closer proximity to the northern end of the Florida Reef Tract. Wastewater effluent can contain pathogens, nutrients, and chemicals. Effluent discharge to the open ocean is possible for some Florida municipalities and thus remains a concern for the Florida Reef Tract. Other Southern Florida municipalities have various percentages of the population on septic, and improper maintenance causes pollution to enter groundwater and ocean waters.

- Marine-based influences: Many marine activities along the Florida Reef Tract can cause localized damage and exposure to pollutants or increased turbidity. Examples include improper anchoring/grounding of boats; transfer of disease from boats, snorkelers, and divers; snorkeler and scuba divers damage reefs by touching or removal, grey water discharge from boats; and dredging activities. Overfishing, improper, or destructive fishing are also implicated in reef destruction.

- Sunscreen active ingredients: Peer-reviewed published research has not shown that UV filters will harm native Atlantic coral reef populations or decrease their ability to respond to other environmental stressors. Concerns for some sunscreen active ingredients and their effect on coral are based on recent preliminary laboratory acute toxicology studies of oxybenzone and octinoxate with non-US native *Stylophora pistillata* coral larvae (planula) conducted at concentrations higher than expected in the environment. Oxybenzone and octinoxate are effective UV filtering ingredients used in sunscreen active ingredients since the 1970s. Monitoring for these ingredients in the Florida Keys has not been reported; however, levels measured in populated beach areas including the Virgin Islands and Waikiki Beach, Hawaii, have been non-detectable or in the parts per trillion except for a single water sample that stands out as an outlier reported in parts per million (ppm). In contrast to studied environments, coral reefs around Key West are mostly many miles from the shoreline and therefore, exposure from sunscreen active ingredients use on swimmers in beach areas and from divers in limited boating excursions to reef areas will likely be lower.

Improving the ecological status (health) of coral in the Keys requires prioritizing efforts on the most significant stressors. Mitigation efforts to restore damaged coral have been successful to some extent but are labor and time intensive. Conservation efforts should continue around recreational practices such as educational efforts on boaters, divers, and other activities in and around the coral reef to reduce the spread of SCTLD disease and minimize structural damage to the reefs.

2.0 BACKGROUND AND OBJECTIVE

Coral decline has been observed worldwide, including the Florida Reef Tract (Figure 1). Multiple stressors have been implicated as contributors to the decline, including climate change, disease, and tourism. An investigation was conducted to evaluate environmental stressors to coral in the Keys with specific emphasis on areas in the vicinity of Key West (Figure 2).

The investigation included the following components:

- A systematic review of literature on coral reef stress factors from PubMed (https://www.ncbi.nlm.nih.gov/pubmed/) and Google Scholar (https://scholar.google.com/) that are known or suspected to contribute to coral decline and their relative magnitude of impact. Coral reef impact assessments, performed by governmental or other bodies, were also reviewed;
- A summary of monitoring results for sunscreen active ingredients measured in marine and coastal waters (Table 1);
- A screening evaluation of local anthropogenic factors in Key West (e.g., agriculture, WWTP, tourism, shipping traffic) in context with their proximity to coral and associated bathymetry and ocean currents;
- A relative ranking of factors that may be contributing to degradation of coral in marine waters around Key West; and
- Recommendations for next steps for the protection of reef resources in Florida waters as suggested by local, regional, and national governmental agencies.

3.0 FACTORS ATTRIBUTED TO FLORIDA KEY CORAL HEALTH DECLINE

The Florida Reef Tract and Atlantic coral are experiencing unprecedented coral damage and loss at an alarming rate (Figure 3, McClenachan et al., 2017). Corals in Florida, in general, are in a perpetual state of stress and have been for decades. Use of high-resolution historical nautical charts to quantify changes to benthic structure over 240 years in the Florida Keys has found an overall loss of 52% (SE, 6.4%) of the area of the seafloor occupied by corals (McClenachan et al., 2017). Coral reef stressors have been documented and studied globally and locally. A comprehensive list of stressors to Florida reefs documented by coral experts is tabulated below. Recent scientific research suggests some sunscreen active ingredients may cause harm to coral. Section 4.0 discusses the issues and conclusion of this recent research.

3.1 Global Factors to Coral Health Decline

3.1.1 Sea Surface Water Temperature

Sea surface water temperature as a coral health stressor has been well documented and studied over the world (Hoegh-Guldberg et al. 2007; Manzello et al., 2007; Manzello, 2015; Eakin et al., 2010; NOAA, 2014, 2015; Office of National Marine Sanctuaries, 2011; Precht et al., 2016; Randall et al., 2014; Randall and van Woesik, 2015; Selig et al., 2006). Several correlative field studies have shown a close association between warmer-than-normal conditions (at least 1°C higher than the annual maximum) and the incidence of bleaching (Hoegh-Guldberg, 1999). Records show that coral bleaching events have been occurring for many years in the Florida Keys (Jaap 1979, 1984), **indications are that the frequency, duration, and severity has steadily increased over the past 20 years** (Waddell and Clark 2008; Manzello, 2015).

Corals are sensitive to small changes in temperature. Two types of heat-related stress can generate bleaching – the first is a short-term, acute temperature stress (i.e., several days of temperatures between 25°C and 32°C) and the second is cumulative temperature stress (weeks of consistent moderately high-water temperatures) (Plass-Johnson et al., 2015). Coral polyp stress response happens when they expel endosymbiotic algae living inside their tissues. Coral without algae turn white, or "bleach." Coral without algae are deprived of most of their nutrients and energy and will ultimately starve to death. Coral bleaching can occur in coral due to a range of environmental stressors including too high or too low water temperatures, sedimentation, high irradiance or turbidity, mechanical disturbance, or infection by microbial pathogens (Plass-Johnson et al., 2015).

The concept for a bleaching threshold temperature was introduced in 1990 as one degree above the summertime maximum temperature. Coral Reef Watch (NOAA) defines the summertime maximum temperature as being the maximum of the monthly mean temperatures which varies by latitude. The timing of coral bleaching episodes observed in the Florida Keys between 1989 and 2005 was well explained by maximum monthly mean sea surface temperatures (SST) and by the number of days that water temperature was above 30.5°C (Manzello et al., 2007). Coral communities are also susceptible to cold water. In 2010, a cold snap caused many corals in the Florida Reef Tract to bleach and die off, inshore and mid-channel reefs from Biscayne Bay to Summerland Key were the hardest hit (Lirman et al., 2011). Records show that coral bleaching has been occurring for over 20 years in the Florida Keys. The frequency and severity of these events has steadily increased since the 1980s. Large-scale mass coral bleaching events are driven by unusually warm sea temperatures and calm seas with the one bleaching event due to cool temperatures in 2010. Recorded mass bleaching along the Florida Reef by the NOAA's Coral Reef Watch have occurred in 1996-1997, 2005, 2010, 2014, 2015, and 2016. In July into early August 2017, bleach warnings were issued for the Florida Keys. Fortunately, only low-level bleaching occurred and dissipated mid-September 2017. Potentially late summer's hot temperatures of 2019 could trigger another bleaching event, currently as of September 4th conditions are at a 60% probability of bleaching per NOAA Coral Reef Watch climate, conditions, and field observations (NOAA, 2019).

Coral bleaching and disease outbreaks are often inter-related phenomena, since many coral diseases are a consequence of opportunistic pathogens that further compromise thermally stressed colonies (Precht et al., 2016; Miller et al., 2003; Miller et al., 2009; Rogers et al., 2009). Thermal-stress events have been linked to coral-disease outbreaks, particularly in the Caribbean (Randall et al., 2014; 2015; Richardson et al., 1998a,b; NOAA, 2014, 2015). There is increasing evidence that corals that have been heat stressed are more susceptible to disease than corals that have not been heat stressed (Bruno et al., 2007). A study on Caribbean reefs bleaching events and sea surface temperature found that 0.1°C increase produces a 35% increase in coral bleaching reports and 42% increase in mean percentage of coral colonies affected by bleaching (McWilliams et al., 2005). The Florida Key reefs have also been associated with the heating trend (Manzello, 2015; NOAA, 2014, 2015). During 2014-2015, nearly 100% of US coral reef areas experienced a partially formed 2014-2015 El Niño, and a record-strength 2015-2016 El Niño (NOAA, 2016). Coral decline was evaluated recently via modeling temperature, solar radiation, depth, hurricanes and anthropogenic stressors using historical data from a large bleaching event in 2005 across the Caribbean (Welle et al., 2017). The modeling results suggest that climate stressors (temperature and radiation) far outweighed direct anthropogenic stressors (using distance from shore and nearby human population density as a proxy for such stressors) in driving coral health outcomes during the 2005 event (Welle et al., 2017). The modeling found temperature exhibited a 4-fold greater influence on both bleaching and mortality response than population density across their observed ranges (Welle et al., 2017).

3.1.2 Acidification

Ocean acidification is due to increased carbon dioxide in the atmosphere. The rising acidity of the oceans threaten coral reefs by making it harder for corals to build their skeletons which are comprised of calcium carbonate (DeCarlo et al., 2015; Hoegh-Guldberg et al., 2007; Office of National Marine Sanctuaries, 2011). Ocean acidification affects all coral reefs including those in the Florida Keys. As atmospheric carbon dioxide levels continue to increase, the ocean takes up around 25% of atmospheric CO_2, which then dissolves in seawater to form carbonic acid. Carbonic acid dissociates to form bicarbonate ions and protons, which in turn react with carbonate ions to produce more bicarbonate ions, reducing the availability of carbonate for coral to build their structure. Atmospheric carbon dioxide levels have increased, and thus the seawater acidity (carbonic acid) has increased by 30% since the beginning of the Industrial Revolution, over 250 years ago (Ocean Acidification Reference User Group, 2009). Ocean pH has dropped from 8.2 to 8.1 since the industrial revolution and is expected by fall another 0.3 to 0.4 pH units by the end of the century (Solomon et al., 2007). Given pH is measured on a logarithmic scale a change of 0.1 is rather large (~30% increase in acidity). This is the fastest known change in global ocean chemistry in 50 million years. This increase in acidity weakens calcification rates for coral, since they produce calcium carbonate skeletons, which are less stable as carbonic acid levels rise (Hoegh-Guldberg, 2007). A study investigating Florida Keys Reef Tract (FKRT) inner and outer reef coral using skeletal cores of reef-building species, *Siderastrea siderea* and *Pseudodiploria strigose,* found skeletal density reductions attributed to ocean acidification (Rippe et al., 2018).

3.2 Local Factors Contributing to Coral Health Decline – Florida Focus

3.2.1 Stony Coral Tissue Loss Disease (SCTLD)

SCTLD is the most pressing and devastating disease to the Florida Reef Tract (FDEP, 2019; NOAA, 2018; Reef Resilience Network, 2019). Concurrent with the first SCTLD outbreak in 2014 off the coast of Miami-Dade County, there was a mass (coral) bleaching event (discussed in detail in Section 3.1.1; see Figure 4 and Figure 5, Florida Keys National Marine Sanctuary). Extensive coastal construction activities involving dredging and deepening the Port of Miami (discussed in Section 3.2.3) were also underway in 2014. A number of wastewater treatment outfalls, discussed in Section 3.2.4, are also located near the site where SCTLD was first discovered. It is difficult to tease out if it was a confluence of stressors or a single stressor that was the tipping point for SCTLD.

SCTLD resembles coral bleaching and white plague disease; however, it is not the same thing. Coral bleaching is a response to stress, wherein the corals eject the colorful symbiotic algae that live within them. Bleached corals maintain living coral tissue and can recover the colorful algae if conditions become favorable. Generally, coral tissues will pale then bleach in a stress response event.

White plague disease, which is discussed later in more detail, has a decrease in progression during cooler months whereas SCTLD does not. White plague disease is only on the margin of the colony whereas SCTLD can cause lesions within coral colony (discussed further in Section 3.2). SCTLD may be caused by one or more pathogens (yet to be identified). Lesions or spots initially on the edge of the colony spread upward leaving exposed white intact skeleton. Lesions are observed to spread linearly at an average rate of 3 cm/day; some lesions coalesce and some cease to spread (FDEP, 2018). Once a coral becomes infected, all coral tissue of susceptible species dies within weeks to months (Muller et al., 2019).

SCTLD affects coral species in a specific order, with highly susceptible species showing initial signs, followed by intermediate susceptible species (FDEP, 2018), this is what is distinguishable from bleaching and white plague. Typically, *Meandrina meandrites* (maze coral) and *Dichocoenia stokesii* (elliptical star coral) are the first to become affected, followed by *Colpophyllia natans* (boulder brain coral) (FDEP, 2018). Other highly susceptible species are as follows: *Dendrogyra cylindrus* (pillar coral) endanger species; *Diploria labyrinthiformis* (grooved brain coral); *Eusmilia fastigiata* (smooth flower coral); *Pseudodiploria strigosa* (symmetrical brain coral); and *Pseudodiploria clivosa* (knobby brain coral) (FDEP, 2018). These are the species that do not show signs of recovery once infected, some are reduced to less than 5% of their population (FDEP, 2018).

Stephanocoenia, Orbicella, and *Siderastrea* are intermediately susceptible to SCTLD, onset of disease must be preceded by the highly susceptible *M. meandrites*, *D. stokesii,* and *C. natans* infections. SCTLD in *Stephanocoenia, Orbicella,* and *Siderastrea* are less deadly and disease progression is slower (FDEP, 2018). *Orbicella* also are affected by yellow blotch disease with yellowish lesions and a darkening of tissue prior to tissue loss and skeletal death (FDEP, 2018). Caribbean ciliate infection primarily affects acroporids and *Orbicella* species of which are less susceptible to SCTLD (FDEP, 2018). Elkhorn coral (*Acropora palmata*) have a low susceptibility to SCTLD.

Since first reported in 2014, SCTLD has spread linearly over 205 linear miles of reef, including Key West and the Florida Keys National Marine Sanctuary (Figures 4 and 5). Half of the stony coral species have been adversely affected. Some species have been completely eliminated, no longer found in certain long-term monitoring sites (FDEP, 2019). SCTLD has been reported in waters off the coast of Jamaica, Mexico, St. Maarten, the US Virgin Islands (Department of Planning and Natural Resources, 2019), and the Dominican Republic (Irazabal and Rodriguez, 2019). The high prevalence of disease, the number of susceptible species, and the high mortality of corals affected suggests this disease outbreak is arguably one of the most lethal ever recorded on a contemporary coral reef (Precht et al., 2016).

The disease is spread via currents or direct contact (Muller et al., 2019). SCTLD has not, to date, shown seasonal patterns in tissue loss linked to warming or cooling ocean temperatures (FDEP, 2018). The disease is found on the outer reef areas first for the Florida Keys (Andrew Bruckner Florida Keys National Marine Sanctuary from Reef Resilience Network Webinar, 2019). A collaborative Mote Marine Laboratory and Florida Institute of Technology study suggests that deeper, diverse coral reefs are at a greater risk of being affected by SCTLD (Muller et al., 2019). Given that the outer reefs are more affected than interior reefs in Florida, the hypothesis suggesting that sunscreen active ingredients, oxybenzone and octinoxate, are causative agents in the decline of Florida coral seems less plausible.

3.2.2 Other Coral Diseases

Disease outbreaks in Florida and Caribbean coral historically have affected less than 5% of general coral populations and were more prevalent during summer months (Muller and van Woesik, 2012) even in coral predisposed to disease due to thermal stress or acidification (Precht et al., 2016).

The first published record of a major coral-disease "white-plague" outbreak was in 1975 on Carysfort Reef, in the upper Florida Keys east of Key Largo (Dustan, 1977) which was nearly decimated. Tissue loss patterns affecting the Caribbean corals led to the disease being termed white plague (Dustan and Halas, 1987; Richardson et al., 1998a,b). White plague presents in a similar fashion to SCTLD with outer white lesions advancing upward on a colony; however, SCTLD has been found as lesions in the middle as well as outer edges and white plague present on the outer edge of a colony only (FDEP, 2018). An increase in coral coverage was observed after white plague affected the Florida reefs (Carysfort and Long Keys Reef) during the late 70s and early 80s; however, diversity and evenness of distribution were reduced (Dustan and Halas, 1987).

In 1995, another plague-like outbreak swept through the corals in the upper Florida Keys (Richardson et al. 1998a,b) about which the term "white-plague type-II" was used as a descriptor to distinguish the 1995 outbreak from previous plague-like disease outbreaks. From 1995 to 1997, the white-plague-type-II disease spread both north and south along the Florida reef tract, affecting a total of 17 scleractinian coral species (Richardson et al. 1998a,b). **The outbreak diminished during each successive winter, and resumed as the water temperatures increased, in the spring and summer** (Richardson et al. 1998a,b). Elkhorn coral (*Acropora palmata*) in the upper Florida Keys declined by 50% from 2004 to 2010 (Williams and Miller, 2011). Thirty percent of this loss was attributable to partial mortality caused by white pox (WPX) and other tissue loss diseases. From 2009 to 2014, seasonal WPX prevalence rates ranged from 23% to 60% in a survey covering 7 reefs throughout the Florida Keys National Marine Sanctuary (Sutherland et al., 2016).

Black band disease is characterized by a dark band separating living tissue from the recently exposed carbonate skeleton and is initially caused by an invasion of coral tissue by the cyanobacterium, *Phormidium corallyticum* (Kuta and Richardson, 1996) and could be associated with sewage discharge (Kaczmarsky et al., 2005). Dark spot disease presents as dark irregular spots with progressions of pitting of the colony at affected areas, affecting *Stephanocoenia,* *Orbicella,* and *Siderastrea* (FDEP, 2018). Caribbean ciliate infection presents as diffuse black or grey band, several mm to 2-cm thick, separating healthy tissue from bare skeleton or the presence of a diffuse scattered patch composed of the black ciliate tests on recently exposed skeleton.

A recent study on 159 Asian-Pacific reefs observed that the likelihood of coral reef disease increased from 4% to 89% when corals were in contact with plastic waste (Lamb et al., 2018). However, the implication that plastics, like ballast water (see Section 3.2.6), could harbor infectious agents and transport these to coral is not a heavily studied coral stressor to date.

3.2.3 Runoff from Urban Development

Urban runoff from nonpoint pollution sources can diminish water quality and transport pollutants to the marine environment. Stormwaters pick up pollutants from lawns, driveways and parking lots, buildings, and streets. Stormwaters may contain fertilizers, lawn care products (e.g., herbicides and pesticides), oil, litter, pet and animal waste, and chemicals. The storm sewer system then transports these pollutants into streams, lakes, or directly into the ocean. The receiving surface waters may introduce additional flow, increased microbial abundance, suspended sediments, nutrients (e.g., nitrogen and phosphorus), metals, and organic compounds. Historically in the Florida Keys, wastewater and stormwater treatment and solid waste disposal facilities were highly inadequate, directly affecting nearshore water quality (Kruczynski and McManus, 2002; Office of National Marine Sanctuaries, 2011); in recent years these have improved.

The federal Port of Miami channel development required deepening and widening with resulting dredging of the channel between late 2013-early 2015 by the Army Corps of Engineers (USACE; Miller et al., 2016). A study was conducted examining the sedimentation impacts that occurred in the coral reef environment surrounding the Port of Miami and found that sedimentation depth was ten-fold higher at the Inner Reef closest to the dredge site as compared to 700 meters away on the same reef (Miller et al., 2016). This dredging coincided with a recent thermal stress event and bleaching in the fall of 2014 (Muller et al., 2008; Miller et al., 2009). Both the thermal event and dredging coincided with the beginning of SCTLD disease in the winter 2014-2015 (Precht et al., 2016) at Virginia Key, the southern portion of the Inner Reef. Despite these coincident disturbances, analysis of tagged coral colony condition during the course of the dredging project demonstrated significant effects in terms of more severe coral tissue loss and increased risk of disease and death in the immediate vicinity of the dredged channel, compared to a reference reef (Miller et al., 2016).

3.2.4 Wastewater and Failed Septic Systems

Effluent from wastewater treatment plants and failed septic systems can introduce pathogens, nutrients, and chemicals to coastal areas. Fecal coliform and Enterococci have been reported reaching offshore Upper Florida reefs (Futch et al., 2010), as have nutrients (Lapointe et al., 1992 and 2019). Domestic wastewater from illegal cesspits and outdated septic systems contributed to nonpoint source pollution in the Florida Keys prior to the completion of the Cudjoe Regional Wastewater System in 2015. Updated wastewater treatment plants in Key West increased residential connection to near 100%. The Cudjoe Regional Wastewater System is a deep well injection system; thus, wastewater effluent into the marine environment is a less important stressor for the Florida Keys.

In contrast, Southern Florida does have more aged wastewater treatment systems in comparison to the Keys. At least 30% of residents in the Southern Florida are connected to septic systems (FDEP Wastewater Statistics, last modified August 29, 2018). Florida Current flows north with intermittent reversals as shown in Figure 6 and Figure 7 (OSCAR / Earth & Space Research, National Oceanic and Atmospheric Administration). Thus, bacterial and chemical contaminants are still of concern to coral reefs in the Florida Keys. The Florida Current is a portion of the Gulf Stream that intrudes into the Gulf of Mexico as the Loop Current and reverses flow to return to the Straits of Florida before moving in a northeasterly direction towards Europe (Jaap and Hallock, 1990). The Florida Current meanders offshore–onshore as a series of gyres (rotating water masses) that persist for 60–100 days at a time depending on environmental conditions (Lee et al., 1994, 2002).

Outfall pipes from six wastewater plants in Miami-Dade (Miami-North and Miami-central), Broward (Broward/Pompano and Hollywood), and Palm Beach (Del Ray Beach and Boca Raton) counties discharge directly into the marine environment and threaten the reef and marine environment (Banks et al., 2008). These were constructed before awareness of reef resources or concern for the environment in general. Stations near both Broward County ocean outfalls were found with bare ocean floor and a lack of live *Porites astreoides* (Fauth et al., 2011). Recently, Ft. Lauderdale has been in the news regarding repairs to its aging water and sewer systems and has replaced crumbling pipes that break without warning. In July, a water main broke and cut off the water supply going to the city's Fiveash Regional Water Treatment Plant, drying up the available water for its 220,000 water customers (Barszewski, 2019).

Cellular diagnostics were used to detect signs of nutrient-related stress in offshores of Broward County when compared to samples from the Bahamas (Fauth et al., 2011). Stress responses of corals adjacent to treated (secondary treatment) human wastewater discharges as well as corals from the Florida Keys National Marine Sanctuary were consistent with sewage exposure while responses of offshore colonies were consistent with xenobiotic detoxification.

Other sources of nonpoint source pollution include abandoned landfills, marinas and live-aboard vessels, and stormwater runoff (NOAA 1996; Futch et al., 2010; Kaczmarsky et al., 2005). In southeast Florida, the St. Lucie Estuary (SLE) and nearshore reef receive freshwater inputs from an artificially large watershed as the result of a network of canals from Lake Okeechobee and massive freshwater releases in 2005, 2013, 2016, which lowered salinity, elevated nutrient concentrations and fecal bacterial counts, and seeded *Microcystis aeruginosa* blooms (Lapointe et al., 2017).

As a result of these discharges from SLE to nearshore reefs, corals also show negative physiological responses associated with changes in water chemistry and light associated with prolonged releases from Lake Okeechobee (Beal et al., 2012). Thus, to improve conditions along these biodiverse nearshore reefs, there is a pressing need to identify and subsequently manage upstream nutrient sources (Lapointe et al., 2012). The data from Lapointe and colleagues long term monitoring of Looe Keys (2019) make clear that the health of coral reefs in

Florida is not an either (temperature) or (nutrients) situation, but rather a “both/and” combination of multiple stressors.

3.2.5 Agricultural Runoff

Agriculture is not a significant land use in Key West (Figure 10, The National Land Cover Dataset, 2011) but is more significant in southeastern Florida mainland where many agricultural areas drain to Biscayne Bay and are in close proximity to the northern end of the Florida Reef Tract.

A recently published study analyzing 3 decades of data showed that in the southern end of Florida, the ratio of nitrogen and phosphorus in marine water was a key factor in determining when, and to what extent, coral bleached at Looe Key (LaPointe et al., 2019). These data showed increased dissolved inorganic nitrogen (DIN), chlorophyll a, DIN:soluble reactive phosphorus (SRP) ratios, as well as higher tissue carbon: phosphorus (C:P) and nitrogen: phosphorus (N:P) ratios in macroalgae during the early 1990s (LaPointe et al., 2019). These data, combined with remote sensing and nutrient monitoring between the Everglades and Looe Key, indicated that the significant DIN enrichment between 1991 and 1995 at Looe Key coincided with increased Everglades runoff, which drains agricultural and urban areas extending north to Orlando, Florida (LaPointe et al., 2019). After a heavy rain event on the mainland of Florida agricultural fertilizers containing nitrogen and phosphorous would run off into the ocean (LaPointe et al., 2019). Increased nutrients in the water caused algae blooms, which in turn seemed to predict mass coral deaths. Nitrogen (dissolved inorganic) was the most important factor related to mass coral bleaching (LaPointe et al., 2019). Three mass bleaching events occurred after heavy rain events that lead to runoff from urban, agricultural, and residential areas from South Florida in to Florida Bay, Looe Key Sanctuary Preservation Ara, and Florida Keys National Marine Sanctuary. Wooldridge (2009) noted in Great Barrier reef coral impacted by an agricultural runoff event that increased nitrogen and decreased phosphorus caused certain membranes to break down and decreased corals tolerance for light and temperature fluctuations. Therefore, the coral was more susceptible to smaller fluctuations and less likely to survive.

3.2.6 Marine Based Influences

Recreational boating and tourism could lead to nonpoint source contaminants, breakage, disturbance of coral community, change marine life, and possible spread of disease (Figure 11 and Figure 12, Florida Fish and Wildlife Conservation Commission). Coral damage can occur from improper anchoring/grounding of boats, improper sanitation of boats and scuba/snorkeling gear, snorkeler and scuba diver damaging reef with touching or removal, grey water discharge from boats, and transfer of disease from boats, snorkelers, and/or divers from infected area.

Recreational boater-generated impacts on water quality generally fall into four categories: toxic metals primarily from anti-fouling paints, hydrocarbons from motor operations and maintenance procedures, solid waste and marine debris from overboard disposal, and bacteria and nutrients from boat sewage (Office of National Marine Sanctuaries, 2011).

The number and frequency of cruise ships visiting the Port of Key west has increased over the past 25 to 30 years. Only a few cruise ships started visiting the Port of Key West, infrequently in the late 1980s. By 2010, between 5 and 13 cruise ships visited the Port of Key West weekly (Office of National Marine Sanctuaries, 2011). In 2003, cruise ship passengers reached a peak of over 1 million passengers (City of Key West, Finance Department 2005). There appears to be no evidence that cruise ship discharges are either occurring illegally or, other than through turbidity and re-suspended sediment, contributing to water quality declines in the area (Thomas J. Murray & Associates, Inc., 2005). However recently, Carnival admitted violating terms of probation from a 2016 criminal conviction for discharging oily waste from its Princess Cruise Line ships and covering it up. Carnival has acknowledged its ships have committed environmental crimes such as dumping “gray water” in prohibited places such Alaska’s Glacier Bay National Park and knowingly allowing plastic to be discharged along with food waste in the Bahamas, which poses a severe threat to marine life (Anderson, 2019).

Ballast water is one of the major pathways for the introduction of nonindigenous marine species per the USDA. Ballast water is fresh, or seawater held in the ballast tanks and cargo holds of ships. The International Maritime Organization Global Treaty to Halt Invasive Aquatic Species entered into force on September 8, 2017. However, boats often transmit waters with non-native species and can be vectors for infectious agents (Aguirre-Macedo et al., 2008). The density of shipping routes in the Gulf of Mexico, Caribbean, and Atlantic region is shown in Figure 8 (Global Shipping Routes, 2004). Bacteria related to coral diseases, *S. marcescens* and *Sphingomonas spp.* are associated with white pox and the white plague type II, respectively (Bythell et al., 2004; Sutherland and Ritchie, 2004). The prevalence of both bacteria was low (3% each) in a study of oil tankers off Cayo Arcas coral reef (Gulf of Mexico). The presence of these bacteria in ballast water poses a potential risk for the Cayo Arcas coral reef (Aguirre-Macedo et al., 2008). Given this research finding, ballast water could be a vector for coral diseases like SCTLD in the Caribbean.

Both commercial and recreational fishing are economically important to the Florida Keys. Reef damage may occur from anchoring on reefs, as well as gear impacts from lost fishing gear (Office of National Marine Sanctuaries, 2011). Marine debris in the form of derelict fishing gear can destroy benthic organisms. The ecological impacts caused by fishing gear that is lost when cut or broken after snagging on the bottom is a growing concern to managers and scientists (Chiappone et al., 2005).

Petroleum (oil, gasoline, other hydrocarbons) can potentially range from small, localized spills to large events that span hundreds of miles of coastline (Office of National Marine Sanctuaries, 2011). The most common and chronic form of spill is from small boat engine operations and usually involves small discharges of fuel, oil, or hydraulic fluid. In addition to the threat of oil spills, more than 300 vessel groundings (vessels 50 feet or less; FKNMS unpublished data; per the Office of National Marine Sanctuaries, 2011) are reported annually within the sanctuary, causing physical damage to sanctuary resources such as seagrass, hard-bottom, and coral reef habitats. There are also many grounding incidents that damage resources but are not reported (NOAA, 2007).

3.2.7 Florida Currents

The Florida current, which represents the convergence of the Yucatan Current and the Loop current from the Gulf of Mexico, transports warm water from the Caribbean and ultimately flows north up the southeastern US coast to the Atlantic Ocean into the Gulf Stream (See Figure 6 and Figure 7). The current brings nutrient and temperature fluxes from southern Florida to the Keys and may have direct and indirect consequences to coral reef health by increasing benthic macroalgae and harming coral tissues (Office of National Marine Sanctuaries, 2011, Leichter et al., 2003, LaPointe et al., 2019). Macroalgal overgrowth of reefs can directly cause coral death and can increase competition for space.

SCTLD disease was found to move at a similar rate both north and south from the point of origin; north, along the southeastern part of the mainland of Florida and south into the Florida Keys (Muller et al., 2019) in a manner following spatial and temporal patterns consistent with a contagious disease. The disease spread was slower than previously predicted and appeared to follow the same spatio-temporal exponential function moving both north along the southeast coast of Florida and south into the Florida Keys. These results suggest that water velocity and flow may have less of an effect than previously thought, although waterborne transmission is still likely, further testing is needed in this area (Muller et al., 2019).

4.0 SUNSCREEN ACTIVE INGREDIENTS AND CORAL HEALTH

4.1 Sunscreen Active Ingredients Benefits

Oxybenzone and octinoxate are effective UV filtering ingredients used in sunscreen active ingredients since the 1970s. Sun exposure causes most skin cancers (Skin Cancer Foundation, 2019). One in five Americans will develop skin cancer in their lifetime, and one person dies from melanoma, the deadliest form of skin cancer, every hour. According to Len Litchfield, MD, (Deputy Chief Medical Officer of the American Cancer Society), experts who have examined the data have concluded that the potential risk of not using sunscreen far outweighs the risks of using sunscreen (American Cancer Society, 2019). Melanoma was reduced by 50 percent and squamous cell carcinoma by 40 percent in those who used sunscreen active ingredients daily (Green et al., 2011; Watts et al., 2018).

4.2 Toxicity Studies

A few studies on sunscreen active ingredients components, oxybenzone (BP-3; benzophenone-3; 2-hydroxy-4-methoxyphenyl-phenylmethanone; 2-hydroxy-4-methoxybenzophenone; CAS No. 131-57-7) and octinoxate (OMC; ethylhexyl-4-methoxycinnamate; trans-octyl methoxycinnamate; ethylhexylmethoxycinnamate; CAS No. 5466-77-3), and toxicity were recently published (Danovaro et al, 2008; He et al., 2019a&b; Downs et al., 2016).

Danovaro and colleagues (2008) exposed small fragments of Acropora corals (branch tip - nubbins) to commercial or lab-created sunscreen formulas. These exposures included high levels of oxybenzone and octinoxate as well as other individual chemicals. Coral were incubated for 96 hours inside plastic bags (polyethylene bags for in-situ incubation). The coral reef areas tested were Siladen, Celebes Sea (Indonesia); Akumal, Caribbean Sea (Mexico); Phuket, Andaman Sea (Thailand), and Ras Mohammed, Red Sea (Egypt). Concentrations of sunscreen formulas used were 10, 33, 50, and 100 µL/L, some of which contained 6% oxybenzone and/or octinoxate in purified seawater. The Acropora coral fragments in the bags in Red Sea, Egypt, Indian Ocean, *in* *situ* exposure to 10 µL/L of a formula containing 6% octinoxate bleached in 2 hours and zooanthellae were reported to be released. Oxybenzone exposure took 24 hours for evidence of bleaching with associated zooanthellae release at the 10 µL/L exposure group. In a second *in situ* experiment in the Andaman Sea, Thailand, Indian Ocean, on oxybenzone and octinoxate (10 µL/L, 6%) both caused bleaching after 48 hours with *Acropora pulchra.* The study was an attempt to mimic real world *in situ* exposure; however, temperatures were 30°C vs 28°C and as discussed in Section 4.2, a degree shift in temperature could increase bleaching in coral. Crucially, these studies did not include analytical testing of the exposure water or water quality measurements, nor were the components of the carrier lotion described. Additionally, the authors indicate that exposure was higher than expected in nature, stating, "We tested sunscreen (10 µL/L) containing concentrations of UV filters higher than those reported in most natural environments. At the same time, the coral response to sunscreen exposure was not dose dependent, as the same effects were observed at low and high sunscreen concentrations." The authors conclude that the lack of dose dependence suggests that effects would likely occur at lower, environmentally-relevant concentrations. However, physical stress due to the holding system's water quality, high temperature, and possible low dissolved oxygen in the plastic bag exposure scenario (*see* Section 3.2.2 for discussion of how proximity to plastic can increase rates of infection) could also have caused or exacerbated the bleaching and mortality observed.

Downs and colleagues (2016) exposed day-old non-US native *Stylophora pistillata* coral larval (planula) to high concentrations of oxybenzone. This study did not examine intact coral colonies. The larvae were placed in artificial seawater containing a range of concentrations of oxybenzone and DMSO to solubilize it. After a few hours, the coral larvae became increasingly pale (bleached) with higher concentrations of oxybenzone. The most sensitive ecosystem-relevant toxicity endpoint reported was a 50% lethal concentration (LC_{50}) of 139 µg/L (which was incorrectly reported as 1.39 µg/L in one table of the paper, apparently due to a typographical error) (Downs et al., 2016). As in the previously described study by Danovaro *et al.*, no analytical measurements were made of oxybenzone concentrations used. The values reported are nominal. This study tested concentrations several orders of magnitude higher than those observed by most of the monitoring studies as discussed in Section 4.3 below. Moreover, concerns with the study design, including a lack of positive controls and temperature control, failure to include study blanks and replicate samples, and use of the cosolvent DMSO, which is known to interfere with membrane integrity and promote the passage of chemicals into organisms' bodies compared to exposure in water alone, lead to a lack of confidence in the values reported in this study.

More recently, a study on larval and adult toxicity of oxybenzone on *Pocillopora damicornis* and *Seriatopora caliendrum* was conducted (He et al., 2019b). These two species are widely distributed species in the Western Indo-Pacific and were collected from southern Taiwan Kenting National Park Headquarters and cultured in a mesocosm. In this study, lowest observed effects levels reported for all endpoints (mortality, bleaching, zooxanthellae density, settlement rate) were at or above the highest nominal concentration tested (1 mg/L) except for observations of polyp retraction, which appeared to have a lower effect concentration. He *et al.* (2019) stated that, "retraction of all polyps on a nubbin and no re-opening during the day (total polyp retraction)was regarded as a toxic effect in this study." No statistical benchmark (NOEC, EC_{10}, etc.) appears to have been calculated by the authors for this endpoint. Instead, they appear to have assumed statistical significance for the lowest nominal concentration where a reduction in polyp retraction was observed (10 µg/L), occurring on days 5-7 of the seven-day test. It appears from the supplemental data published with the study that this effect was observed in only one individual organism (n = 6) at nominal concentrations of 10 and 100 µg/L. Due to the lack of statistical rigor in the authors' treatment of this effect, the endpoint was not considered here as an adverse endpoint. Again, in this study, oxybenzone concentrations were not monitored during exposure. However, the authors note rapid degradation of oxybenzone in their test system, and as a result, report estimated effects levels much lower than the nominal levels, leading to uncertainty in the quantitative results.

All of the toxicity studies discussed above are of relatively short duration and lack testing to establish actual UV-filter exposure levels in water and have not been reproduced by other researchers. Longer term studies at concentrations observed in seawater are needed to better understand the possible effects of oxybenzone and octinoxate on coral. Lastly, these studies were conducted with isolated corals, so there is a lack of evidence of negative impacts on the community and/or ecosystem level for coral reefs.

4.3 Oxybenzone and Octinoxate Monitoring Data

Concerns for UV filters and their effect on coral are based on limited preliminary laboratory acute toxicology studies of oxybenzone and octinoxate at concentrations higher than observed in the environment (Danovaro et al, 2008; He et al., 2019a&b; Downs et al., 2016). Seawater column concentrations of oxybenzone and octinoxate around coral reefs are limited and sparse to date. A survey of the published literature reporting on measured levels of oxybenzone and/or octinoxate in seawater was conducted; Table 1 summarizes this review. No monitoring for these ingredients in the Florida Keys has been reported; however, levels measured in populated beach areas including the Virgin Islands and Waikiki Beach were below the level of detection or in the parts per trillion (ng/L) levels. The highest concentration reported has been 1.395 ppm in Trunk Bay, a body of water and a beach on St. John in the United States Virgin Islands, in Virgin Islands National Park (Downs et al., 2015). This value is more than two orders of magnitude higher than the next highest concentration reported in the literature by other authors (see Table 1). The study in which this outlier value was reported did not include replicates or blanks. Taken together, these facts suggest the 1.395 mg/L value contains contamination or included a non-aqueous phase "glob" or film of sunscreen rather than representing the amount present in the water column.

An initial analysis of seawater at Trunk Bay reported oxybenzophenone concentrations in the water column between 1 ppm and 90 parts per billion (ppb); Downs et al., 2011). Further sampling revealed oxybenzone concentrations of 1.395 ppm (mg/L) at a site near the edge of the Trunk Island coral community (Downs et al., 2015). A sampling site 93 m east of this site contained 580 ppb (µg/L or 0.580 mg/L) of oxybenzone. Samples were collected at 11:00–11:24 h with more than 180 swimmers in the water and 130 sunbathers on the beach within 100 m of the two sampling sites. Oxybenzone levels at Hawksnest Bay (230 swimmers) were lower (75-95 ppb 75-95 µg/L or 0.075 and 0.095 mg/L) and were undetectable at Caneel Bay (17 swimmers over 48 hr).

Another study, conducted at Trunk Bay by US Geological Survey personnel with well documented sampling techniques, analytical methods, replicates, and proper statistical calculations reported much lower concentrations of oxybenzone (6073 ng/L; 6.073 µg/L; 0.006073 mg/L) at Trunk Bay (Bargar et al., 2015).

4.4 Oxybenzone Exposure Calculations

Given this variation in magnitude of the concentrations for oxybenzone, a calculation to estimate the number of people needed to create the concentrations reported in these two studies (Downs et al., 2016; Bargar et al., 2015) was performed to help establish whether the high value is realistic.

The following worst-case, highest use of oxybenzone-containing sunscreen was used to create the hypothetical ceiling exposure value. Assumptions made for this calculation were as follows:

- the highest allowed concentration for oxybenzone sunscreen active ingredients is 6% (US),
- one-ounce sunscreen per application,
- reapplication every two-hours for an eight-hour stay on the beach and water (e.g., 4 applications per person per day),
- *complete* wash-off of oxybenzone from the skin once entering water,
- water volume determination was estimated by approximating a polygon of the Bay, 100 meter out from the shore of Trunk Bay and depth of 1.5 m (see Figure 4.4.1 below), and
- no water mixing or dissipation to ocean water.

Water volume estimated with Google Earth polygon, 100 m out from the shore of Trunk Bay and uniform depth of 1.5 m = 86386.5 m^3

Figure 4.4.1 Trunk Bay Water Volume Determination (Google Earth)

Figure 4.4.2 Trunk Bay in Relation to Florida Keys (Google Earth)

To achieve the highest reported concentration of 1.395 mg/L (Downs et al., 2016), given the assumptions above (noting that they will overestimate the actual exposure due to conservative assumptions regarding application rate, wash-off, and dilution) would require 16,964 people in the water. The next highest concentration of 0.580 mg/L (Downs et al., 2016) would require approximately 7053 people in the water. In stark contrast, the description was 180 people in the water and 130 people on the beach at Trunk Bay on this testing day. This is a strong indication that these measured concentrations are not accurate, potentially due to an error in sampling, analysis, or contamination. Study blanks were not utilized to rule out contamination. Notably, all other measured concentrations of oxybenzone are several orders of magnitude lower.

Measured seawater concentrations of oxybenzone, are less than the level of the most sensitive environmentally-relevant toxicological endpoint reported.

These worst-case assumptions for the calculation are not realistic scenarios. Products containing oxybenzone comprise 70% – not 100% – of the market, sunscreen active ingredients do not instantly and completely wash off in the water, and the concentration of oxybenzone would decrease exponentially as distance from the shore increases. The US Geological Survey study at Trunk Bay found that oxybenzone concentrations decrease exponentially (r^2=0.86) with distance from the beach (Bargar, et al., 2015). Also, most people do not apply sunscreen at a rate of 2 mg/cm^2, which is the recommended amount; in a recent study lotion was applied on average 1.1 mg/cm^2; spray 1.6 mg/cm^2; and stick 0.35 mg/cm^2 (Novick et al., 2015).

Indeed, the conservatism of the scenario confirmed when the data of Bargar et al. (2015) are used. Their measured concentration of 6073 ng/L would suggest a total of only about 74 bathers in the water.

4.5 Preliminary Aquatic Risk Assessment and Conclusion on Sunscreen Active Ingredients and Coral Health Correlation

The available data addressing the toxicity of active sunscreen ingredients to coral are uncertain, because the researchers reporting sensitive responses to UV-screen exposure in coral did not measure the concentration to which the coral were exposed. However, even if the rough estimates of exposure in these studies were accepted, they suggest that any risk to coral from UV-screen exposure is not likely. The best designed toxicity study published to date (He et al., 2019b) suggests a lowest observed adverse effects concentration for coral around 1000 µg/L (with significant uncertainty due to the rapid degradation of oxybenzone under study conditions). If an assessment factor of 100 were applied to account for interspecies and subchronic-to-chronic extrapolation, a resulting estimate of the predicted no-effect concentration would be on the order of 10 µg/L. In comparison, reliable detected values in monitoring studies in seawater yielded UV-screen concentrations ranging from ng/L levels to a maximum of 6 µg/L (See Table 1).

The majority of coral reefs around Key West are many miles from the shoreline and therefore, exposure from sunscreen active ingredients use on swimmers in beach areas and from divers in limited boating excursions to reef areas are expected to be significantly lower (*e.g.*, Bargar et al., 2015 showed exponential decreases in oxybenzone concentration with distance from the busiest bathing area). Reefs are primarily affected by those humans who come within close proximity of the reefs - such as snorkelers and scuba divers. It should be noted that many water recreationists, particularly snorkelers, wear rash guard clothing to protect against stinging cells and the sun and therefore likely represent far lower potential sources of sunscreen active ingredients UV filter exposure.

“Many reefs are remote, without tourists, and many of them nonetheless are showing impact from climate change... the media's extrapolations that sunscreen active ingredients is threatening the world's coral ‘are a bit of a stretch.’,” Terry Hughes, director of the Australian Research Council Centre of Excellence for Coral Reef Studies at James Cook University based on the data from sunscreen active ingredients coral toxicity study conducted by Craig Downs (Bogle, 2015).

5.0 KEY WEST IN CONTEXT

Figure 9 to Figure 12 illustrate the location of land- and marine-based factors relative to coral reefs in the vicinity of Key West. Depicted are population centers, land use, wastewater treatment plants, marinas, boat ramps and anchorages, public beaches, and beach access locations (Florida Keys National Marine Sanctuary, OSCAR / Earth & Space Research, National Oceanic and Atmospheric Administration, Global Shipping Routes, WorldPop database, The National LandCover Dataset, Florida Fish and Wildlife Conservation Commission, Coral Reef Environmental Monitoring Program, The Water Quality Monitoring Project, Florida International University). Coral reefs in the vicinity of Key West are generally several miles from the coastline (Figure 13) and not likely to experience high concentrations of sunscreen active ingredients use on land, beach or during marine activities. Monitoring stations exist to evaluate coral reef and water quality monitoring (Figure 14, Coral Reef Environmental Monitoring Program, The Water Quality Monitoring Project, Florida International University), and recent research states that increased nitrogen and phosphorus contribute to coral reef declines (Lapointe et al., 2019). This data has not been evaluated as part of this investigation with respect to constituents monitored or specific results.

Monitoring for UV filters in the Florida Keys has not been reported; however, levels measured in populated beaches areas including the Virgin Islands and Waikiki Beach, have been below the levels of detection or in the parts per trillion. In contrast to studies in the Caribbean and Hawaii, the majority of coral reefs around Key West are many miles from shoreline and therefore, exposure from sunscreen active ingredients use on swimmers in beach areas and divers in boating excursions to reef areas will likely be lower. Therefore, even if the number of swimmers were used as a surrogate for potential UV filter exposure, it is highly unlikely that bleaching events as recorded over the past three decades is related to the use of sunscreen active ingredients.

6.0 DISCUSSION

Banning the UV filters oxybenzone and octinoxate is unlikely to have a measurable impact on coral health. The toxicity studies used as support for banning oxybenzone and octinoxate suffer from technical limitations, and hence are suggestive of a need for further study rather than conclusive evidence of an emerging stressor (Downs et al., 2016 and Danovaro et al., 2008; He et al., 2019a&b). These studies were conducted on non-Atlantic or Caribbean coral species and toxicity was observed at concentrations higher than what is found in reliable monitoring studies.

Improving the health of coral in the Florida Keys requires prioritizing efforts on the most significant stressors. Mitigation efforts to restore damaged coral have been successful to some extent but are labor and time intensive. Conservation efforts should continue on recreational practices such as educational efforts on boaters, divers, and other activities in and around the coral reef to reduce the spread of SCTLD disease and minimize structural damage to the reefs.

Specific to SCTLD, per the Florida Keys National Marine Sanctuary:

> “Florida's coral reefs are experiencing a multi-year outbreak of Stony Coral Tissue Loss Disease (SCTLD). While disease outbreaks are not uncommon, this event is unique due to its large geographic range, extended duration, rapid progression, high rates of mortality and the number of species affected. The disease is thought to be caused by bacteria and can be transmitted to other corals through direct contact and water circulation.”
>
> This disease started in 2014 off the coast of Miami near Key Biscayne and has progressed in a northern and southern pattern associated with waterborne disease. SCTLD resembled the coral disease known as white plague (WP) (Richardson et al., 1998a; Weil & Rogers, 2011). The disease outbreak continued into 2015 and increased in frequency and severity during the summer months (Peters and Fogarty, 2016).

The results of most recent disease modeling and mapping efforts support the conclusion that the SCTLD outbreak follows the spatial and temporal patterns consistent with a contagious disease (Muller et al., 2019). This study found that deeper sites and sites with more coral diversity were at a greater risk of having disease. Diving surveys clearly show a rapidly progressing, highly fatal disease front that has already infected the majority of the Florida Reef Tract and will likely infect the rest within upcoming months. Transmission appears to be via water currents and is unlikely to be contained.

> Additionally, a regional approach should be considered to advise, protect, and consider early intervention at other sites. Within the continental United States, the Dry Tortugas, Florida Gulf Coast, and Flower Garden Banks may be naturally isolated from the disease but may be highly susceptible to receiving it through anthropogenic means. Other Caribbean countries and territories may similarly be more vulnerable if human-related transmission is not considered and addressed. Creating an early warning system for reporting, response, and treatment at even a localized level may help protect these other regions (Neely, 2018).

Unfortunately, there is little that local resource managers can do to stop a thermal-stress event, stop a disease outbreak, or change the overall trajectory of coral loss associated with regional and global disturbances (Precht et al., 2016). Best practices for divers, snorkelers, and recreational boaters, are to move from clean to diseased areas as well as decontaminate gear. Per NOAA and Florida Department of Environmental Protection, SCTLD is likely spread by touch and water flow, so cleaning diving gear is essential. They caution of cleaning solution disposal and suggest to not pour it back into the ocean (NOAA, 2018; FDEP, 2019).

General Guidelines to decrease the spread of SCTLD from NOAA, Florida Keys:

- Remove debris and sediment following each dive.
- Between dives, sanitize gear that contacts corals with a bleach solution. Other gear should be washed in freshwater with an antibacterial soap.
- Use quaternary ammonium solutions to decontaminate dive gear after return to shore.
- Properly dispose of disinfectant solutions and rinse water in a sink, tub or shower. Never pour into the ocean or a storm drain.

Large teams of scientists are working on mitigation efforts to control or slow SCTLD progressing to other reef areas (antibiotics and bleaching of infected coral have been successful but labor and time intensive). The Department of Environmental Protection’s Florida Coastal Office, along with the Florida Keys National Marine Sanctuary and the NOAA Coral Reef Conservation Program created the Coral Rescue Collection Plan. The idea is to help slow the continued spread of disease and saving “priority corals,” which include collecting numerous healthy corals that haven’t yet been impacted and house them in on-shore coral nurseries (Donzelli, 2019). Conservation efforts should focus on recreational practices such as educational efforts on boaters, divers, and other activities in and around the coral reef to reduce the spread of the disease. Decontamination of boats, diving equipment, and proper anchoring messaging and communication would prove to be more effective in reducing the spread of the disease. Florida

Department of Environmental Protection and National Oceanic and Atmospheric Administration (NOAA), and Reef Resilience have informative and current status of disease progressing, best management practices, and ways to help.

Table 1. Surface Seawater, Surface Freshwater. Sediment, and Coral Tissue Published Monitoring Data on Oxybenzone and Octinoxate

		Oxybenzone (BP-3)			Octinoxate (EHMC)			Reference
Location	**Site Description**	**Range**	**Median**	**Average**	**Range**	**Median**	**Average**	
Surface Seawater (ng/L)								
Ka'a'awa Hawaii Shallow	Nearshore (n=3)	2.6 – 7.1	5.0	4.7	<LOD	<LOD	<LOD	Mitchelmore et al., 2019
Ka'a'awa Hawaii Deep	Offshore (n=3)	0.1 – 7.5	5.4	3.9	0 – 1.5	1.5	1.0	
Ka'a'awa Hawaii Near and Offshore		0.1 – 7.5	5.0	4.8	0 – 1.5	<LOD	0.3	
Kaneohe Bay Hawaii Shallow	High impact tourist, scuba and recreation site (n=3)	4.7 – 11.3	6.9	7.3	<LOD	<LOD	<LOD	
Kaneohe Bay Hawaii Deep	Mixture of low and high impact tourist/use sites (n=4)	0.1 – 48.1	4.8	9.6	<LOD	<LOD	<LOD	
Kaneohe Bay Hawaii Near and Offshore		0.1 – 48.1	6.3	8.6	<LOD	<LOD	<LOD	
Waikiki Beach Hawaii Shallow	Nearshore tourist beach areas (n=3)	8.8 – 142.7	61.3	70.8	0 – 1.5	1.5	0.0	
Waikiki Beach Hawaii Deep	Offshore tourist beach areas (n=3)	9.4 – 73.1	24.2	26.2	<LOD	<LOD	<LOD	
Waikiki Beach Hawaii Near and Offshore		8.8 – 142.7	26.8	48.5	0 – 1.5	<LOD	<LOD	
South Carolina	Totals for all sampling sites	<LOD – 2203	-	256	<LOD 438	-	46.7	Bratkovics et al., 2015
South Carolina	Myrtle Beach, tourist areas	<LOD – 575	-	135	0 – 35	-	10.7	
South Carolina	North Inlet, North Inlet National Estuarine Research Reserve	<LOD – 138	-	37.6	0 – 77	-	8.58	
South Carolina	Coast Guard station northeastern Folly Beach	<LOD – 467	-	71.8	0 – 235	-	41.6	
South Carolina	Wash Out, residential, local Folly Beach	<LOD - 366	-	201	0 – 172	-	55.6	
South Carolina	Fishing Pier, Folly Beach	<LOD - 1298	-	591	0 – 438	-	96.9	
South Carolina	County Park, Southwestern Folly Beach	<LOD - 303	-	497	0 – 154	-	46.3	

		Oxybenzone (BP-3)			Octinoxate (EHMC)			Reference
Location	**Site Description**	**Range**	**Median**	**Average**	**Range**	**Median**	**Average**	
Surface Seawater (ng/L)								
Virgin Island	Shoreline Trunk Bay 30 m offshore island at 1 m depth	1943 - 4643	-	-	-	-	-	Bargar et al., 2015
Virgin Island	Shoreline Trunk Bay <1 m depth, Figure 3 of Bargar et al., 2015	-	-	6073	-	-	41	
Virgin Island	210 m off Trunk Bay	-	-	116.3[1]	-	-	5.8	
Virgin Island	Lameshur Bay, Figure 3 of Bargar et al., 2015	-	-	Almost 100	-	-	>10	
Virgin Island	Brown Bay, Figure 3 of Bargar et al., 2015	-	-	Almost 100	-	-	>10	
Virgin Island	Leinster Bay, Figure 3 of Bargar et al., 2015	-	-	Almost 100	-	-	>10	
Virgin Island	Maho Bay, Figure 3 of Bargar et al., 2015	-	-	Over 100	-	-	>10	
Virgin Island	Cinnamon Bay, Figure 3 of Bargar et al., 2015	-	-	Over 100	-	-	>10	
Folly Beach South Carolina	Estuary	2013						Bratkovics and Sapozhnikova, 2011
Greece	seawater	6.5 – 8.2			7.4 – 10.7			Giokas et al., 2005
South China Sea	Wu Pai – wet season	-	-	13.9	<LOD	-	-	Tsui et al., 2017
South China Sea	Sharp Island – wet season	-	-	24.4	<LOD	-	-	
South China Sea	Ung Kong – wet season	-	-	6.1	<LOD	-	-	
South China Sea	Sung Kung – wet season	-	-	8.5	<LOD	-	-	
South China Sea	Wu Pai – dry season	-	-	17.0	<LOD	-	-	
South China Sea	Sharp Island – dry season	-	-	8.1	<LOD	-	-	
South China Sea	Ung Kong – dry season	-	-	4.2	<LOD	-	-	
South China Sea	Seawater	13.2 – 31.7						Tsui et al., 2015
Taiwan	Seawater	19 – 1233						Kung et al., 2018
Gran Canaria Island	Seawater	up to 3317						Sanchez-Rodriguez et al., 2015
Virgin Island	Seawater	$0 – 1.395\times10^9$						Downs et al., 2016

[1] This data was taken from the Figure 3; however, the text states 2.7 ng/L. We believe this was an error in reporting and the 2.7 ng/L was for homosalate.

		Oxybenzone (BP-3)			Octinoxate (EHMC)			Reference
Location	Site Description	Range	Median	Average	Range	Median	Average	
Freshwater (ng/L)								
Swiss Lake	Freshwater	<5 – 125	-	-	<LOD - 26	-	-	Poiger et al., 2004
Swiss Lakes/River	Wastewater	<2 – 35	-	-	-	-	-	Balmer et al., 2005
Slovenia	Wastewater	11-400	-	-	-	-	-	Cuderman and Heath, 2007
Swiss River	Freshwater	6 – 68	-	-	-	-	-	Fent et al., 2010
Japan River/Lakes	Freshwater	16 – 41	-	-	-	-	-	Kameda et al., 2011
Japan	Freshwater	<LOD – 1340	-	-	-	-	-	Tashiro and Kameda, 2013
Norway	Freshwater	<LOD – 439.9	-	-	-	-	-	Langford and Thomas, 2008
Italy	Freshwater	<LOD – 216	-	-	-	-	-	Nguyen et al., 2011
China, US, Japan, Thailand	Freshwater	-	<250	-	-	-	-	Tsui et al., 2014
Palau	Jelly Fish Lake	<LOD – 1.4	-	-	0	-	-	
Palau	Clear Lake	<LOD – 1.2	-	-	-	-	-	Bell et al., 2017
Palau	Ngermeuangel Lake	<LOD – 1.9			<LOD - 1800	-	-	
Southern Caribbean	Freshwater	0.10 – 1.56 $\times 10^6$	-	-	-	-	-	Schaap and Slijkerman, 2018
Czech Republic	Freshwater	Up to 620	-	-	-	-	-	Grabicova et al., 2013
Sediment (ng/g dw)								
Ka'a'awa Hawaii Shallow	Nearshore (n=3)	<LOD – 0.75	0.00	0.14	<LOD - 0.05	0.00	0.01	
Ka'a'awa Hawaii Deep	Offshore (n=3)	<LOD – 0.02	0.00	0.01	<LOD - 0.08	0.00	0.02	
Ka'a'awa Total		<LOD – 0.75	0.00	0.08	<LOD - 0.08	0.00	0.01	
Kaneohe Bay Hawaii Shallow	High impact tourist, scuba and recreation site (n=3)	<LOD – 0.55	0.12	0.12	<LOD - 31.43	3.55	7.73	
Kaneohe Bay Hawaii Deep	Mixture of low and high impact tourist/use sites (n=4)	<LOD – 4.49	0.06	1.11	<LOD - 7.79	0.48	3.13	Mitchelmore et al., 2019
Kaneohe Bay Hawaii Total		<LOD – 4.49	0.12	0.68	<LOD - 31.43	3.12	5.10	
Waikiki Beach Hawaii Shallow	Nearshore tourist beach areas (n=3)	<LOD – 0.72	0.54	0.52	<LOD - 0.08	<LOD	0.01	
Waikiki Beach Hawaii Deep	Offshore tourist beach areas (n=3)	<LOD – 0.02	<LOD	<LOD	<LOD	<LOD	<LOD	
Waikiki Beach Hawaii Total		<LOD – 0.72	0.02	0.26 3	<LOD - 0.08	0.00	0.00	
Palau	Jelly Fish Lake (n=8)	<LOD – 15	-	-	<LOD - 59	41.5	35.88	
Palau	Clear Lake (n=8)	<LOD	-	-	-	<LOD	<LOD	Bell et al., 2017
Palau	Ngermeuangel Lake (n=8)	28 – 241	-	-	<LOD	<LOD	<LOD	

Location	Site Description	Oxybenzone (BP-3) Range	Oxybenzone (BP-3) Median	Oxybenzone (BP-3) Average	Octinoxate (EHMC) Range	Octinoxate (EHMC) Median	Octinoxate (EHMC) Average	Reference
Spain River		4 – 27	-					Gago-Ferrero et al., 2012
South America		< LOD – 5.38	-					Baron et al., 2013
Norway			-	<5				Langford et al., 2015
South China Sea		4.2 - 17	-					Tsui et al., 2017
South China Sea – Wu Pai – wet season		-	-	9.8	< LOD	-	-	
South China Sea – Sharp Island – wet season		-	-	6.5	< LOD	-	-	
South China Sea – Ung Kong – wet season		-	-	6.1	< LOD	-	-	
South China Sea – Sung Kung – wet season		-	-	8.5	< LOD	-	-	
South China Sea – Wu Pai – dry season		-	-	17.0	< LOD	-	-	
South China Sea – Sharp Island – dry season		-	-	8.1	< LOD	-	-	
South China Sea – Ung Kong – dry season		-	-	4.2	< LOD	-	-	
Hong Kong – August 2013 (n=13)		1 – 39.8	8.6	-	1.4 – 447	8.3	-	Tsui et al., 2015
Hong Kong – February 2013 (n=13)		2.5 – 2.5	2.5	-	0.8 – 291	6.5	-	
Tokyo Bay – June 2013 (n=13)		0.05 – 10.2	5.7	-	0.6 – 119	5.1	-	
Tokyo Bay – July 2013 (n=8)		< LOD	< LOD		0.3 – 54.5	10.3		
Coral Tissue (ng/g dw)								
Ka'a'awa Hawaii Shallow (species unspecified)	Nearshore (n=3)	<LOD – 131.4	8.7	22.1	<LOD	<LOD	<LOD	Mitchelmore et al., 2019
Ka'a'awa Hawaii Deep (species unspecified)	Offshore (n=3)	<LOD – 393.9	23.2	76.96 ± 1.2	<LOD - 12.1	<LOD	1.21	
Ka'a'awa Hawaii Total (species unspecified)		<LOD – 393.9	8.7	61.3 ± 48.3	<LOD	<LOD	<LOD	
Kaneohe Bay Hawaii Shallow (species unspecified)	High impact tourist, scuba and recreation site (n=3)	1.2 – 89.6	28.8	31.2 ± 0.3	<LOD	<LOD	<LOD	
Kaneohe Bay Hawaii Deep (species unspecified)	Mixture of low and high impact tourist/use sites (n=4)	3.0 – 102.3	18.4	24.4 ± 12.6	<LOD	<LOD	<LOD	
Kaneohe Bay Hawaii (species unspecified) Total		1.2 – 102.3	19.2	27.4 ± 9.9	<LOD	<LOD	<LOD	
Waikiki Beach Hawaii Shallow (species unspecified)	Nearshore tourist beach areas (n=3)	<LOD – 570.5	72.4	159.6 ± 0.2	<LOD – 4.8	<LOD	0.4	
Waikiki Beach Hawaii Deep (species unspecified)	Offshore tourist beach areas (n=3)	<LOD – 71.7	20.1	25.8 ± 12.5	<LOD - 12.1	<LOD	1.0	
Waikiki Beach Hawaii (species unspecified) Total		<LOD- 570.5	48.1	89.8 ± 0.1	<LOD - 12.1	<LOD	0.7	

Location	Site Description	Oxybenzone (BP-3)			Octinoxate (EHMC)			Reference
		Range	Median	Average	Range	Median	Average	
Coral Tissue (ng/g dw)								
South China Sea – Hong Kong		2.8 – 31.8	-	-	<LOD	-	-	Tsui et al., 2017
South China Sea – Wu Pai Wet Season - *Favites abdita* (n=3)		-	-	17.6	<LOD	-	-	
South China Sea – Wu Pai Wet Season - *Porites sp.* (n=3)		-	-	11.8	<LOD	-	-	
South China Sea – Wu Pai Wet Season - *Pavona decussata* (n=3)		-	-	13.8	<LOD	-	-	
South China Sea – Sharp Island Wet Season - *Favites abdita* (n=3)		-	-	13.7	<LOD	-	-	
South China Sea – Sharp Island Wet Season - *Porites sp.* (n=3)		-	-	31.8	<LOD	-	-	
South China Sea – Sharp Island Wet Season - *Pavona decussata* (n=3)		-	-	18.8	<LOD	-	-	
South China Sea – Ung Kong Wet Season - *Favites abdita* (n=3)		-	-	10.9	<LOD	-	-	
South China Sea – Ung Kong Wet Season - *Porites sp.* (n=3)		-	-	15.4	<LOD	-	-	
South China Sea – Ung Kong Wet Season - *Pavona decussata* (n=3)		-	-	3.4	<LOD	-	-	
South China Sea – Sung Kung Wet Season - *Favites abdita* (n=3)		-	-	10.4	<LOD	-	-	
South China Sea – Sung Kung Wet Season - *Porites sp.* (n=3)		-	-	18.6	<LOD	-	-	
South China Sea – Sung Kung Wet Season - *Platygyra acuta* (n=3)		-	-	10.2	<LOD	-	-	
South China Sea – Wu Pai Dry Season - *Porites sp.* (n=3)		-	-	10.9	<LOD	-	-	
South China Sea – Wu Pai Dry Season - *Platygyra acuta* (n=3)		-	-	5.4	<LOD	-	-	
South China Sea – Sharp Island Dry Season - *Porites sp.* (n=3)		-	-	8.6	<LOD	-	-	
South China Sea – Sharp Island Dry Season - *Platygyra acuta* (n=3)		-	-	4.1	<LOD	-	-	
South China Sea – Ung Kong Dry Season - *Porites sp.* (n=3)		-	-	9.2	<LOD	-	-	
South China Sea – Ung Kong Dry Season - *Platygyra acuta* (n=3)		-	-	3.6	<LOD	-	-	

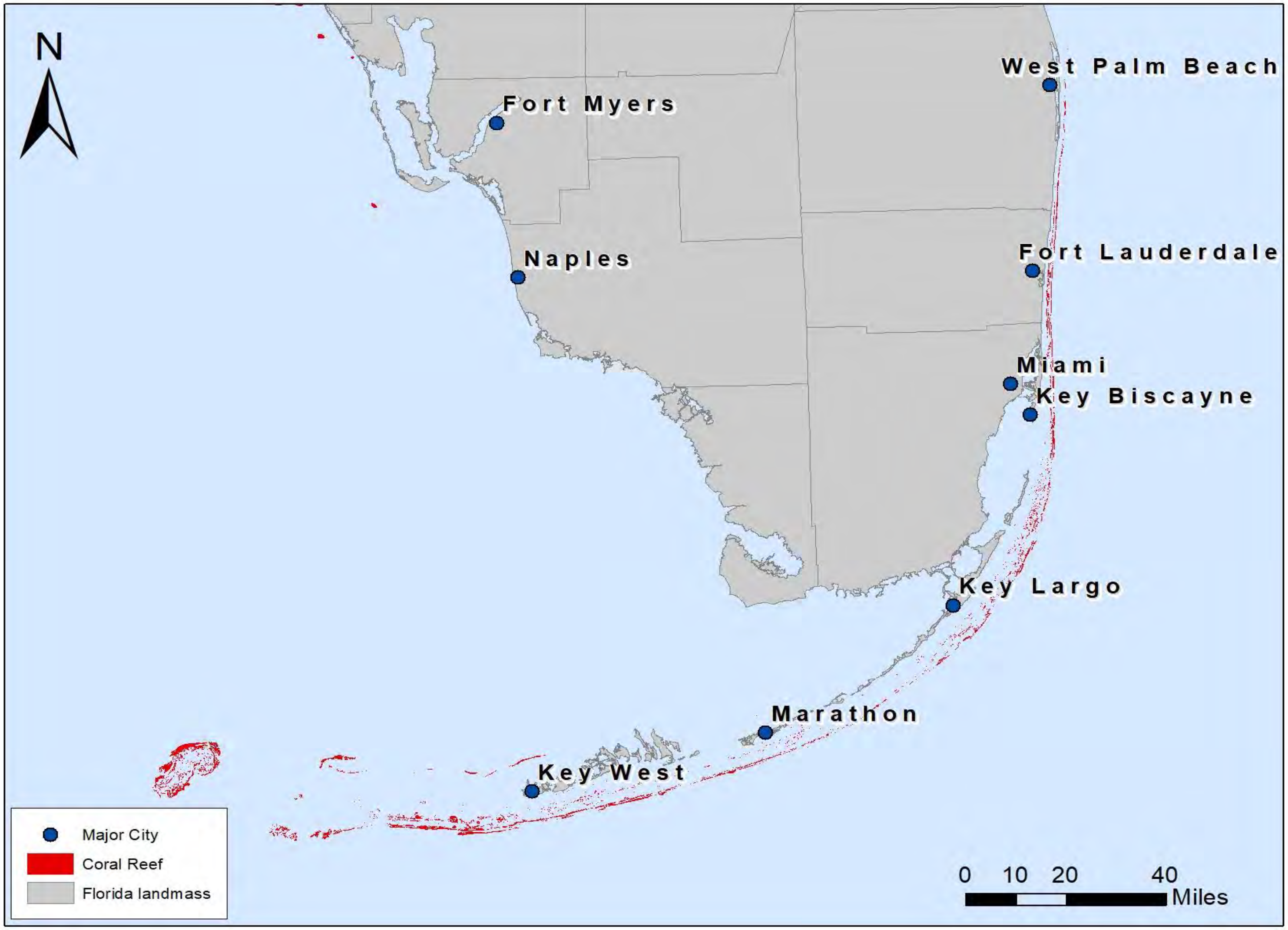

Figure 1. Extent of coral reefs around South Florida

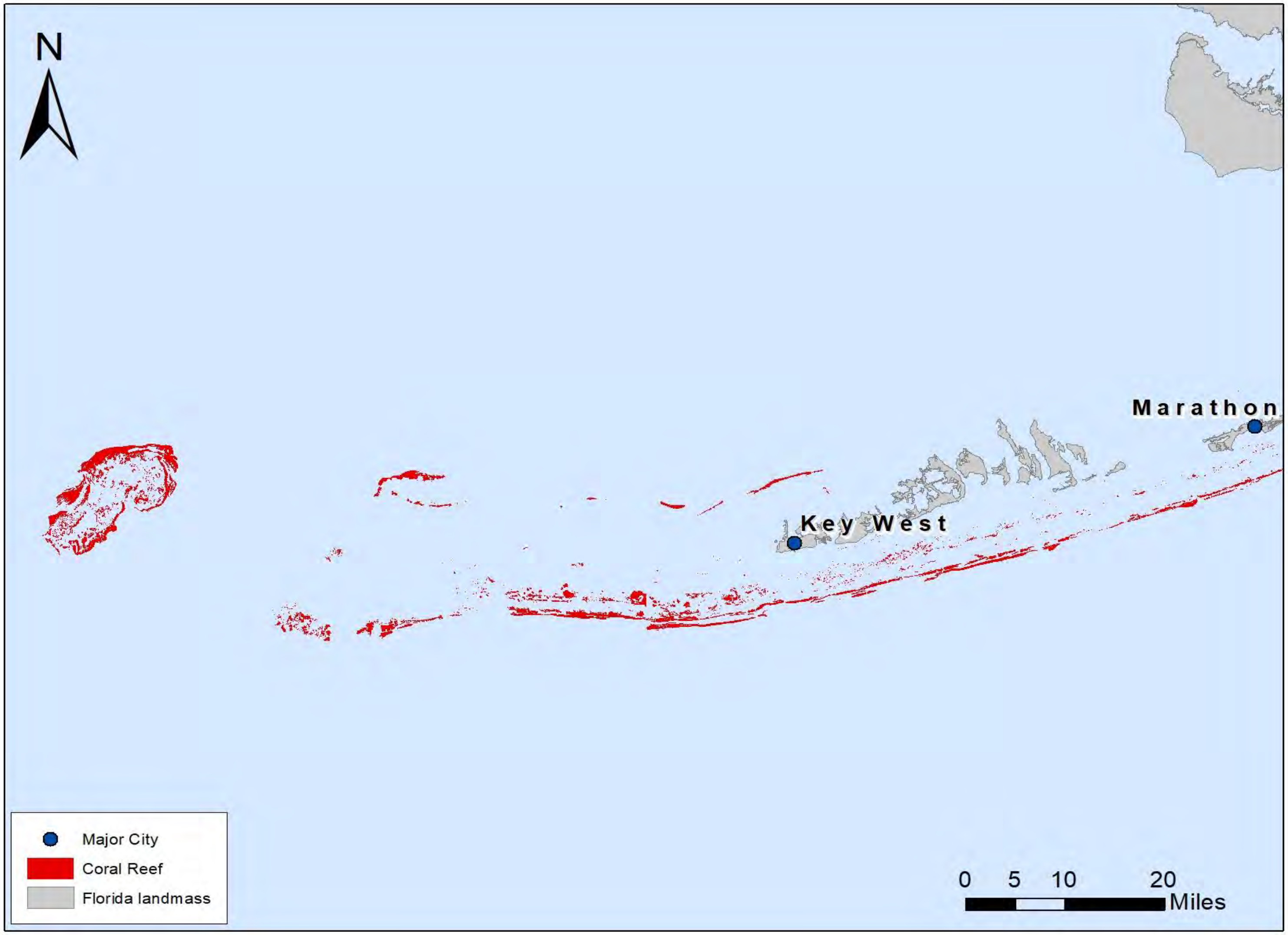

Figure 2. Coral reefs around Key West

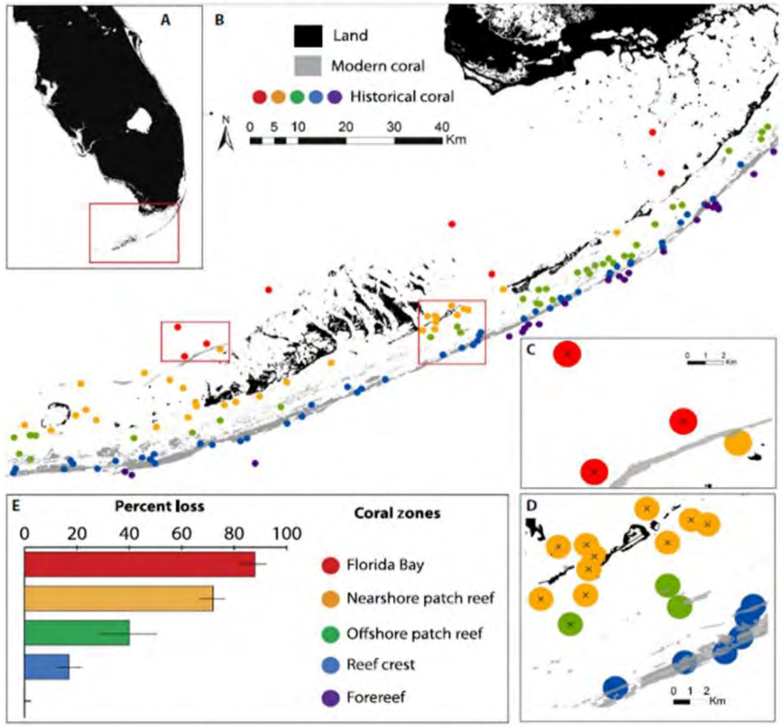

Table 1. Characteristics of the five reef zones, number of historical coral observations, mean depth of historical coral observations, and mean percent loss across zones. Percent loss represents the number of discrete historical observations in each zone that are represented by modern coral on modern benthic habitat maps. Values are mean estimates of change using three threshold distances (0.25, 0.5, and 0.75 km). na, not applicable.

Zone	Name	Depth range of corals (m)	Historical coral observations	Mean percent loss (SE, range)
1	Florida Bay	2.1–11.4	8	87.5 (7.2, 75–100)
2	Nearshore patch reef	0.6–9.1	31	68.8 (7.5, 61.3–83.9)
3	Offshore patch reef	0.6–12.3	35	40.0 (11.9, 22.9–62.9)
4	Reef crest	1.2–14.6	47	12.1 (6.8, 4.3–25.5)
5	Forereef	12.8–58.5	22	0 (0, na)

Figure 3. Coral loss over time. Noticed overall loss of 52% of the area of the seafloor occupied by corals

(Source: McClenachan et al., 2017)

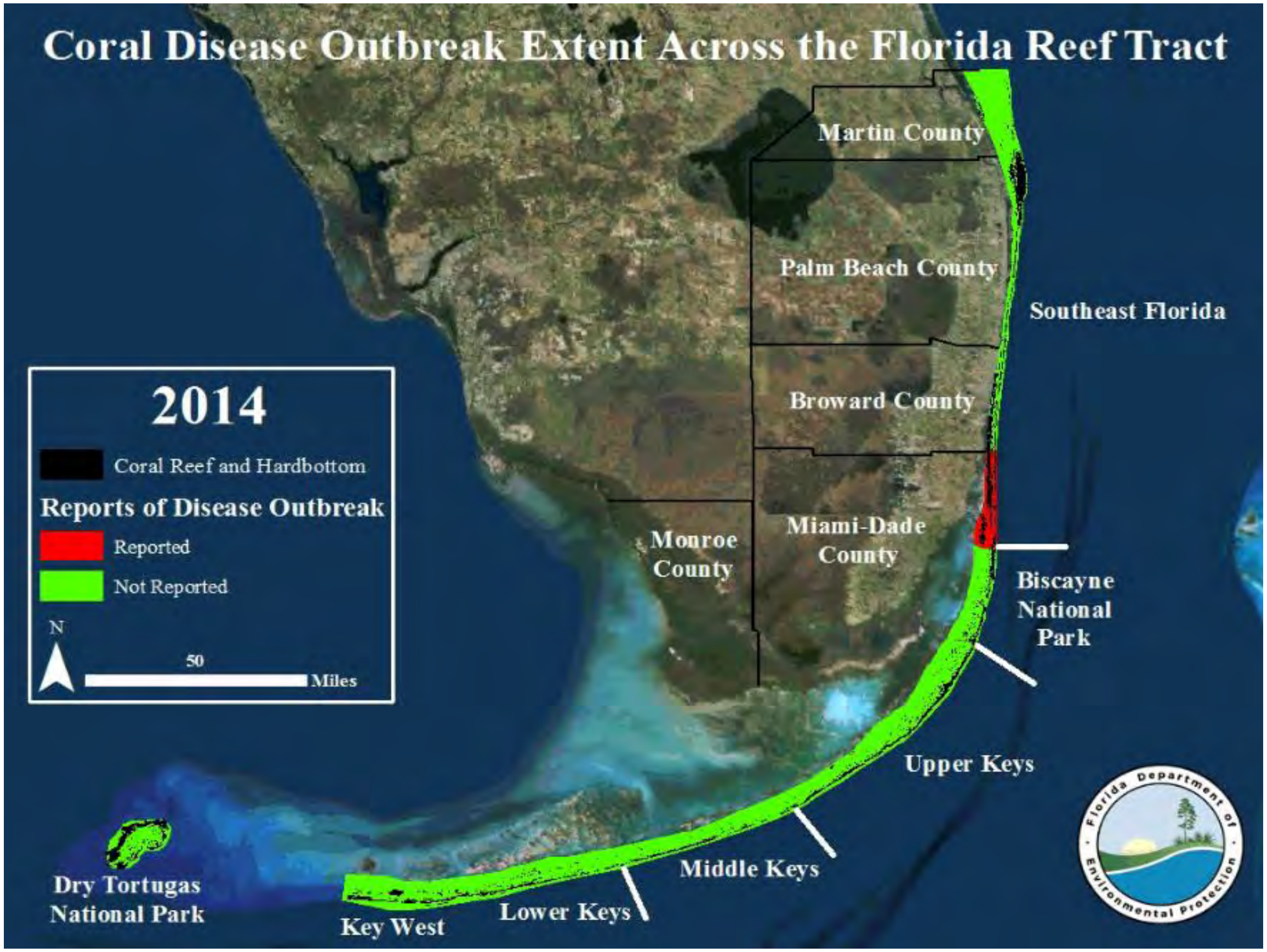

Figure 4. Florida Reef Tract Coral Disease Outbreak Progression in 2014 (note the onset in Miami area)

(Source: Florida Keys National Marine Sanctuary. https://floridakeys.noaa.gov/coral-disease/disease.html)

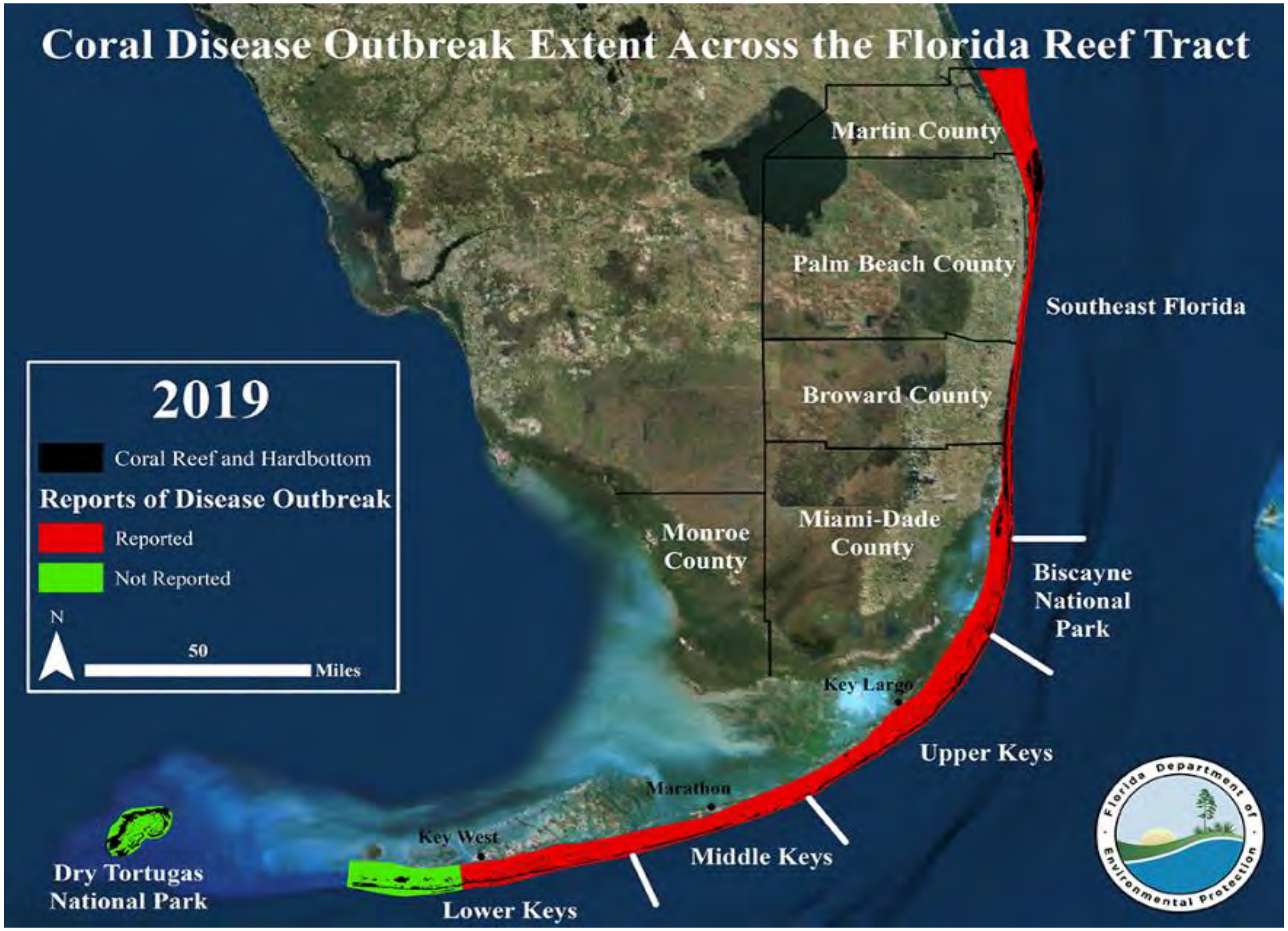

Figure 5. Florida Reef Tract Coral Disease Outbreak Progression in 2019 (note the spread North and South towards the Florida Keys)

(Source: Florida Keys National Marine Sanctuary. https://floridakeys.noaa.gov/coral-disease/disease.html)

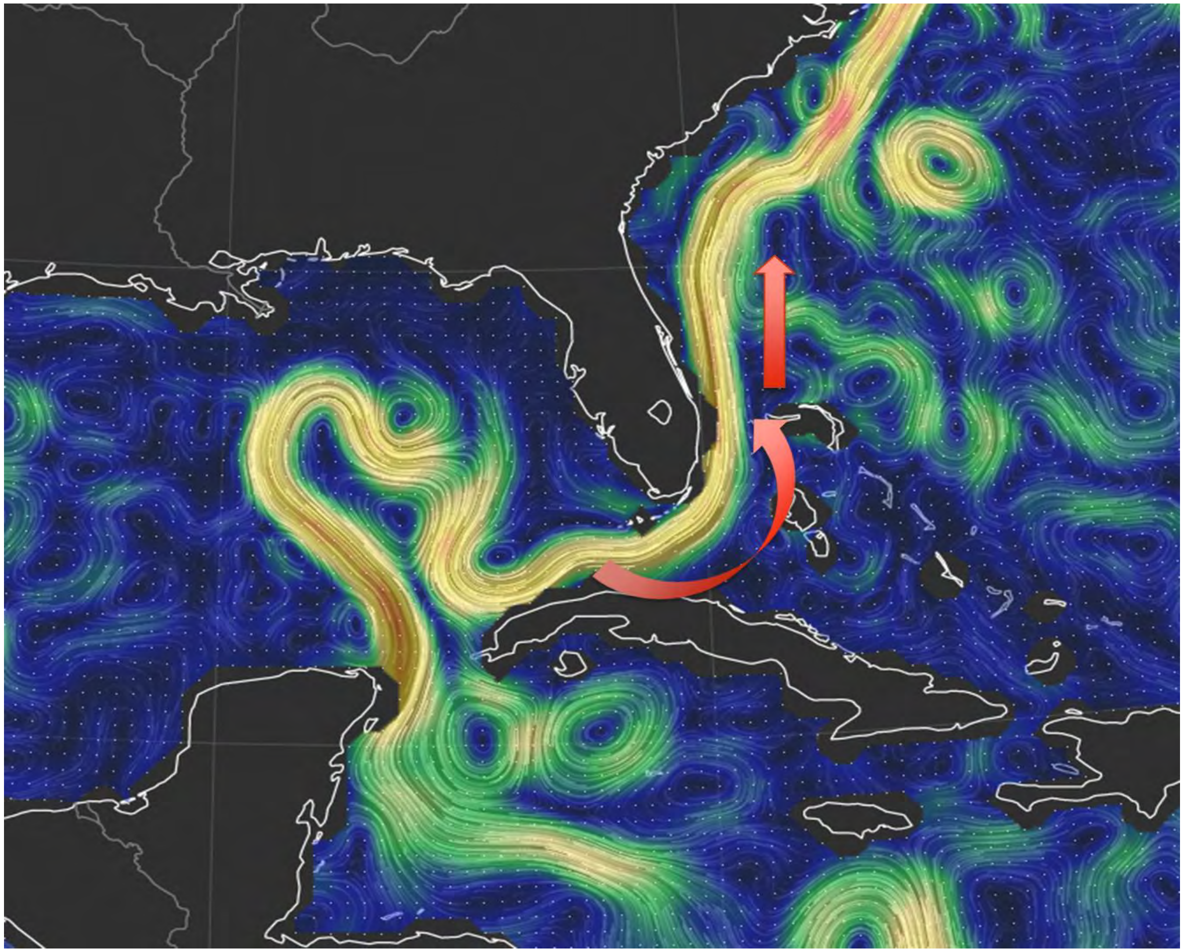

Figure 6. Major ocean currents around Florida indicates Northward travel from the Florida Keys towards Miami and further North

(Source: OSCAR / Earth & Space Research, https://earth.nullschool.net/#current/ocean/surface/currents/grid=on/orthographic=-86.26,27.03,3000)

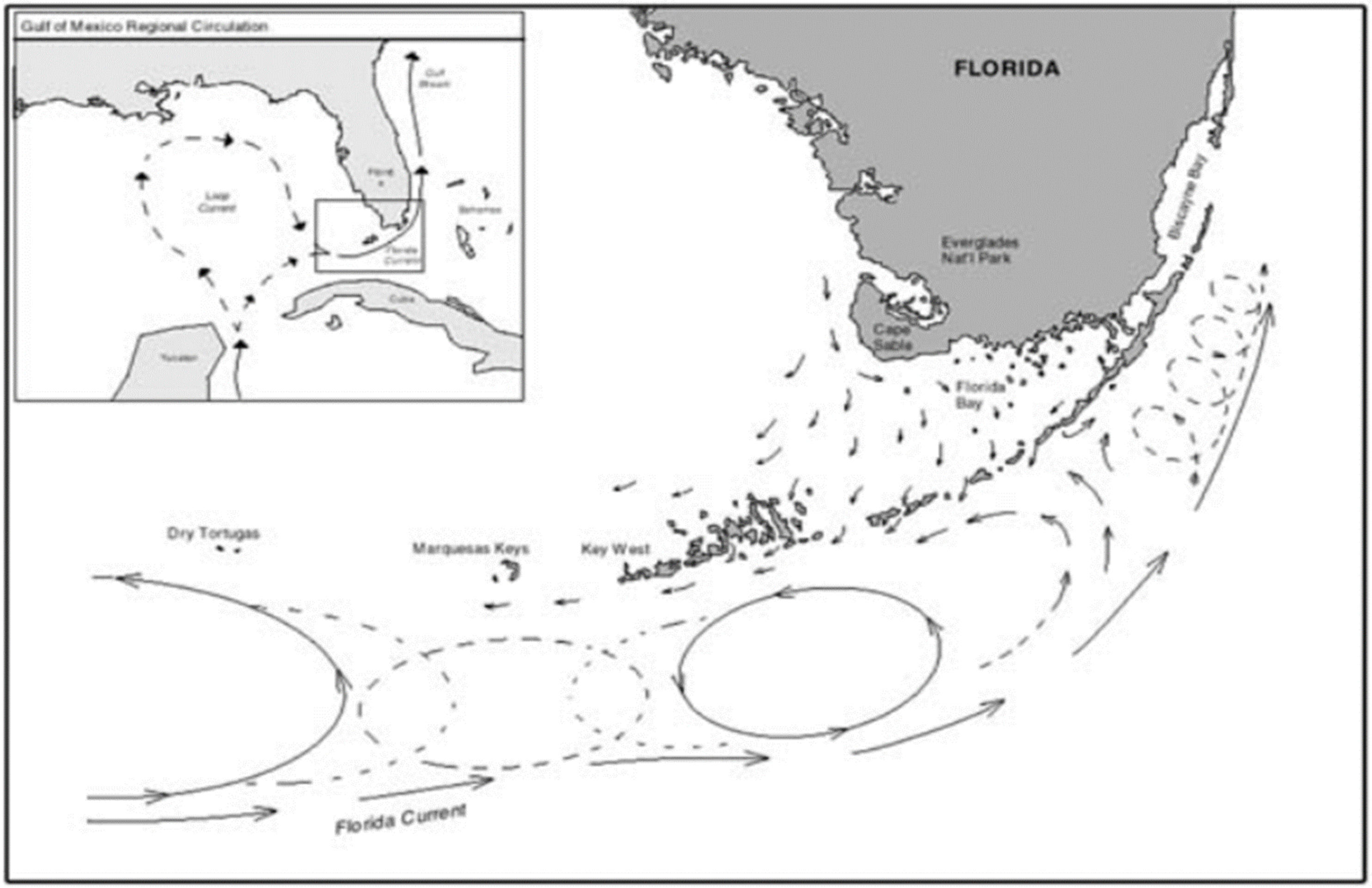

Figure 7. Water circulation patterns around Key West

Source: National Oceanic and Atmospheric Administration (https://oceanexplorer.noaa.gov/explorations/islands01/background/wind/media/fl_currents.html)

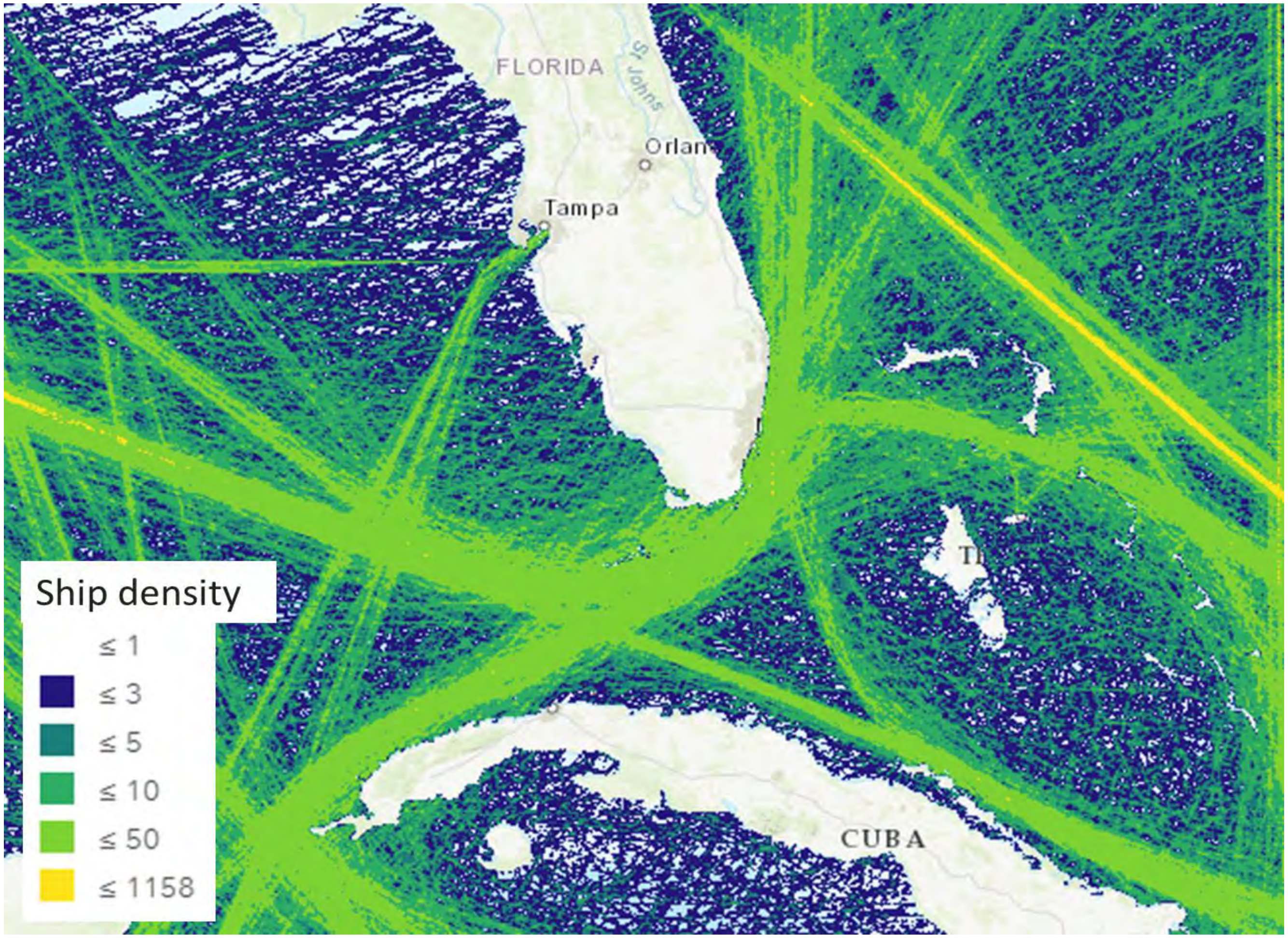

Figure 8. Ship routes and traffic density. Key West area highlighted, falls in high traffic zone

(Source: Global Shipping Routes, 2004. https://www.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=f5557ba2eb3f493dafe6b8b5bff373e3)

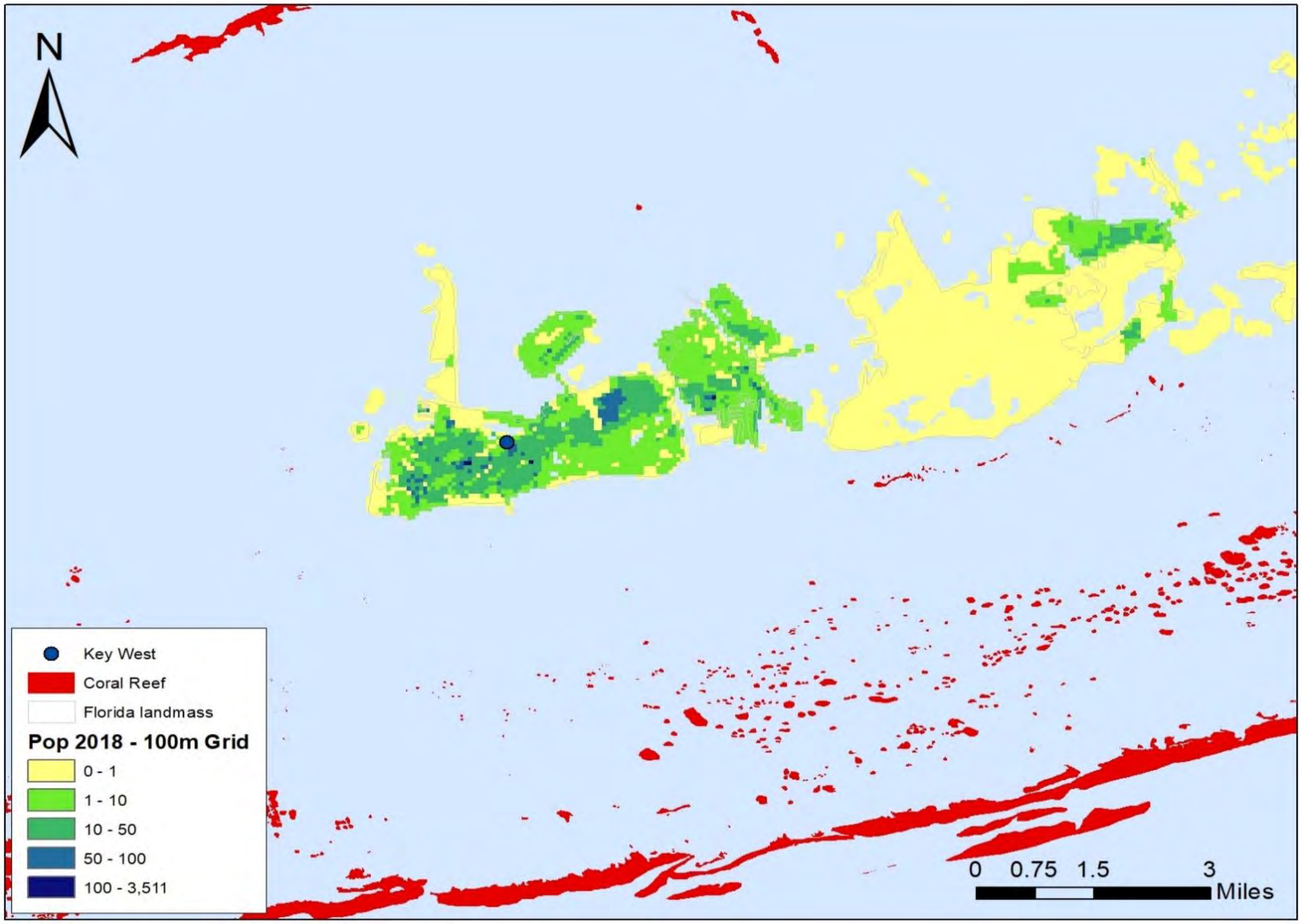

Figure 9. Human population density at 100-meter scale in Key West

(Source: WorldPop database, 2018. https://www.worldpop.org/)

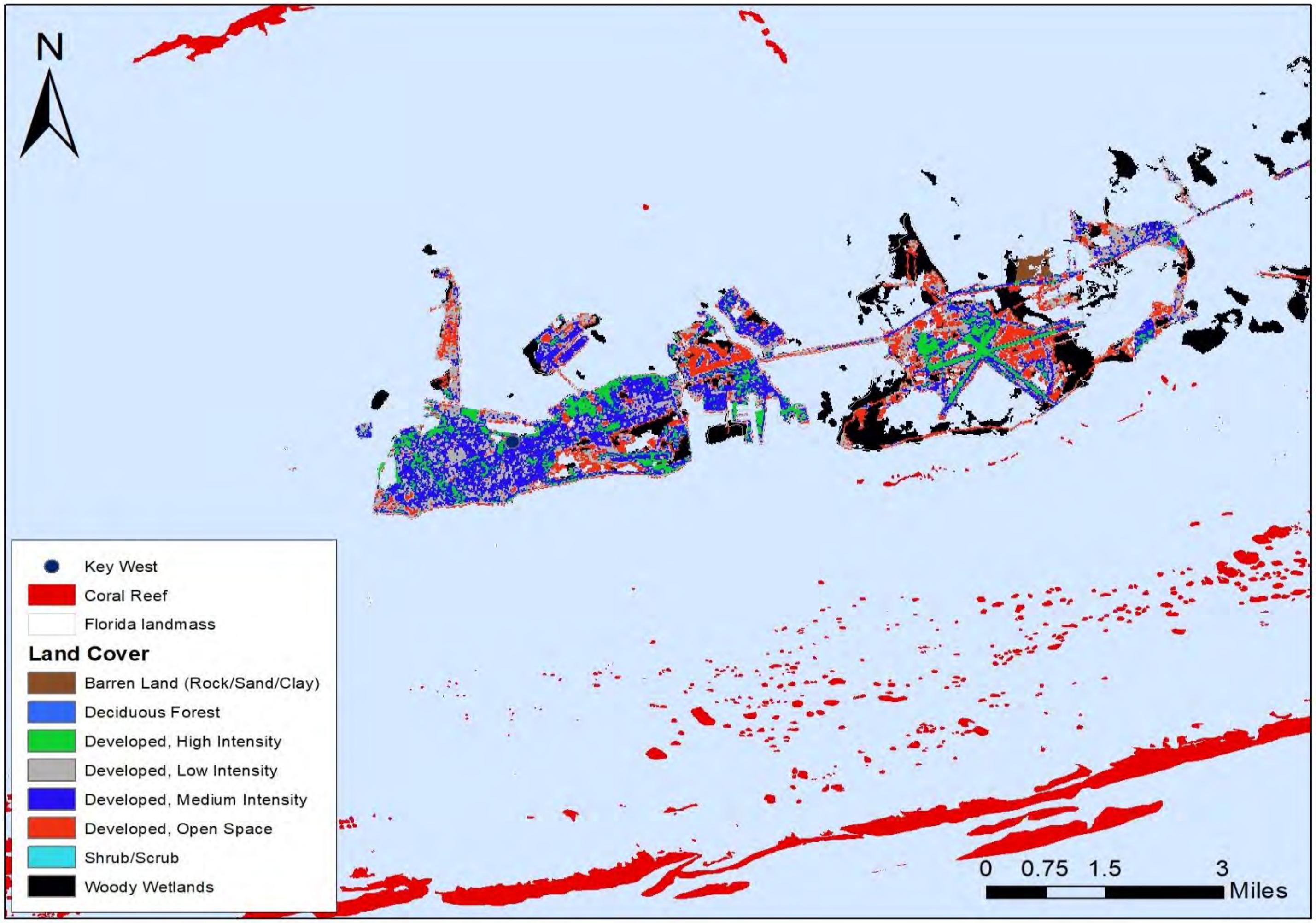

Figure 10. Major land cover classification in Key West (indicates no agriculture)

(Source: The National LandCover Dataset, 2011. https://www.mrlc.gov/data)

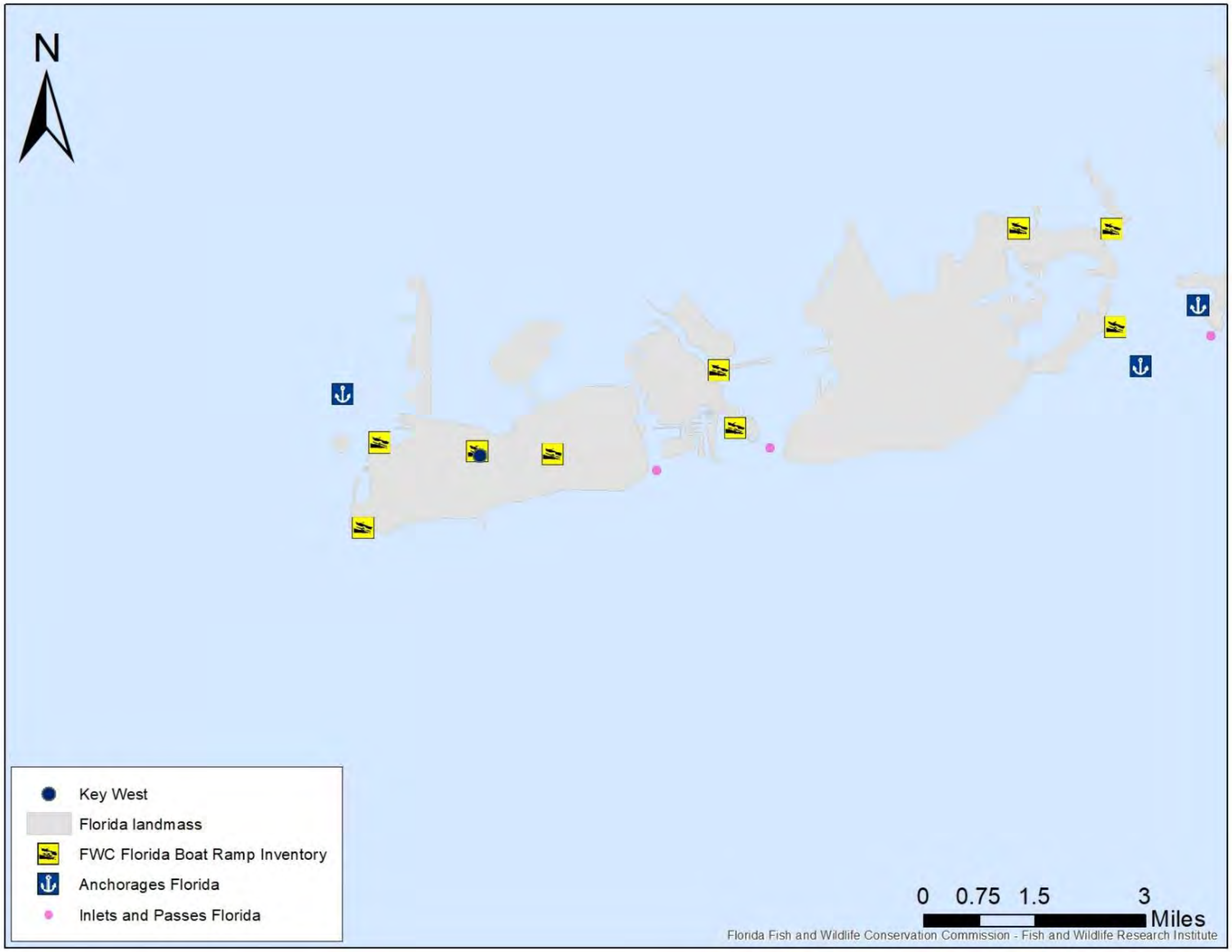

Figure 11. Boat ramps and anchorages in Key West

(Source: Florida Fish and Wildlife Conservation Commission)

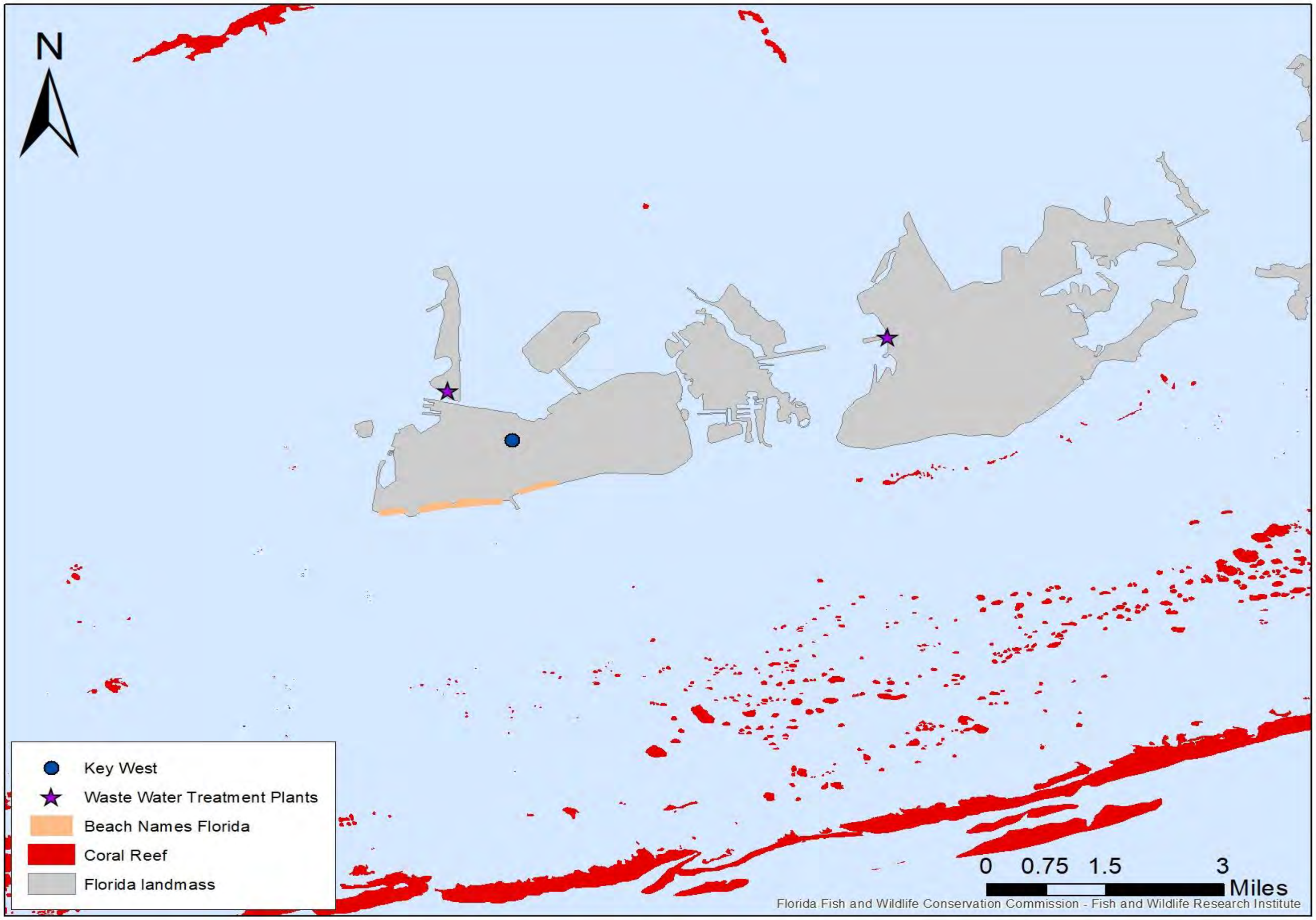

Figure 12. Public beach locations in Key West

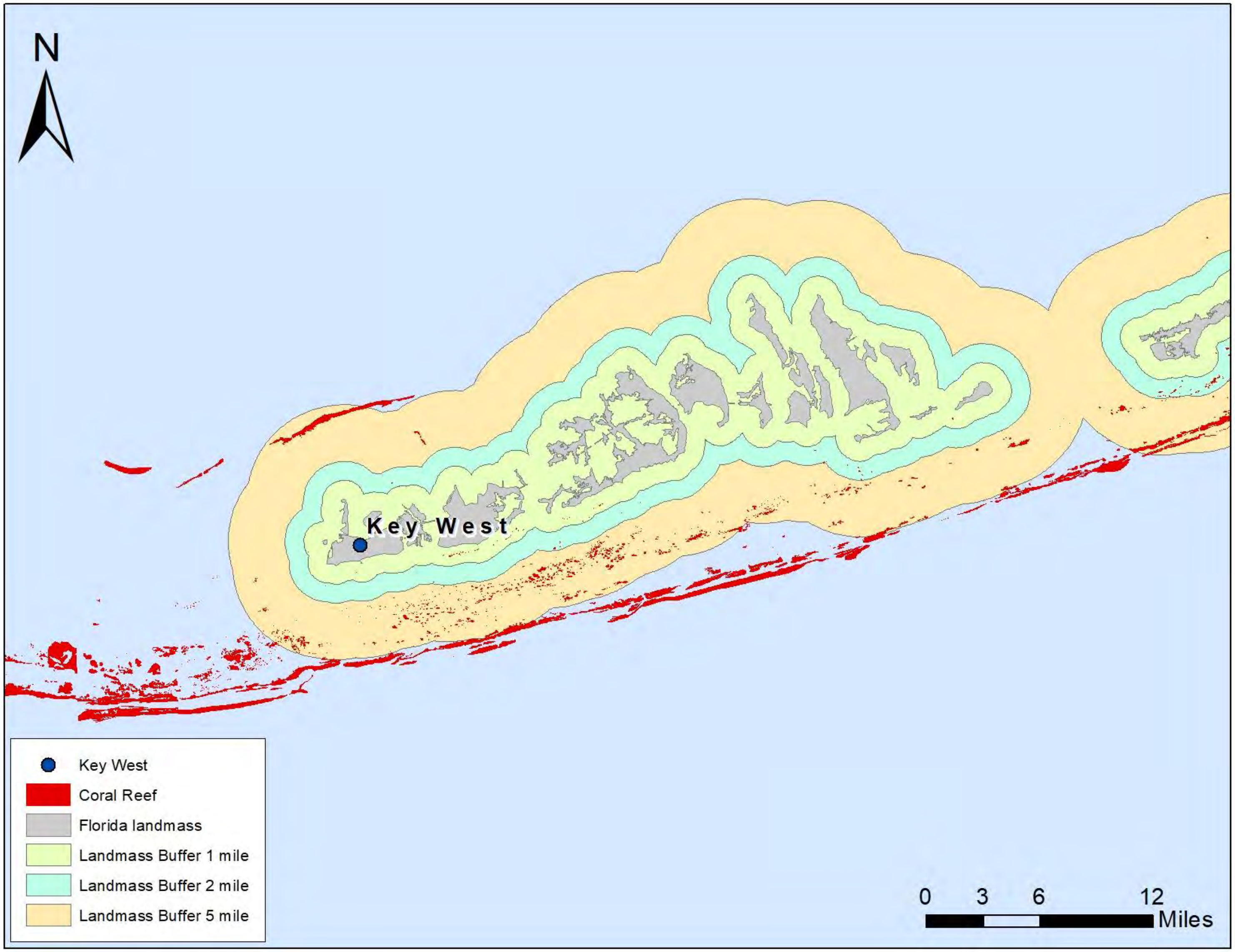

Figure 13. Proximity of coral reefs to landmass around Key West

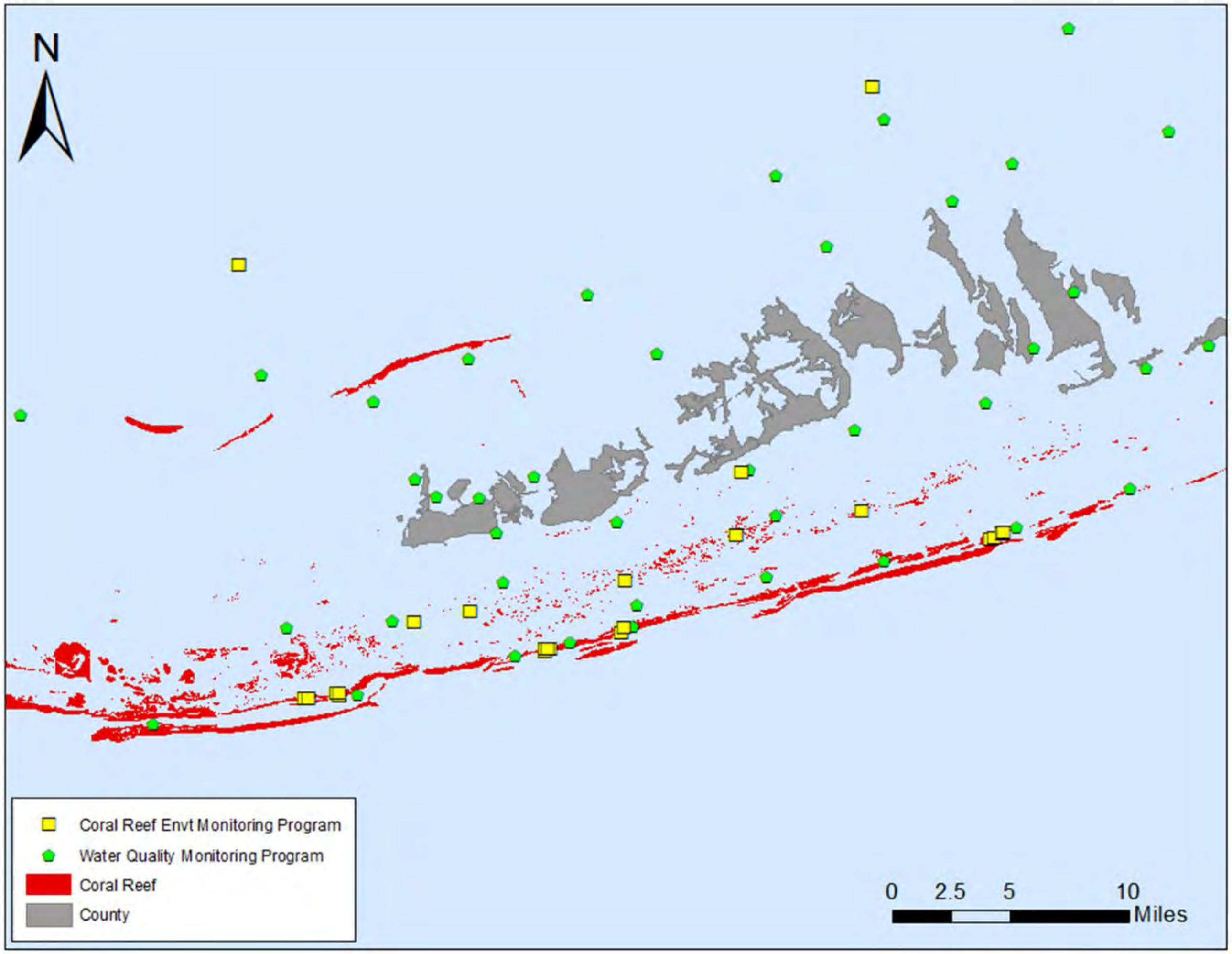

Figure 14. Coral reef health and water quality monitoring locations around Key West

(Source: Coral Reef Environmental Monitoring Program. http://ocean.floridamarine.org/FKNMS_WQPP/gisData.htm, The Water Quality Monitoring Project, Florida International University. http://serc.fiu.edu/wqmnetwork/FKNMS-CD/DataDL.htm)

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