Effects of Land-Based Nutrient Pollution on Coral Reefs: Lessons from the Florida Keys

BRIAN L. LAPOINTE, REX E. BAUMBERGER, SCOTT W. HURLEY, and BRADLEY J. BEDFORD
Harbor Branch Oceanographic Institute at Florida Atlantic University, Center for Marine Ecosystem Health, 5600 U.S. 1 North, Ft. Pierce, Florida 34946 USA

ABSTRACT

The Florida Reef Tract is the third largest barrier-bank reef in the world and has provided considerable ecological services to the local economy of the Florida Keys through commercial and sport fishing as well as tourism. Coral reefs are adapted to oligotrophic conditions and low level nutrient enrichment from anthropogenic sources can lead to eutrophication and loss of these vital resources. Long-term water quality monitoring of dissolved inorganic nitrogen, soluble reactive phosphorus, and chlorophyll *a* at Looe Key reef in the lower Florida Keys, established as a Marine Protected Area in 1983, has shown a doubling of these variables between 1984 and 1998. The most dramatic nutrient enrichment occurred between 1991 and 1995 when water managers increased flows of nitrogen-rich agricultural runoff from the Everglades into the Florida Bay/Florida Keys region. The long-term nutrient enrichment correlated with decreased coral cover, increased coral disease, and increased cover of algae, bioeroding sponges, soft corals, and other opportunistic biota. Comparisons among fish censuses in the early 1980s and in 2002 indicate that the relative abundances of snapper, grouper, and grunt assemblages decreased by 75 % at Looe Key, whereas the herbivorous fish assemblage doubled in relative abundance. Measurement of stable nitrogen isotopes in macroalgae provide a useful means of quantifying the relative importance of various nitrogen sources, such as natural nitrogen fixation, wastewater, fertilizers, and atmospheric deposition. These data demonstrate the sensitivity of coral reefs to nutrient enrichment and the importance of water quality management to the survival of coral reefs, associated fisheries and ecological services.

KEY WORDS: Eutrophication, nitrogen, phosphorus, coral reef, macroalgae, fishes

Efectos de la Contaminación Nutriente con Base en Tierra en los Arrecifes los Cayes de la Florida

Los arrecifes de los cayos de la Florida son la tercera barrera arrecifal mas grande del mundo y ha proporcionado considerables servicios ecológicos a la economía local de los callos de la Florida a través de la pesca comercial y deportiva así como el turismo. Los arrecifes coralinos se adaptan a las condiciones oligotróficas y el enriquecimiento nutriente bajo de fuentes antropogénicas puede llevar a la eutroficación y a la pérdida de estos recursos vitales. Monitoreos a largo plazo de la calidad del agua del nitrógeno inorgánico disuelto, del fósforo reactivo soluble, y de la clorofila a en el arrecife Looe Key en los cayos de la Florida, fueron establecidas como área protegida marina en 1983, y estas variables se han duplicado entre 1984 y 1998. El enriquecimiento nutriente más dramático ocurrió entre 1991 y 1995 cuando los encargados del agua aumentaron flujos de la salida de agua rica en nitrógeno de la zona agrícola de los Everglades hacia la bahía de la Florida/los cayos de la Florida. El enriquecimiento nutriente a largo plazo correlacionado con la disminución de la cubierta coralina, aumento la enfermedad coralina creciente, y la cantidad de algas, bioerosionando las esponjas y los corales suaves, y de la otra biota oportunista. Las comparaciones entre censos de peces al principio de los años 80 y en 2002 indican que los pargos, meros y roncadores han disminuido por el 75% en Looe, Key mientras que la abundancia relativa de los peces herbívoros se duplico en ese periodo. La medida de los isótopos estables del nitrógeno en macroalgae proporciona medios útiles de cuantificar la importancia relativa de las varias fuentes del nitrógeno, tales como fijación de nitrógeno natural, aguas residuales, fertilizantes, y deposición atmosférica. Estos datos demuestran la sensibilidad de los arrecifes coralinos al enriquecimiento debido a los nutrientes y la importancia del manejo de la calidad del agua para la supervivencia de los arrecifes coralinos, de las pesquerías asociados a estos y de los servicios ecológicos.

PALABRAS CLAVES: Eutroficación, nitrógeno, fósforo, coral, macroalgae

Effet de la Pollution sur lest Récifs Coralliens par des Nitriments D'orogine Terrestre: Leçons à Tirer à Partir des Cayes de Floride

Les récifs de Floride constituent le troisième système de barrières et de bancs récifaux du monde et ont fourni des ressources écologiques considérables à l'économie des Cayes de Floride, à travers la pêche sportive et commerciale, ainsi que le tourisme. Les récifs coralliens sont adaptés à des eaux oligotrophiques et de faibles niveaux de nutriments d'origine anthropique peuvent les conduire à l'eutrophisation et à la perte de leurs ressources vitales. Un suivi à long terme de la qualité des eaux concernant l'azote minéral, le phosphore soluble réactif et la chlorophylle-a, sur le récif de Looe Key (devenu une aire marine protégée en 1983) dans les Cayes de Floride du sud, a montré un doublement de la valeur de ces variables de 1984 à 1998. L'enrichissement en nutriments le plus remarquable est intervenu entre 1991 et 1995, lorsque les gestionnaires des eaux accrurent les apports à la mer d'eaux douces agricoles enrichies en azote originaires des Everglades, dans la région de la baie de Floride et des Cayes. L'enrichissement à long terme des eaux en nutriments a été corrélée avec la décroissance de la couverture en coraux des récifs, un accroissement de leur couverture en algues, d'éponges perforantes, de coraux mous et d'autres organismes opportunistes. La comparaison entre les recensements de poissons effectués au début des années 80 et en 2002 montre que les groupes de lutjans, mérous et haemulons ont décru de l'ordre de 75% à Looe Key, alors que l'abondance relative des peuplements de poissons herbivores a doublé sur la même période. L'analyse des isotopes stables de l'azote dans les macro-algues est un moyen efficace pour quantifier l'importance relative des différentes sources d'azote, comme la fixation de l'azote naturel, celui provenant des eaux usées, des engrais et des dépôts atmosphériques. Les données obtenues démontrent la sensibilité des récifs à l'enrichissement en nutriments et l'importance d'une bonne gestion de la qualité de l'eau pour la survie des récifs, des pêcheries associées et des ressources économiques basées sur l'écologie.

MOTS CLÉS: Eutrophisation, azote, phosphore

INTRODUCTION

Increasing sewage discharges from development in the Florida Keys and stormwater runoff from agricultural areas of South Florida have increased nutrient concentrations in Florida Bay and the Florida Keys over the past two decades (Lapointe *et al*. 2002, Lapointe *et al*. 2004, Brand 2002). In the early 1980s, water managers increased flows of nitrogen-rich freshwater from agricultural areas of the northern Everglades to the Florida Bay/Florida Keys region (Lapointe *et al*. 2002, Brand 2002). Following these increased nutrient loads, over 100,000 acres of *Thalassia testudinum*, turtle grass, died off in Florida Bay in 1987 while occurrences of phytoplankton and macroalgal blooms increased. The turtle grass die-off was initially ascribed to hypersalinity (Zieman *et al*. 1989, 1999), a slime mold (Durako and Kuss 1994), and losses of large herbivores due to historical overfishing (Jackson 2001), with little attention given to the impacts of nutrients and other water quality stressors until much later (Boesch *et al*. 2001, Rudnick *et al*. 2005).

There is now considerable evidence that declining water quality and eutrophication were factors in the *Thalassia testudinum* die-off in Florida Bay. Historical records of salinity in Florida Bay clearly indicate that 1987 did not have significantly higher salinity (46.6 psu) than the highest on record (70 psu); average salinity maxima were often 40 - 50 psu over the past 45 years (Brand 2002). The effects of nutrient (especially nitrogen) enrichment of Florida Bay from Everglades runoff were evident when flows from both Shark River Slough and Taylor Slough were again increased significantly between 1991 and 1995. Increases in chlorophyll *a* concentrations in the western and central regions of Florida Bay have been linked to nitrogen rich water entering the bay (Fourqurean *et al*. 1993), causing blooms of phytoplankton and macroalgae (Lapointe et al. 2002; Brand 2002) as well as coral die-off in southern Florida Bay (Lapointe *et al*. 2007b) and widespread increase in coral diseases (Porter *et al*. 2002). The hypersalinity model did not consider the cumulative buildup of land-based nutrients and organic matter that contributed to light attenuation in seagrass beds of Florida Bay (Gunderson and Walker 2002) or hypoxia/anoxia in downstream waters of the Florida Keys National Marine Sanctuary, FKNMS, (Lapointe and Matzie 1996). Sulfide toxicity became a factor in the seagrass decline as a result of eutrophication (Carlson *et al*. 1994, Lapointe and Barile 2004). These conditions were from light attenuation as a result of increased turbidity, phytoplankton, epiphytes, and macroalgae (Lapointe *et al*. 2002, Brand 2002), as well as possible interacting factors of temperature and salinity (Koch *et al*. 2007). Unfortunately, the current Comprehensive Everglades Restoration Plan (CERP) still contains suggestions for decreasing salinity with increased freshwater flows (Lee *et al*. 2006) without consideration of the impacts of associated nutrient loads (Rudnick *et al*. 2005).

The interaction between eutrophication of Florida Bay and downstream coral reefs of the Florida Keys has been investigated through long-term monitoring at Looe Key. Looe Key is a spur-and-groove barrier-bank reef 8.5 km^2 in area, located 6.4 km south of Big Pine Key in the lower Florida Keys (NOAA 1983) and subject to nutrient advection from Florida Bay and the Gulf of Mexico. The reef has long been a prime dive destination, and has been studied since 1978 for its ecological significance. It became a "no-take-zone" marine protected area (MPA) in 1984 (LKNMS) and was recently designated a sanctuary preservation area (SPA) of the FKNMS. As a result of human activities on its upland watersheds, Looe Key has experienced significant nutrient enrichment and eutrophication (Lapointe *et al*. 2002). Twenty-five years of nutrient monitoring at Looe Key have shown significant increases in dissolved inorganic nitrogen (DIN), soluble reactive phosphorous (SRP), and chlorophyll *a* (Lapointe *et al*. 2007a). Stable nitrogen isotope data indicate that land-based nitrogen enrichment from both sewage in the Florida Keys as well as agricultural runoff from Everglades runoff has supported algal blooms at Looe Key (Lapointe *et al*. 2004).

Coral reefs are sensitive to increases in nutrient concentrations and turbidity, which can worsen coral disease outbreaks (Voss and Richardson 2006), decrease coral growth, and enhance bioerosion (Fabricius *et al*. 2005). *Acropora palmata*, Elkhorn Coral, populations that historically dominated the shallow fore reef at Looe Key have decreased by > 93% (Miller *et al*. 2002), and live coral cover in the Florida Keys averaged below 6.4% by 1999 (Porter *et al* 2002). This loss of coral cover has resulted from coral diseases (Porter and Meyer 1992) and expansion of non-toxic harmful algal blooms (HABs), including macroalgae, algal turf, coralline algae, and cyanobacteria. The water clarity in the Florida Keys has also diminished from increasing eutrophication and urbanization, placing additional stresses on corals from light attenuation (Yentsch *et al*. 2002). The increased reproduction and growth of phytoplankton and benthic algae can overwhelm grazing controls by fishes and invertebrates, and a trophic cascade may reduce the abundance of these grazers, exacerbating the situation.

One factor widely cited as the cause for macroalgal blooms in the Caribbean region is the loss of *Diadema antillarum* (Hughes *et al*. 1985), which suffered a mass mortality in 1984. The die-off of *D. antillarum*, the longspined sea urchin that occurred throughout the Caribbean prior to 1984, was a result of an unknown pathogen that decimated populations (Lessios 1988). Although macroalgae on historically overfished Caribbean reefs devoid of herbivorous fishes were found to respond immediately with rapid growth upon release from grazing pressure (Liddell and Ohlhorst 1986), such was not the case at Looe Key, where fish grazing pressure was substantial (Littler *et al*.1986). While a healthy *D. antillarum* population was present before 1984 (A. Hooten Pers. com), coral decline and macroalgal overgrowth occurred many years after the loss of *D. antillarum,* not immediately as was suggested for the entire Western Atlantic by Jackson (2001). Studies have demonstrated the importance of finfish grazers, which in lightly or non-fished areas were more substantial than that of urchins (Randall 1961, Lubchenco and Gaines 1981, Hay 1984). Despite historical accounts of the importance of herbivorous reef fishes (Randall 1965, Hay 1983) and current research supporting this (Mumby *et al*. 2006), *D. antillarum* has often been referred to as a "keystone" herbivore throughout the Caribbean since their decline in 1984.

However, as a protected reef with many large herbivorous fishes (NOAA 1983), benthic algal blooms at Looe Key were kept in check by fishes until nutrient concentrations reached critical nutrient thresholds (Lapointe 1997) in the 1990s following increased agricultural runoff into Florida Bay and the FKNMS. Looe Key did not immediately respond with macroalgal blooms in 1984 following the loss of *D. antillarum*. Nutrient monitoring indicated that Looe Key was below nutrient thresholds during that period (Lapointe *et al*. 2002; Lapointe *et al*. 2007a). Losses of large herbivores such as sea turtles and Manatees, which occurred centuries ago, were not immediately followed by algal blooms, seagrass die-offs, and coral diseases as suggested by some (Jackson 2001). Rather, the expansion of algal blooms and coral disease at Looe Key began when eutrophication on the reef reached the "tipping point" for eutrophication in the 1990s (Lapointe *et al*. 2007a).

Looe Key has been studied for over 30 years with multiple assessments and monitoring methods, providing historical baselines for future comparisons. Habitat surveys of Looe Key date back to the late 1970s (Antonius *et al*. 1978), when the reef supported over 200 species of fish, over 30 species of coral, many octocorals, and invertebrates such as *D. antillarium* and *Strombus gigus,* Queen conch, in the adjacent seagrass beds. The initial assessment indicated very little macroalgae, which was largely confined to back reef habitats. The high-relief and biodiversity at Looe Key has long attracted divers from all over the world. Pre-sanctuary assessment in the mid 1980s indicated a similarly healthy reef community: coral cover of 50% for the forereef (Wheaton and Japp 1988) and algal cover that averaged < 10% (Littler *et al.* 1986). Deep fore reef algae percent cover values were below 5%, and maximum 30% in the back reef, where frondose macroalgae suggested some nutrient enrichment (Littler *et al*. 1986). DIN levels on the fore reef in the 1980s averaged < 0.5 µM (Lapointe *et al*. 2002), below nutrient thresholds for macroalgal blooms (Lapointe 1997, Bell *et al*. 2007). Monitoring of the fishes in 1983 showed similar diversity to the 1978 study, and provided one of the most detailed surveys of fishes on any Florida Keys reef (NOAA 1983)

Because the catastrophic loss of live coral and expansion of HABs occurred at Looe Key, which has not been subjected to fishing pressures for the past 23 years, we hypothesized this "phase-shift" may have altered the reef fish community via alteration or loss of habitat. Eutrophication can have effects on coastal fisheries but its potential impacts have not been considered for coral reef fish communities within the FKNMS.

MATERIALS AND METHODS

Project Rationale

To evaluate the long-term performance of the LKNMS for protecting the fish community, a retrospective was conducted 18 years after the initial fish census conducted in 1983. Stationary fish census methods (Bohnsack and Bannerot 1986) were used to coincide with the original assessment in 1983. Data were collected from five distinct zones: deep fore reef, shallow fore reef, rubble zone, and two ecologically distinct sites in the back reef. These zones were outlined by Littler *et al*. (1986) as areas of distinctive habitats.

Fish Assemblage Data

Collection of quantitative data on the Looe Key reef fish community during the 2002 sampling was randomized for each zone, and consisted of 10-minute stationary counts. Censuses were conducted between 0900 and 1600 hours, to coincide with the historical records (NOAA 1983). SCUBA counts were conducted in all zones; snorkel counts were also employed in two areas of shallow water and low species diversity, rubble zone and backreef. Raw data were recorded on dive slates in situ and entered into a MS Access database upon return to the lab. Metadata consisted of date, time, depth, buoy location, GPS coordinates, site, and count number. Census data recorded consisted of species, number of individuals, and life-history stage of each fish observed. Trophic analysis was conducted according to Bohnsack *et al.* (NOAA 1983).

Benthic Cover Estimating

Benthic data were collected using 25 m video transects, filmed by a diver and scored in the laboratory for percent cover of major benthic groups. Percent cover was calculated for ten individual video frames per transect, every 2.5 m, and scored with a random point count method. Corals and macroalgae were identified to the lowest taxonomic level possible, turf algae, unless morphologically distinct, were considered as "algal turf". The remaining categories were sponge, octocorals, *Palythoa* sp., and sand.

RESULTS

Trophic Distribution

Trophic classification according to Bohnsack (NOAA 1983) is summarized in Table 1, compared with report data from 1983. Herbivorous fishes, e.g. Scaridae and Acanthuridae (Parrotfish and Surgeonfish), increased in relative abundance by 50%. Historical 1983 data for herbivores indicated that they comprised 14% of all individuals and 17% of the 188 species recorded. In this study, herbivores represented 27.7% of all individuals and 28% of all species. A corresponding reduction in relative number of fishes in families such as Haemulidae (Grunts), Lutjanidae (snappers) and Serranidae (Sea Basses and Groupers) was also observed. Nearly 80% fewer macro-invertivore individuals were observed during this study, down from 24% of the total from 1983. These families now represent only 5% of all individuals.

Coral Cover

The losses in some fish species were similarly reflected in reduction in shallow water corals such as *Acropora palmata* and increase by opportunistic, R-selected zoanthid species like *Palythoa caribaeorum*. Of primary importance is the zonation pattern observed between corals and zoanthids. The shallow fore reef (0.5 – 5M) has exhibited a large coral die off since 1983. This once coral-, and fish-rich area is now typified by nearly 30 percent *Palythoa* cover representing a 3-fold expansion based on previous estimates of 11% (Wheaton and Japp 1988) and lower fish species diversity (H^1 2.18 versus 2.39) on the fore reef.

Coral cover averaged < 5% overall. On the deep fore reef, spurs with massive corals such as *Montastrea* and *Diploria* still had 27% cover, but shallow fore reef spurs were only 8% coral. Back reef and rubble zone coral cover was < 1%. Percent cover of *Palythoa caribaeorum* on the shallow fore reef was 24%, and regression analysis showed an inverse relationship with live coral cover ($p < 0.001$, $r^2 = 0.425$). The relationship between fish species richness and coral cover showed a positive (but poor) correlation ($p = 0.007$, $r^2 = 0.167$). The low r-square value was due to eleven of the fish counts occurring in zero percent coral cover locations.

Algal Cover

Benthic algal data from transects showed a dramatic dominance in all locations. On the fore reef, where grazing is highest, algal turf and macroalgae made up nearly 60% of total benthic cover. The highest values were found at back reef locations where macroalgal cover alone averaged accompanied by 35% algal turf.

Table 1. Overall trophic distribution of fishes at Looe Key, July 2002 and June, 1983, (1983 data adapted from Bohnsack *et al*. 1987; NOAA 1983).

Trophic Level	Species 2002	% of Total 2002	Species 1983	% of Total 1983
Herbivore	29	28	17	14
Planktivore	11	41	17	48
Micro-invertivore	15	19	16	10
Macro-invertivore	18	5	29	24
Piscivore	20	5	14	2
Browser	10	2	7	2

DISCUSSION

The decline in coral cover at Looe Key over the past several decades has correlated with decreases in the fish assemblage and parallel increases in nutrient concentrations, macroalgae and algal turf populations. Due to the influx of DIN enriched water from the back reef coming over the reef crest (Neumann and Macintyre 1985), white band and white pox diseases, severe bleaching events and Hurricanes, coral cover has precipitously declined. The trophic shifts observed in the fish assemblage at Looe Key suggest the losses of live coral habitat are having a detrimental impact on the fishes. Despite being protected from fishing prior to the onset of these problems, the fish community at Looe Key has still declined. Similar impacts to the fishes have been observed at other declining reefs in Japan (Sano *et al*. 1984), the Florida Keys (Lirman 1999), Kingston Harbor, Jamaica (Aiken *et al*. In press), and Australia (Feary 2007). If the end results of eutrophication are similar to what has been suggested for overfishing and the loss of invertebrate grazers, it then follows that all these factors should be seriously considered when an area is designated as an MPA.

With over 20 years of protection from fishing, Looe Key would be expected to show some improvement with regards to the fish assemblage, in the absence of other mitigating circumstances. Studies of marine reserves have shown as little as 4 - 6 years of protection can provide significant density increases of large predators and fishery targets (Russ and Alcala 2002). However, the combination of eutrophication and alteration of the habitat through coral loss an macroalgal encroachment has led to continued decline despite protection from fishing. Algal dominance has become reef-wide at LKNMS following increased availability of DIN and SRP. Nutrient enrichment at Looe Key has also affected the algal assemblage on both the back reef and fore reef. The growing standing crop of algae, comprising up to 60% cover on the fore reef and 90 percent in the back reef, supports an expanding herbivorous fish assemblage. Nutrient "indicator species" typically found in enriched environments, were observed invading areas of the back reef. In particular, *Dasycladus* *vermicularis*, typically found in nutrient-enriched mangrove habitats (Littler and Littler 2000), covered the benthos at the back reef site. Similar long-term effects of eutrophication have led to the proliferation of nutrient indicator species in intertidal zones of the Florida Keys over the past fifty years (Smith *et al*. 2007).

The Looe Key story is an example of "classic management", a term previously applied to fisheries managers (Rosenberg 2003) who failed to protect fish stocks from depletion. We apply this term for Looe Key, where resource managers overlooked existing data and science pointing to an incipient nutrient enrichment problem, and promoted policies that increased nitrogen loading from the agricultural watersheds of the Everglades. This failure was recognized by the Pew Oceans Commission in their May 2003 report that listed the Florida Bay/Florida Keys region as a dead zone, indicating the relation of land-based nutrient pollution to hypoxia and anoxia (Lapointe and Matzie 1996). Resource managers and advisors are beginning to recognize the importance of protecting marine reserves not only from fishing, but also from pollution and other land-based development impacts (Murray *et al*. 1999; Lubchenco *et al*. 2003). Simply designating a reef as a "no take" zone does not ensure protection for resident reef dwellers, without additional steps to minimize environmental impacts from land-based sources. The Great Barrier Reef Marine Park Authority (GBRMPA) has recognized the importance of nitrogen as a stressor of corals in the GBR Lagoon, (Bell 1992, Fabricius 2005) and has taken steps to decrease nitrogen loading from river discharges. Clearly, the "connectivity" of MPAs must be evaluated, not just for larval supply and recruitment, but also stress from land-based sources of pollution. Although arguments for the primacy of overfishing in the decline of coastal ecosystems continue (Jackson *et al*. 2001), worldwide opinions are that other factors, including nutrient enrichment and eutrophication, are supporting the proliferation of HABs and the decline of coral reefs (NRC 2000, MEA 2005).

The eutrophication at Looe Key will continue to worsen if steps are not taken to moderate and control nutrient inputs as part of the management plan for the FKNMS. The issues associated with eutrophication and coral reef degradation will become more pressing as population growth continues in South Florida. In particular, the CERP includes policies similar to those that failed in the 1990s (Lee *et al*. 2006) with regard to increasing nitrogen loads to the Florida Bay/ Florida Keys region. New approaches to remove excess nutrients from water in the upland watersheds before discharge into coastal waters must be undertaken to protect downstream seagrass meadows and coral reefs. The U.S. EPA, under the Clean Water Act, has recently determined nutrient water quality criteria are necessary in Florida, and expects Florida to adopt numeric nutrient criteria. The Florida DEP was notified of this mandate January 14, 2009 and the EPA expects these changes within 12 - 24 months, which would be incorporated into rivers, lakes, estuaries, and coastal ocean management sectors. However, the current focus on global warming may distract from the importance of the more immediate problem of land-based sources of pollution, which has a far better prognosis for successful management than decreasing or reversing the world-wide warming trend.

LITERATURE CITED

Aiken, K., A.R. Pal, and G. Perry. [2009]. Nursery areas in Kingston Harbor-do they still exist? Proceedings of the 61st Gulf and Caribbean Fisheries Institute. November 2008. Gosier, Guadeloupe, FWI.

Antonius, A., A.H. Weiner, J.C. Halas, and E. Davidson. 1978. Looe Key Reef resource inventory. Florida Reef Foundation report to NOAA. 74 pp.

Baumberger, R.E. 2002. Bottom-up control of the top-down trophic assemblages at Looe Key, Fl. Harbor Branch Oceanographic Institute Summer Intern Report. Ft. Pierce, FL. 38 pp.

Bell, P.R.F. 1992. Eutrophication and coral reefs: some examples in the Great Barrier Reef lagoon. *Water Research* **26**:553-568.

Bell, P.R.F., B.E. Lapointe, and I. Elmetri. 2007. Reevaluation of ENCORE: support for the eutrophication threshold model for coral reefs. *Ambio* **36**(5):416-424.

Boesch, D., *et al*. 2001. Factors in the decline of coastal ecosystems. *Science* **293**(5535):1589-1591.

Bohnsack, J.A., and S.P. Bannerot. 1986. A stationary visual census technique for quantitatively assessing community structure of coral reef fishes. Department of Commerce. NOAA Technical Reports NMFS 41. 15 pp.

Brand, L.E. 2002. The transport of terrestrial nutrients to south Florida coastal waters. Pages 353-406 in: J.W Porter and K.G. Porter (Eds.) *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook.* CRC Press, Boca Raton, Florida USA.

Carlson, P.R., L.A. Yarbro, and T.R. Barber. 1994. Relationship of sediment sulfide to mortality of *Thalassia testudinum* in Florida Bay. *Bulletin of Marine Science* **54**:733-746.

Durako, M.J. and K.M. Kuss. 1994. Effects of Labyrinthula infection on the photosynthetic capacity of *Thalassia testudinum*. Symposium on Florida Keys regional ecosystem. *Bulletin of Marine Science* **54** (3):727-732.

Fabricius, K.E. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* **50**:125-146.

Fabricius, K.E., G. De'ath, L. McCook, E. Turak, and D.M.B. Williams. 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. *Marine Pollution Bulletin* **51**:384-398.

Feary, D.A., G.R. Almany, G.P. Jones, and M.I. McCormick. 2007. Coral degradation and the structure of tropical reef fish communities. *Marine Ecology Progress Series* **333**:243-248.

Fourqurean, J.W., R.D. Jones, and J.C. Zieman. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, Fl, USA: inferences from spatial distributions. *Estuarine Coastal and Shelf Science* **36**:295-314.

Gunderson, L.H. and C.J. Walters. 2002. Resilience in wet landscapes of southern Florida. In: L.H. Gunderson and L. Pritchard, Jr. (Eds.) *Resilience and Behavior of Large-scale Systems. Scope 60.* Island Press, Washington, D.C. USA 287 pp.

Hay, M.E. 1984. Patterns of fish and urchin grazing on Caribbean coral reefs: are previous results typical? *Ecology* **65**(2):446-454.

Hay, M.E. 1991. Fish-Seaweed interactions on Coral Reefs. Pages 96-119 in: P.F. Sale (Ed.) *The Ecology of Fishes on Coral Reefs*. Academic Press. San Diego, California USA.

Hughes, T.P., P.D. Keller, J.B.C. Jackson, and M.J. Boyle. 1985. Mass mortality of the echinoid *Diadema antillarum* (Philippi) in Jamaica. *Bulletin of Marine Science* **36**(2):377-384.

Jackson, J.B.C., *et al*. 2001. Historical over fishing and the recent collapse of coastal ecosystems. *Science* **293**:629-638.

Koch, M.S., S. A. Schopmeyer, M. Holmer, C.J. Madden, and C. Kyhn-Hansen. 2007. *Thalassia testudinum* response to the interactive stressors hypersalinity, sulfide and hypoxia. *Aquatic Botany* **87** (2):104-110**.**

Lapointe, B.E., B.J. Bedford, and R.E. Baumberger. 2007a. Looe Key, FL: nutrients and climate change pose threat to coral reefs. Pages 104-105 in: S. Bricker, B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner (Eds.) *Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change*. NOAA Coastal Ocean Program Decision Analysis series No. 26. National Centers for Coastal Ocean Science, Silver Spring, Maryland USA.

Lapointe, B.E., B.J. Bedford, M.M. Littler, and D.S. Littler. 2007b. Shifts in coral overgrowth by sponges and algae. *Coral Reefs* **26**:515.

Lapointe, B.E. and P.J. Barile. 2004. Comment on J. C. Zieman, J.W. Fourqurean, and T. A. Frankovich. 1999. Seagrass die-off in Florida Bay: long term trends in abundance and productivity of turtlegrass, *Thalassia testudinum*. *Estuaries* **22**(2B):460-470. *Estuaries* **27**(1): 157-178.

Lapointe, B.E., P.J. Barile, and W.R. Matzie. 2004. Anthropogenic nutrient enrichment of seagrass and coral reef communities in the Lower Florida Keys: discrimination of local versus regional nitrogen sources. *Journal of Experimental Marine Biology and Ecology* **308**:23–58

Lapointe, B.E., W.R. Matziem and P.J. Barile. 2002. Biotic phase shifts in Florida Bay and fore reef communities of the Florida Keys: linkages with historical freshwater flows and nitrogen loading from everglades runoff. Pages 629-648 in: J.W Porter and K.G. Porter (Eds.) *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook*. CRC Press, Boca Raton, Florida USA.

Lapointe, B.E. and M.W. Clark. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. *Estuaries* **15**:465-476.

Lapointe, B.E. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. *Limnology and Oceanography* **42**(5):1119-1131.

Lapointe, B.E., and W.R. Matzie. 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. *Estuaries and Coasts* **19**(2):422-435.

Lee, T.N., E. Johns, N. Melo, R.H. Smith, P. Ortner, and D. Smith. 2006. On Florida Bay hypersalinity and water exchange. *Bulletin of Marine Science* **79**(2):301-327.

Lessios, H.A. 1988. Mass mortality of *Diadema antillarum* in the Caribbean: what have we learned? *Annual Review of Ecology and Systematics* **19**:371-393.

Liddell, W.D. and S.L. Ohlhorst. 1986. Changes in benthic community structure following the mass mortality of *Diadema* at Jamaica. *Journal of Experimental Marine Biology and Ecology* **95**(3):271-278.

Lirman, D. 1999. Reef fish communities associated with *Acropora palmata*: relationships to benthic attributes. *Bulletin of Marine Science* **65**(1):235-252.

Littler, M.M., and D.S. Littler. 1985. Factors controlling relative dominance of primary producers on biotic reefs. *Proceedings of the 5th International Coral Reef Congress* **4**:35-39.

Littler, M.M., D.S. Littler, and B.E. Lapointe. 1986. Baseline studies of herbivory and eutrophication on dominant reef communities of Looe Key National Marine Sanctuary. NOAA Tech Memo NOS MEMD 1.

Littler, D.S. and M.M. Littler. 2000. *Caribbean Reef Plants*. Offshore Graphics. Washington, D.C. 542 pp.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and human well- being: wetlands and water synthesis. World Resources Institute, Washington, D.C. USA. 80 pp.

Miller. M., A. Bourque, and J. Bohnsack. 2002. An analysis of the loss of acroporid corals at Looe Key, Florida, USA: 1983-2000. *Coral Reefs* **21**(2):179-182.

Mumby, P. J., et al. 2006. Fishing, trophic cascades, and the process of grazing on coral reefs. Science 311: 98-101.

NOAA. 1983. Resource Survey of Looe Key National Marine Sanctuary. J.A. Bohnsack., A.Y. Cantillo, and M.J. Bello (Eds.) 2002. NOAA Technical memorandum NOS NCCOS CCMA 160/NMFS-SEFSC-478. U.S. Department of Commerce-National Oceanic and Atmospheric Administration, Silver Spring, MD., USA. 362 pp.

National Research Council (NRC). 2000. Clean coastal waters: understanding and reducing the effects of nutrient pollution. Ocean Studies Board, Water Science and Technology Board, National Academy Press, Washington, D.C. USA.

Neumann A.C. and I. Macintyre. 1985. Reef response to sea level rise: keep-up, catch-up, or give-up. *Proceedings of the 5th International Coral Reef Symposium* **3**:105-118

Pew Ocean Comission. 2003. America's Living Oceans: Charting a Course for Sea Change. A report to the nation, Recommendations for a New Ocean Policy. May 2003. The Pew Charitable Trusts, Washington, D.C. USA. 166 pp.

Porter, J.W. and O.W. Meier. 1992. Quantification of loss and change in Floridian reef coral populations. *American Zoologist* **32**:625-640.

Porter, J.W., *et al.* 2002. Detection of coral reef change by the Florida Keys Coral Reef Monitoring Project. Pages 749-769 in: J.W. Porter and K.A. Porter (Eds.) *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook.* CRC Press, Boca Raton, Florida USA.

Randall, J.E. 1961. Overgrazing of algae by herbivorous marine fishes. *Ecology* **42**:812.

Randall, J.E. 1965. Grazing effect on sea grasses by herbivorous reef fishes in the West Indies. *Ecology* **46**(3):255-260.

Russ, G.R. and A.C. Alcala. 2003. Marine Reserves: rates and patterns of recovery and decline of predatory fish, 1983-2000. *Ecological Applications* **13**(6):1553-1565.

Rudnick, D.T., P.B. Ortner, J.A. Browder, and S.M. Davis. 2005. A conceptual ecological model of Florida Bay. *Wetlands* **25**(4):870-883.

Sano, M., M. Shimizu, and Y. Nose. 1984. Changes in structure of coral reef fish communities by destruction of hermatypic corals: observational and experimental views. *Pacific Science* **38**(1):51-79.

Smith, T.B., J. Purcell, and J.F. Barimo. 2007. The rocky Intertidal biota of the Florida Keys: fifty-two years of change after Stephenson and Stephenson (1950). *Bulletin of Marine Science* **80**(1):1-19.

Tomasko, D.A., and B.E. Lapointe. 1991. Productivity and biomass of *Thalassia testudinum* as related to water column nutrient availability and epiphyte levels: field observations and experimental studies. *Marine Ecology Progress Series* **75**:9-17.

Voss, J.D. and L.L. Richardson. 2006. Nutrient enrichment enhances black band disease progression in corals. *Coral Reefs* **25**(4):569-576.

Wade, B. 1994. Nutrient levels in Negril wetland and coastal waters: the problem of nutrient enrichment and algal overgrowth in Long Bay. Extended abstracts, Caribbean water and wastewater association conference, Kingston Jamaica, October 3-7, 1994.

Wheaton, J.L., and W.C. Japp. 1988. Corals and other prominent benthic Cnidaria of Looe Key National Marine Sanctuary, Florida. Florida Marine Research Publications No. 43. St. Petersburg, Florida USA.

Yentsch, C.S., C.M. Yentsch, J.J. Cullen, B. Lapointe, D. A. Phinney, and S.W. Yentsch. 2002. Sunlight and water transparency: cornerstones in coral research. *Journal of Experimental Marine Biology Ecology* **268**:171-183.

Zieman, J.C., J.W. Fourqurean, and T.A. Frankovich. 1999. Seagrass Die-off in Florida Bay: Long-term Trends in Abundance and Growth of Turtle Grass, *Thalassia testudinum*. *Estuaries* **22** (2B):460-470.

Zieman, J.C., J.W. Fourqurean, and R.L. Iverson. 1989. Distribution, abundance, and productivity of seagrasses and macroalgae in Florida Bay. *Bulletin of Marine Science* **44**:292-311.