The Reef Tract of Continental Southeast Florida (Miami-Dade, Broward and Palm Beach Counties, USA)

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The Reef Tract of Continental Southeast Florida (Miami-Dade, Broward and Palm Beach Counties, USA)

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5.1 Introduction

Although South Florida coral reefs are frequently considered to be confined to the Florida Keys, a complex of relict early Holocene shelf-edge and mid-shelf reefs as well as limestone ridges extends along the continental coast of Southeast Florida (Fig. 5.1) from offshore south Miami (N25°34′) northward to offshore West Palm Beach (N26°43′). This extends the distance spanned overall by reefs in SE Florida by 125 km (Fig. 5.2). The nomenclature proposed by Moyer et al. (2003) and Banks et al. (2007) identifying these structures as ridge complex and inner, middle, and outer reef will be used herein. The reefs are arranged linearly and parallel to the trend of the shoreline. They are separated by sandy sedimentary deposits of varying thicknesses that overly erosional hardground surfaces (Duane and Meisburger 1969a, b; Raymond 1972; Shinn et al. 1977; Banks et al. 2007). The reefs themselves are presently not framebuilding but are colonized by a rich tropical fauna otherwise characteristic of the West Atlantic/Caribbean reef systems.

The continental shelf along the SE Florida coast is narrow and bathed by the relatively warm waters of the Florida Current, a branch of the Gulf Stream flowing northward between SE Florida and the Bahamas banks. Although SE Florida is located at the convergence of the subtropical and temperate climate zones (Chen and Gerber 1990), the influence of the Florida Current and the absence of any major rivers in the early and mid Holocene provided conditions suitable for reef building and, after the demise of framebuilding, the maintenance of extensive coral reef associated communities.

Rohmann et al. (2005) estimated that 30,801 km^2 of inshore areas are situated in less than 18.3 m depth around South Florida and could potentially support shallow-water coral reef ecosystems. An area of 19,653 km^2 remains outside the Florida Keys and Dry Tortugas and is discussed here with regard to SE Florida and in Chapter 4 by Hine et al. with regard to the West Florida shelf. In comparison, estimates for other areas capable of providing habitat for reefs and reef-associated fauna in the United States are 108 km^2 in Guam, 1,231 km^2 in the Main Hawaiian Islands and 2,302 km^2 in Puerto Rico.

Goldberg (1973) provided the first description of the reef communities north of the Florida Keys based on studies of the reef community offshore Boca Raton, Florida (N26°20.8′). This work was limited to a small area in the northern part of the reef complex. Infrequent and regionally isolated reef community monitoring carried out in association with dredging for beach nourishment projects followed (Courtney et al. 1972, 1975, 1980; Continental Shelf Associates 1980, 1984; Goldberg 1981; Blair and Flynn 1989; Dodge et al. 1995). These projects, however, did not provide a continuous record of biotic dynamics nor were the study sites chosen to describe regional patterns of reef community structure.

Beginning in 1997, the Broward County Environmental Protection Department instituted a long term status and trends monitoring program at 18 fixed sites distributed across the shelf from N26°00.26′ to N26°20.80′ latitudes (Gilliam et al.

B.M. Riegl and R.E. Dodge (eds.), *Coral Reefs of the USA*,

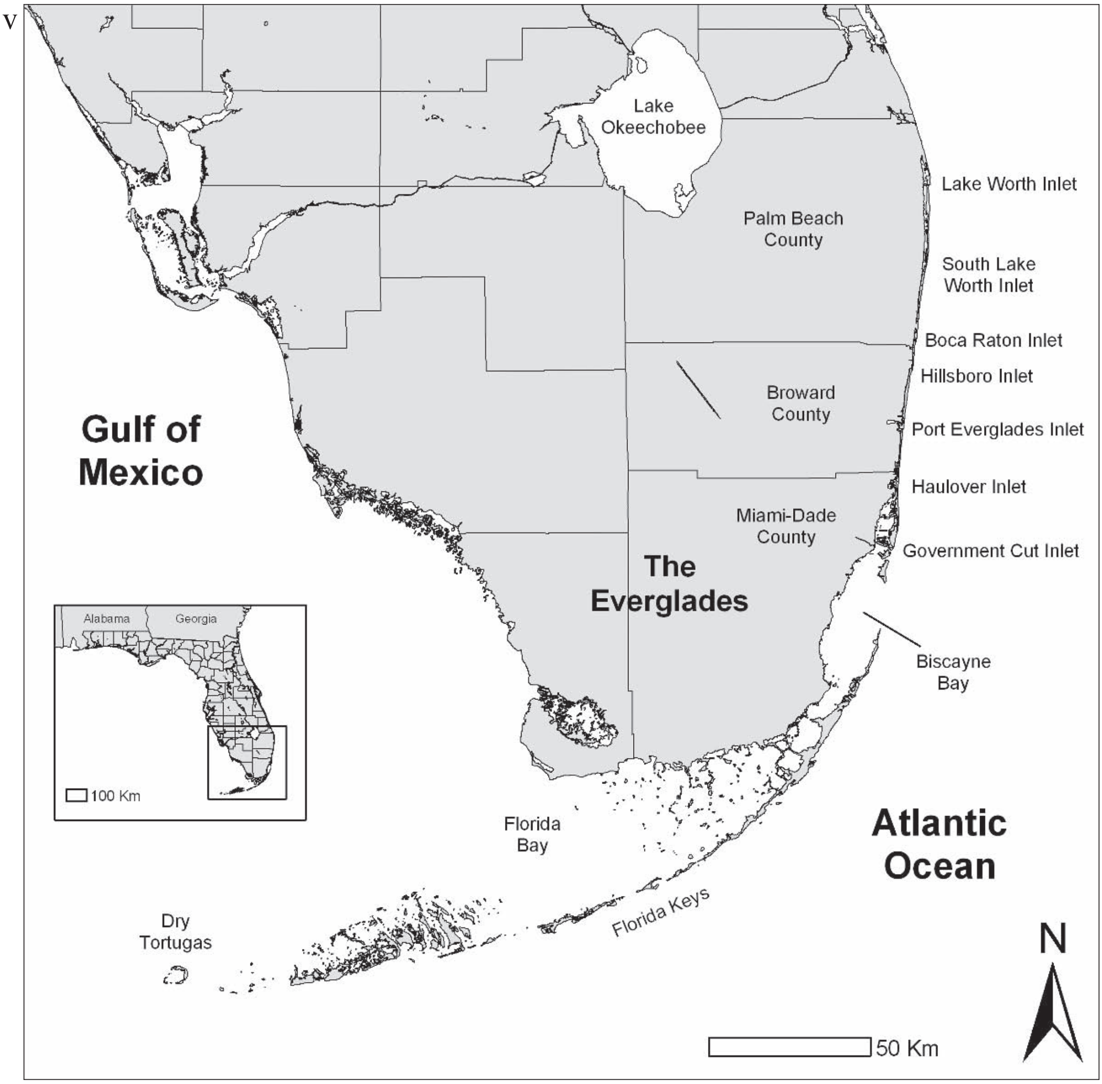

FIG. 5.1. Location map of Southeast Florida with key geographic features

2007). Coral cover, as well as octocoral and sponge density, have been measured annually using a single, fixed, 30 m^2 belt-transect (1.5 × 20 m) at each site. In 2004 the program was expanded to 25 sites.

In 2003, the Florida Fish and Wildlife Conservation Commission extended the Florida Keys Coral Reef Evaluation and Monitoring Program (CREMP) into the SE Florida region (Southeast Florida Coral Reef Evaluation and Monitoring Program [SECREMP]) by installing 10 permanent stations. Relative bottom cover is determined annually from video transects at each station (total transect area at each station = 528 m^2). In addition, stony coral species inventory, clionid sponge cover (at 66 m^2 transect), *Diadema antillarum* abundance, and stony coral condition are measured. This activity covers the area from Palm Beach County (N26°42.63′) to Miami-Dade County (N25°50.53′) with 3 sites in each county and one additional site in Broward County at a site of unusually high *Acropora cervicornis* cover (Gilliam 2007).

An extensive investigation of spatial patterns in community structure among reef tracts was carried out in Broward County by Moyer et al.

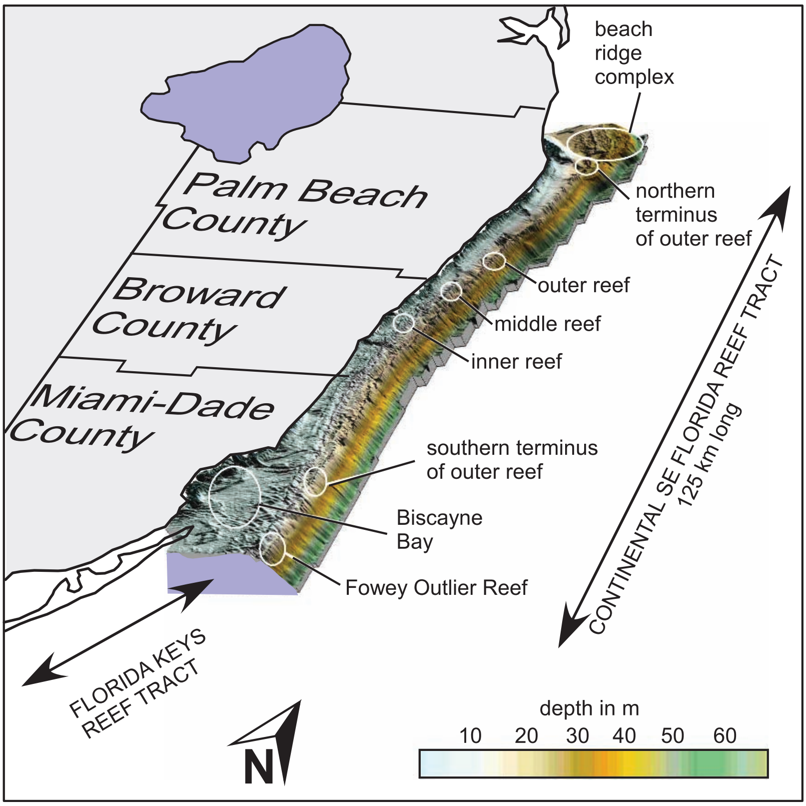

FIG. 5.2. The continental Southeast Florida reef tract extends from Biscayne Bay in Miami-Dade County (N25°34′) northward to West Palm Beach in northern Palm Beach County (N26°43′). It is composed of a complex of limestone ridges and shelf-edge and mid-shelf reefs

(2003) who measured relative bottom cover using six replicate, 50 m point intercept transects at 31 sites within three cross-shelf corridors (Broward County north, central and south), each containing all three reef tracts. While limited to the central part of SE Florida, the study was extensive enough to identify some latitudinal and cross-shelf patterns. Foster et al. (2006) expanded this study to include community patterns within reef tracts at the three corridors, the effects of sampling scale on the analysis of community structure, and the influence of certain environmental factors on community structure. Their measurements were based on 32 photoquadrats (0.75 × 0.50 m each), replicated six times (72 m^2) at each of 99 sites (33 in each corridor; north, central, south).

A SE Florida regional reef habitat mapping project was begun in 2004 by the National Coral Reef Institute (NCRI) for the Florida Fish and Wildlife Research Institute (FWCC). Data from laser airborne depth sounder (LADS) bathymetry, multi- and single-beam bathymetry, acoustic seafloor discrimination, ecological assessments, and ground-truthing were integrated into maps created with Geographic Information System (GIS) (Walker et al. 2008). Habitat categories were based on the NOAA biogeography program. Field verification of habitat types was used for quality assurance. Maps were completed for Broward County and Palm Beach and Miami-Dade counties are planned or underway (NCRI 2004).

5.2 Regional Setting

The reef tracts are believed to be founded on shore-parallel lithified Late Pleistocene beach ridges (Shinn et al. 1977; Banks et al. 2007). These ridges are likely an offshore extension of the shore-parallel ridge complex (Fig. 5.2).

The continental shelf of SE Florida is narrow, approximately 3 km wide offshore Palm Beach County and 4 km wide offshore Miami-Dade County. Bottom slope steepens at approximately 80 m depth where the East Florida Escarpment begins (Fig. 5.3). The East Florida Escarpment terminates at a depth of 200–375 m at the Miami Terrace, a drowned early to middle Tertiary carbonate platform (Mullins and Neumann 1979). The Terrace extends from N25°20′ northward to N26°30′ and resembles a long, low obtuse triangle. It covers approximately 740 m^2 with a maximum width of 22 km and two levels separated by a discontinuous ridge. The upper terrace is a drowned limestone formation which was subaerially exposed in the middle to late Miocene and is presently marked by karst features. The ridge is probably a drowned Miocene or post-Miocene bank margin complex. The lower terrace (600–700 m depth) is erosional and discontinuous. Its formation is believed to be related to increased flow of the Florida Current and subsequent bioerosion at the time of tectonic uplift and closure of the Isthmus of Panama in mid-Miocene time. Seaward of the lower terrace a large linear depression parallel to the Florida-Hatteras slope separates the Miami Terrace from a broad, unconsolidated sedimentary ridge near the center of the Straits of Florida (Mullins and Neumann 1979).

5.2.1 Climatology

The climate of SE Florida and the Florida Keys is defined as Tropical Savanna (Aw) in the Köppen Climate Classification System (Trewartha 1968). This class is characterized by a pronounced dry season with the driest month having less than 60 mm precipitation and the total annual precipitation less than 100 mm. Average temperature for all months is 18°C or greater. Table 5.1 presents a summary of climatological data for SE Florida.

During the dry fall/winter/spring months (November–March), Florida experiences the passage of mid-latitude synoptic-scale cold fronts (Hodanish et al. 1997) which bring strong winds from the northeast. These "northeasters" usually last for 2–3 days. From late spring to early fall (the wet season, June–September), differential heating generates mesoscale fronts, creating sea breezes. Convergence of these moisture-laden sea breezes, developing from the different water bodies (Atlantic Ocean, Gulf of

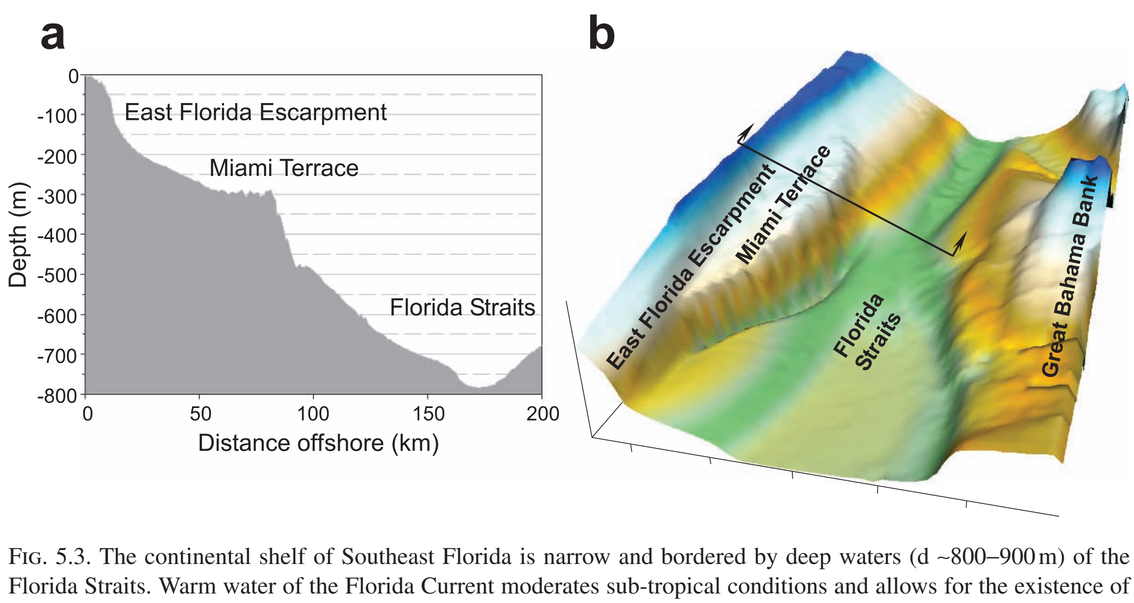

Fig. 5.3. The continental shelf of Southeast Florida is narrow and bordered by deep waters (d ~800–900 m) of the Florida Straits. Warm water of the Florida Current moderates sub-tropical conditions and allows for the existence of tropical coral reef associated communities

TABLE 5.1. Climate data for West Palm Beach and Miami, Florida (West Palm Beach, upper number; Miami, lower number). Temperatures (C°) are based on means from 1971 to 2000. West Palm Beach and Miami wind data are based on means from 1942 to 2005 and 1949 to 2005, respectively (T_{ave} = average monthly temperature, T_{max} = maximum monthly temperature, T_{min} = minimum monthly temperature, W_{ave} = average monthly wind speed (m/s), W_{dir}=average monthly wind direction) (NOAA 2005).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
T_{ave}	19.0	19.6	21.4	23.2	25.7	27.3	28.1	28.2	27.6	25.6	22.8	20.2	24.1
	20.1	20.6	22.4	24.3	26.4	28.0	28.7	28.7	28.0	26.0	23.6	21.1	24.8
T_{max}	23.9	24.6	26.2	27.8	29.9	31.4	32.3	32.3	31.5	29.4	26.9	24.7	28.3
	24.7	25.4	27.1	28.8	30.7	31.9	32.7	32.6	31.7	29.7	27.3	25.3	29.0
T_{min}	14.1	14.6	16.6	18.6	21.4	23.2	23.9	24.1	23.7	21.8	18.8	15.6	19.7
	15.3	15.8	17.8	19.8	22.2	24.0	24.7	24.7	24.3	22.3	19.7	16.8	20.6
W_{ave}	4.5	4.7	4.9	4.9	4.4	3.7	3.4	3.4	3.9	4.5	4.6	4.5	4.3
	4.2	4.5	4.6	4.7	4.2	3.7	3.5	3.5	3.7	4.1	4.3	4.1	4.1
W_{dir}	NW	NW	NW	NW	SE	SE	SE	SE	ESE	ESE	ESE	ESE	ESE
	N	N	ESE	ESE	ESE	ESE	ESE	ESE	E	ENE	E	N	ESE

Mexico, and Lake Okeechobee), coupled with high humidity in the Everglades, result in a low pressure trough developing across the Florida peninsula. This leads to intense thunderstorm activity, which moves from inland to the coasts, delivering large amounts of freshwater to the coastal shelf. South Florida receives 70% of its annual rainfall during these months. Trewartha (1968) refered to the daily sea breeze circulation as a "diurnal monsoon". The mean wind direction during most of the SE Florida wet season is from southeast (tropical)

5.2.2 Hurricanes

From June through November, Florida is a prime landfall target for tropical cyclones, although storms have been documented as early as March and as late as December. The numbers of direct hits of hurricanes (strength based on the Saffir-Simpson scale) affecting SE Florida in the 100 years from 1899–1998 (Neumann et al. 1999) are: 5, Category 1 (winds of 119–153 km/h); 10, Category 2 (winds of 154–177 km/h); 7, Category 3 (winds of 178–209 km/h); 4, Category 4 (winds of 210–249 km/h); and 1, Category 5 (winds >249 km/h). Table 5.2 presents the number of hurricanes and tropical storms affecting Palm Beach, Broward, and Miami-Dade counties from 1871–2006.

Hurricanes Floyd, 1987; Andrew, 1992; Irene, 1999; Frances, 2004; Katrina and Wilma, 2005 affected SE Florida in the last decade. Hurricane Andrew was the most severe with winds at landfall in SE Florida (Elliot Key in Biscayne Bay) of 269 km/h (Landsea et al. 2004). Tropical storm winds extended 225 km from the center. Wave hindcast predicted significant wave heights of 7 m at water depths of 8–9 m. This prediction accounted for the attenuation of the Bahamas Banks (Neumann et al. 1999; Grymes and Stone 1995) which, coupled with the high forward speed of the storm, substantially weakened Hurricane Andrew (Boss and Neumann 1995).

Hurricanes that form in June and July are spawned entirely in lower latitudes on the western side of the Atlantic and in the Western Caribbean. Storms at this time of year are usually weak. Hurricanes occurring in August and September usually form in the Atlantic Ocean and often become mature, severe storms. Hurricanes late in September through October and into November form mainly in the western Caribbean and Gulf of Mexico (USACE 1996).

Hurricanes can have significant influence on the reefal biota of Florida (Tilmant et al. 1994), which can range from wholesale destruction of biota with subsequent regeneration (Shinn 1976) to facilitation of asexual recruitment in some coral species (Fong and Lirman 1995; Lirman 2003) and by cleaning macroalgal and bacterial overgrowth from corals (K. Banks, personal communication, 2007).

TABLE 5.2. Storm frequencies for Southeast Florida (USACE 1996). Number of tropical storms or hurricanes passing within a 50-mi radius of Palm Beach, Broward, and Miami-Dade Counties (a single storm may affect more than one county).

	Palm Beach County		Broward County		Miami-Dade County	
Period	Hurricanes	Tropical storms	Hurricanes	Tropical storms	Hurricanes	Tropical storms
1871–1880	3	0	1	0	0	0
1881–1890	2	2	1	2	2	2
1891–1900	0	2	0	1	1	1
1901–1910	2	4	2	3	3	2
1911–1920	0	0	0	0	0	1
1921–1930	3	1	4	0	3	0
1931–1940	3	0	2	1	1	2
1941–1950	5	1	4	1	5	1
1951–1960	0	2	0	2	0	2
1961–1970	2	0	2	0	2	0
1971–1980	1	1	1	1	0	1
1981–1990	0	2	0	2	1	1
1991–2000	0	2	1	0	1	1
2001–2006	3	0	1	0	0	1

5.2.3 Regional Physical Oceanographic Processes

5.2.3.1 Water Temperature

Thermograph data from July 2001 to December 2003 are presented in Fig. 5.4 (monthly mean, minimum and maximum temperatures for the 3-year period). Highest monthly temperature observed was 30.5°C in August, 2000, on the ridge complex (Fig. 5.4). The lowest minimum temperature was 18.3°C, also on the ridge complex, was recorded in January 2001. Temperatures on the inner, middle and outer reefs were generally similar to one another but the ridge complex was warmer in the summer and cooler in the winter than the other tracts. This reflects the more rapid heat gain or loss of the shallower water over the ridge complex due to air temperature and/or solar insolation. For the 3-year period, the minimum air temperature also occurred in 2001 (11.9°C, Miami WSCMO Airport).

Long-term temperature records will be available in the future from the FWRI (Fish and Wildlife Research Institute) Southeast Coral Reef Ecological Monitoring Program (Gilliam 2007). Temperature loggers have recently been installed at each of the monitoring sites and continuous temperature data are being collected every 2 h. These data will be publicly available from 2007 onward from FWRI.

5.2.3.2 Circulation

The Florida Current flows north (with intermittent reversals) and is the dominant ocean current affecting the SE Florida shelf. It 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 average monthly low velocity is 1.0 m/s in November and the average monthly high is 2.3 m/s in July. Approximately 2 km offshore, the current velocity is 2.5 m/s (USACE 1996). The western edge of the current meanders from far offshore on to mid-shelf.

The coastal circulation along the SE Florida shelf is strongly related to the dynamics of the Florida Current. The Florida Current follows the steep bottom terrain along the shelf break separating the deep ocean (Florida Straits) from the coastal zone. Mixing between the shelf and deeper ocean waters is affected by transient features created at the western edge of the current. Submesoscale spin-off eddies (Lee and Mayer 1977;

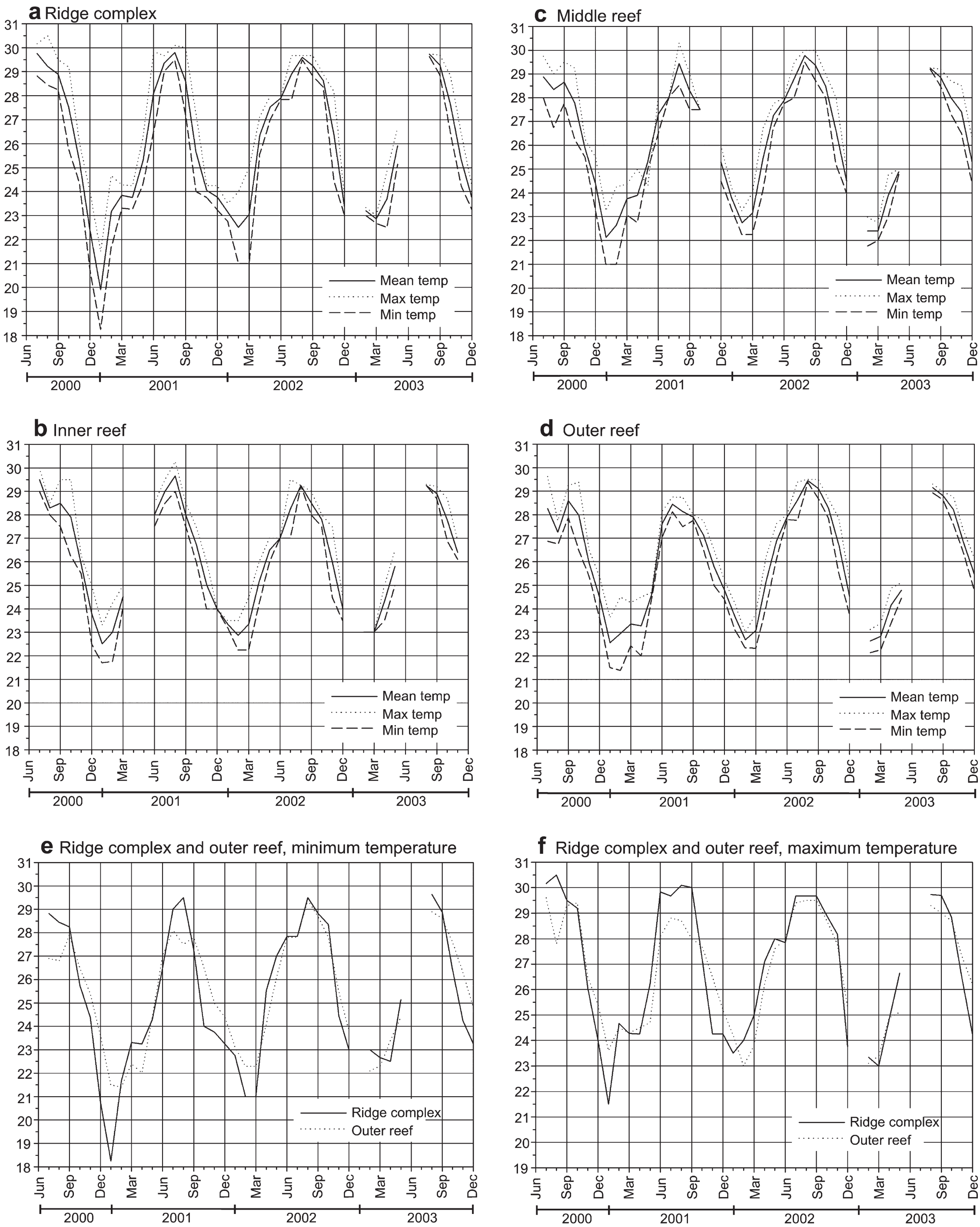

FIG. 5.4. Monthly average, minimum, and maximum water temperatures (C°) from data collected hourly on the seafloor of the: (**a**) ridge complex; (**b**) inner reef; (**c**) middle reef; (**d**) outer reef offshore central and south Broward County from July, 2000, to December, 2003. Cross-shelf variations in water temperature are illustrated by comparing ridge complex and outer reef water temperatures: (**e**) minimum water temperature on ridge complex are lower than the outer reef; (**f**) maximum temperatures are higher on the ridge complex

Shay et al. 2002) are important to local coastal circulation because they affect the continental shelf and largely determine the water properties on the shelf (Soloviev et al. 2003).

Tides in the region are semi-diurnal with amplitudes of approximately 0.8 m and tidal plumes influence coastal circulation near navigation inlets. Seven navigational inlets, approximately 16 km apart, are maintained in SE Florida. At the southern extent of the region, tidal passes allow exchange of water from Biscayne Bay onto the coastal shelf. The relative contribution of the inlets to coastal circulation can be estimated by comparing inlet tidal prisms (volume of water exchanged in the estuary between high and low tide) (Table 5.3). Other factors also affect coastal circulation, such as inlet dimensions, shelf width at the inlets, offshore distance of the Florida Current, tidal plume constituents and salinity. A. Soloviev (personal communication 2007) believes that salinity stratification in the plumes substantially influences local circulation. The salinity of the plumes from the inlets is significantly different in the wet season (June–September) than the dry season (October–May).

5.2.3.3 *Ocean Waves*

In winter, low pressure systems form on the Atlantic coast of the USA. Short-period, wind-driven waves develop near the center of these lows. As these seas move away from the center of low pressure they can develop into long period swells, locally known as "ground swells", and affect SE Florida. The wave climate of SE Florida is influenced by the shadowing effect of the Bahamas and, to a lesser extent, Cuba. In the northern part of the SE Florida region, swells from the north are of relatively high energy since they are not influenced by the shallow Bahamas Banks. Broward and Miami-Dade Counties are less affected by this wave energy because of the shadowing effect of the Bahamas Banks.

Long period swells result in increased sediment suspension and turbidity, particularly in shallow water. If northeasters occur when the moon is in perigee, abnormally high tides can result in greater ebb flows at the inlets, increasing the delivery of inlet waters to the reef system. This combination of events can cause more sediment suspension and turbidity than an average hurricane due to relatively short time duration of hurricanes (USACE 1996). Hanes and Dompe (1995) measured turbidity concurrently with waves and currents *in situ* at depths of 5 m and 10 m offshore Hollywood, Florida (Broward County) from January, 1990 to April, 1992. They found a significant correlation between wave height and turbidity. In addition, there was a threshold wave height (0.6–0.6 m) below which waves do not influence turbidity.

The primary sources of regional wave data are the US Army Corps of Engineers Wave Information Study (WIS, frf.usace.army.mil/cgi-bin/wis/atl_main.html) hindcast and the Summary of Synoptic Meteorological Observations (SSMO, NOAA National Data Center). SSMO is a large dataset of observations and was used to calibrate WIS which is hindcast at 3-h time steps for 1956–1975. Figure 5.5 presents wave information for the SE Florida region from WIS. It is important to note that wave energy flux decreases in a southerly direction due to the increasing wave shadow cast by the Bahamas.

TABLE 5.3. Southeast Florida tidal inlet characteristics (Stauble 1993; Powell et al. 2006).

Tidal inlet/pass	Latitude	Flow area (m^2)	Tidal prism (m^3)	Tidal range (m)
Lake Worth Inlet	N26°46.35′	1,400	24,000,000	1.0
South Lake Worth Inlet	N26°32.72′	100	3,000,000	0.9
Boca Raton Inlet	N26°20.16′	180	4,900,000	0.9
Hillsboro Inlet	N26°15.44′	300	8,100,000	0.9
Port Everglades Inlet	N26°05.63′	2,900	18,000,000	0.9
Bakers Haulover Inlet	N25°54.00′	520	10,194,666	0.8
Government Cut	N25°45.63′	1,400	2,700,000	0.8

5.2.4 Environmental Records in Coral Skeletons

Massive reef building corals, *Montastraea* sp., *Siderastrea* spp., and *Diploria* spp. which possess annual density bands, are present in SE Florida. The size and concomitant age within SE Florida

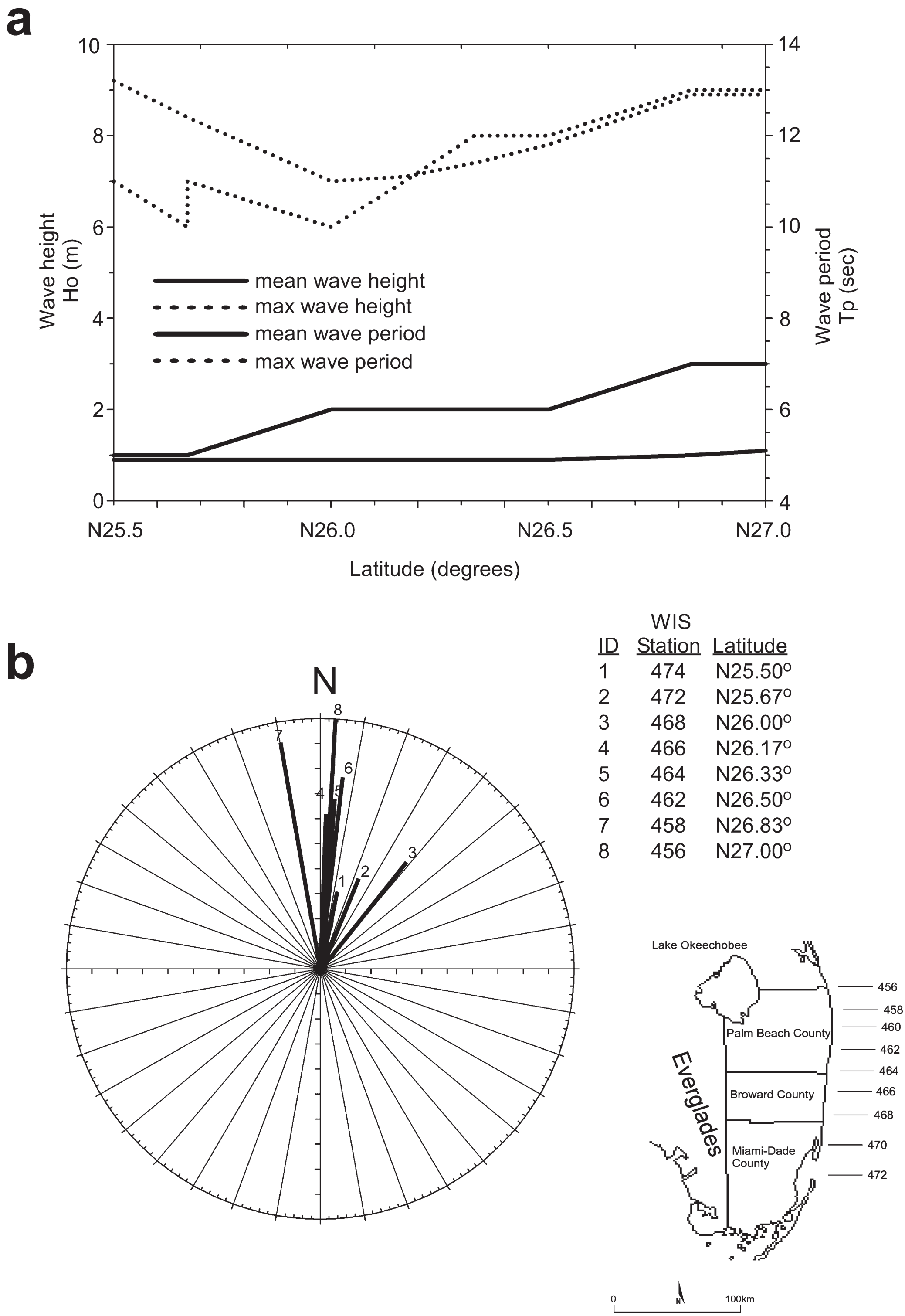

FIG. 5.5. Wave conditions throughout the Southeast Florida region show increasing northerly component of wave energy flux in the northern part of the region. Information based on US Army Corps of Engineers Wave Information System (WIS) hindcast data (http: frf.usace.army.mil/cgi-bin/wis/atl_main.html). WIS data is hindcast at 3-h time steps for 1956–1975: **(a)** mean and maximum wave height (Ho) and period (Tp) increase with latitude (large maximum wave heights and periods at N25.5° are due to the passage of Hurricane Andrew in 1992); **(b)** vector plot of average wave direction and relative magnitude shows that average wave direction trends more northerly with increasing latitude and wave magnitude increases with latitude

is generally limited to small colonies (<1 m) on the order of a few decades in age. Recently, large *Montastraea faveolata* corals with ages of 200–300 years have been discovered and cored (Fig. 5.6). The longest of these records has been dated by the annual density band chronology back to 1694 (K.P. Helmle, personal communication 2007). These multi-century coral records are long enough to identify a range of conditions from natural growth rates to anthropogenically influenced growth and include climatic conditions from the Little Ice Age up to the recent period of rapid climate change.

Measurements of extension, bulk-density, and calcification from coral slab X-radiographs provide a metric for assessing the influences of an ever-changing environment on coral growth rates. For example, a three decade period of stress ca. 1940–1970 (Fig. 5.7, K.P. Helmle, personal communication 2007), defined by significantly decreased extension rates and increased bulk-densities, coincides with dramatically increased fresh-

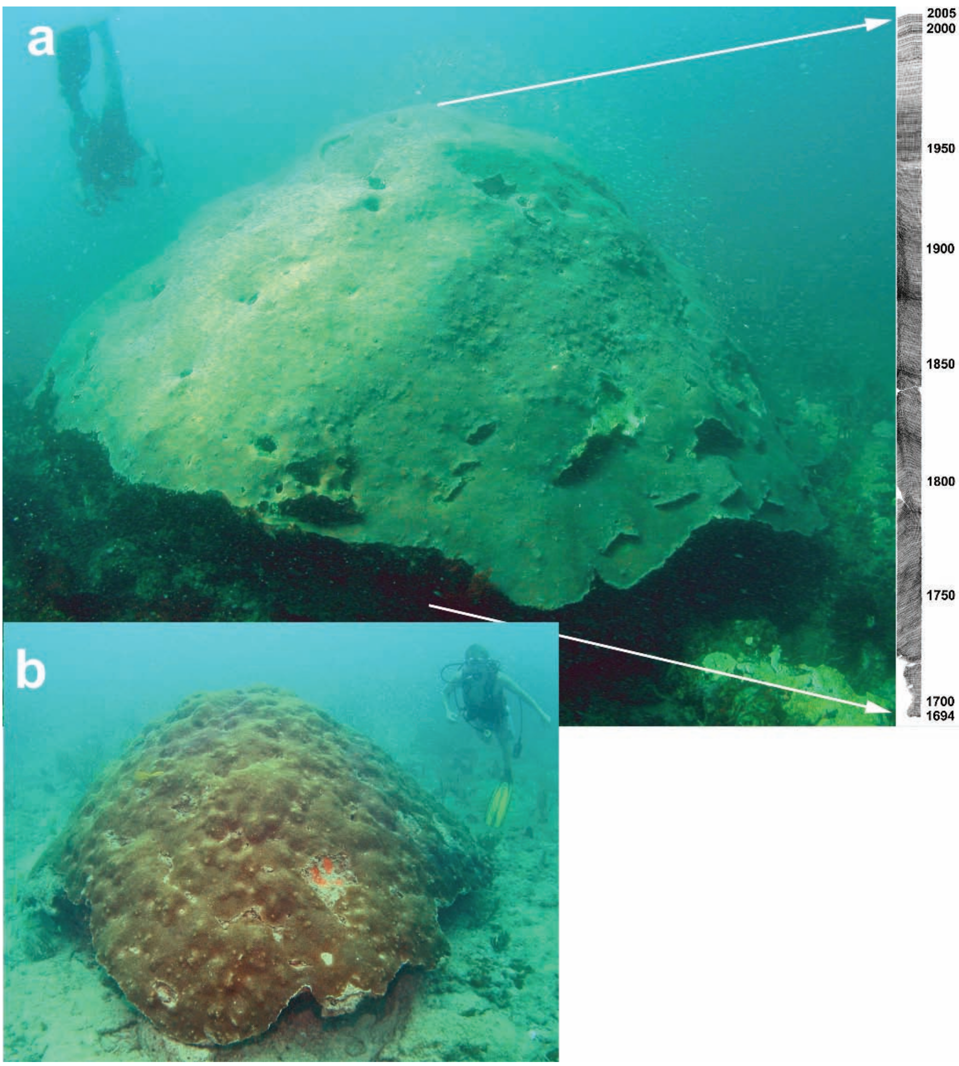

Fig. 5.6. (**a**) *M. faveolata* coral head 2.5 m in height with core X-radiograph on right dating this coral back to 1694. (**b**) *Montastraea faveolata* coral head 2 m in height and dating back to the early 1800s

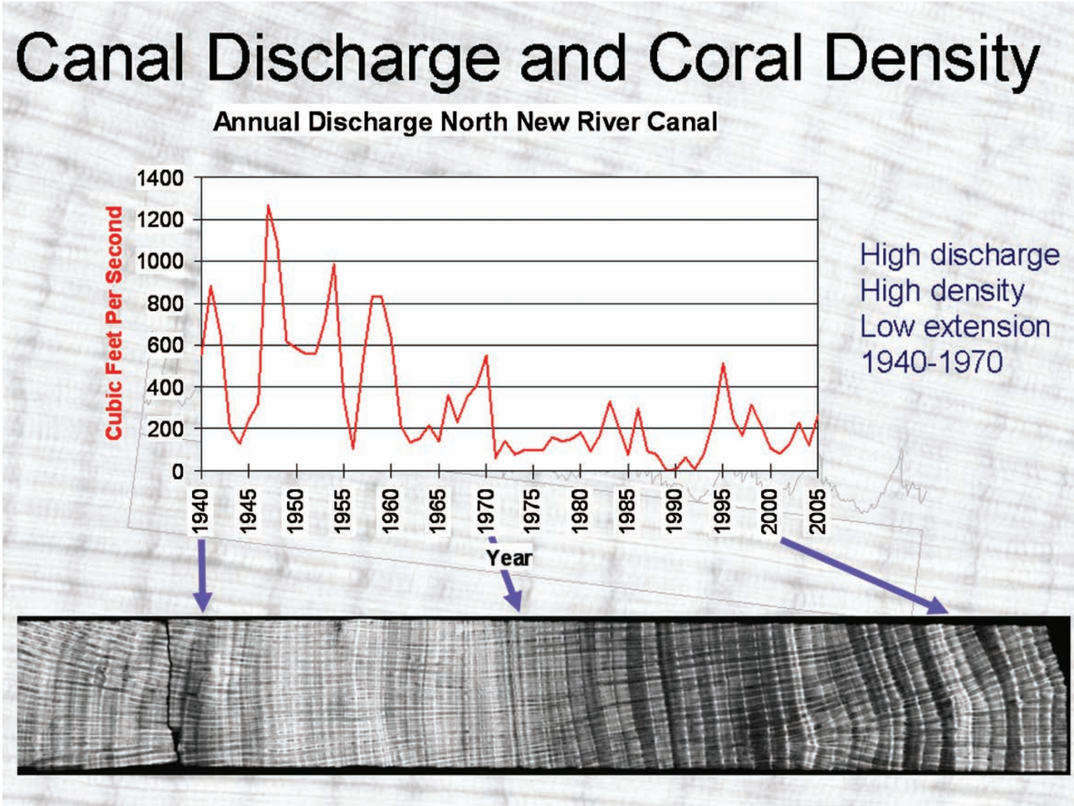

FIG. 5.7. Canal discharge data from North New River Canal illustrating high levels of discharge from 1940 to 1970. Arrows indicate 1940, 1970, and 2000 on coral core X-radiograph below. Note high density skeleton (dark) and low extension rate from 1940 to 1970 compared with 1970–2000

water discharge rates from construction of major canal systems linking Lake Okeechobee to the SE Florida coast. These consecutive stress bands primarily reflect local-scale anthropogenic influences. Conversely, stress bands in 1988 and 1998–99 are present and correspond with two of the strongest El Niños of the past 50 years in 1987 and 1997–98 which illustrates connections between coral growth and global-scale climate patterns.

Linear extension rates for *M. faveolata* in Broward County Florida exhibit strong correlation within and between mid (9 m) and deep water (18 m) from Hollywood, Fort Lauderdale, Pompano Beach, and Deerfield Beach (Table 5.4, provided by Kevin P. Helmle and Richard E. Dodge) The strong correlation within and between depths demonstrates that linear extension rates in *M. faveolata* of SE Florida generally respond commonly to environmental influences and thus provide robust records of historical growth response to anthropogenic impacts and climate change over hundreds of years.

TABLE 5.4. Growth correlations for *Montastraea faveolata* (*M.f.*) for mid (9 m) and deep (18 m) depths.

Correlation coefficients between master chronologies over 1985–1970 n = 16, d.f. = 14 for $p < 0.01$, $r_{crit} > 0.624$

	MID *M.f.*	DEEP *M.f.*	ALL *M.f.*
MID *M.f.*	–	0.82	0.97
DEEP *M.f.*	0.82	–	0.93
ALL *M.f.*	0.97	0.93	–

Average internal correlation

	Mean	N
MID *M.f.*	0.84	6
DEEP *M.f.*	0.73	3
ALL *M.f.*	0.75	21

5.3 Characterization of Southeast Florida Reefs

5.3.1 Geomorphology

Reef growth in Florida is frequently said to be unique to the modern Florida Keys reef tract and considered to terminate at Fowey Rocks (Vaughan 1914; Jaap and Adams 1984; Shinn et al. 1989), but nonetheless reefs and reef-like ridges persist further north (Fig. 5.2). The reef-like ridges are a relict (no active accretion due to exceedingly low cover of reef builders; Moyer et al. 2003). The location of these reefs identifies them as a distinct and also presently non-accreting reef tract (Macintyre 1988), and their geomorphology has recently been described in detail by Finkl et al. (2005) and Banks et al. (2007) and will only be briefly reiterated here.

Between southern Miami-Dade County and Palm Beach County, beginning at the northern end of Biscayne Bay and terminating off the city of Palm Beach at N26°43.1′, up to three shore-parallel, ridge-systems occur in increasing depth. In the early to mid Holocene these were the locus of reef framework development and are called, in increasing distance from shore, the inner reef, middle reef and outer reef (Fig. 5.8). Their morphology is more complicated in the south (Fowey Rocks to Port Everglades) than north of Hillsboro Inlet, where the inner and the middle reefs eventually disappear. The northern termination of the outer reef is off Palm Beach County, where it is replaced by a series of beach ridges that probably represent a drowned headland (Fig. 5.2). The southern termination of the SE Florida reef tract is off Biscayne Bay. In southern Dade County, the middle reef disappears and only the inner and outer reefs remain which then both disappear in a sandy environment seaward of Biscayne Bay. Banks et al. (2007) demonstrated that the SE Florida outer reef is located on a ridge that bends landward near Fowey rocks, and continues behind the Fowey rocks outlier reef. Therefore, the SE Florida outer reef would be most likely equivalent with the Florida Keys shelf-edge-reefs, while the outlier reefs would constitute a separate, more seaward trend initiated on a deeper terrace.

The outer reef (Fig. 5.8b) is a relic acroporid-framework reef (Macintyre and Milliman 1970; Lighty 1977; Lighty et al. 1978) that crests at ~16 m below sea level. It extends more or less uninterrupted (with the exception of reef gaps) from Biscayne Bay northward to its distinct terminus at latitude N26°43′. At a lower sea level

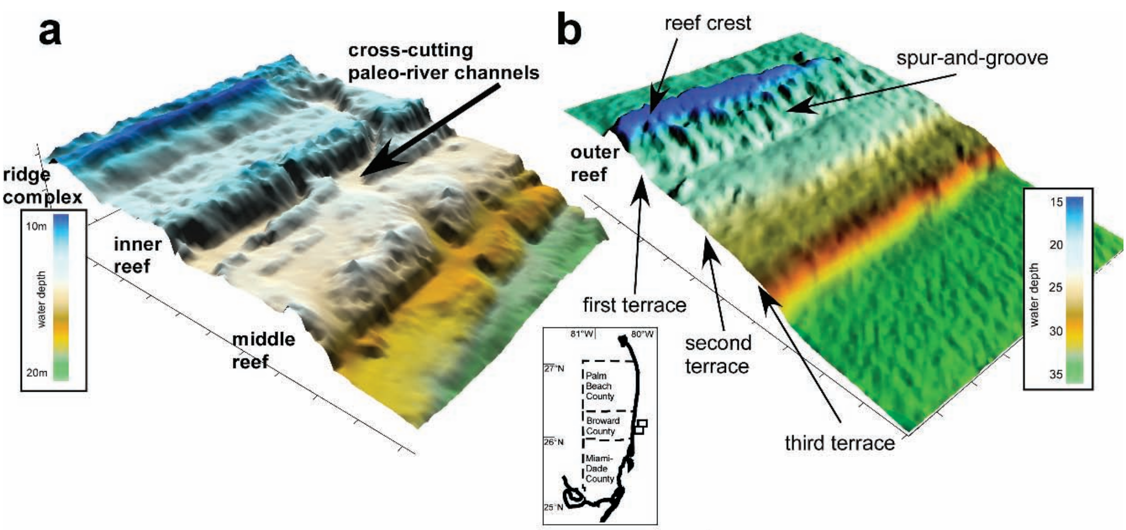

FIG. 5.8. Bathymetric block diagrams showing representative samples of morphology of (**a**) the ridge complex, inner and middle reef, (**b**) the outer reef. Inset map shows location of bathymetry blocks (modified from Banks et al. 2007 by permission of Springer)

stand this distance of about 125 km would have made it one of the best-developed fringing reefs in the western Atlantic, especially when combined with the Florida Keys reefs. Geomorphologic zonation as well as that of major constructors within the framework of the SE Florida outer reef is similar to that of modern Florida Keys reefs (Shinn 1963; Enos and Perkins 1977; Shinn et al. 1981; Lidz et al. 2006). Rubble aprons (talus), back reef, reef crest, spur-and-groove zones and two seaward terraces (17 and 23 m deep) (Fig. 5.6). Reef gaps and collapse features are striking and repetitive features (Banks et al. 2007). The reef gaps are erosional structures with bases deeper than the reef framework and correspond to similar erosional features in the middle and inner reefs. They, thus likely, represent the courses of paleo-river channels. The outer reef initiated before 10.2 cal BP (calibrated ^{14}C-dated years before present) and grew until 8 cal BP (Lighty 1977).

The middle reef is also a mostly continuous feature where it exists and crests at ~15 m below sea level. It extends from South Miami-Dade County northward to Boca Raton Inlet. Unlike the outer reef, it does not display a detectable zonation and reef framework is apparently not continuous throughout or at least variable in development. Any frameworks that do exist are developed on, or drape, a well-defined antecedent slope that is interpreted as the shoreline of the time when the outer reef initiated and began to accrete. Frameworks are mostly dominated by massive corals (*Montastraea* spp., *Diploria* spp.) and only few isolated *A. palmata* frameworks have been found to date. Also the middle reef is dissected by erosional features that connect to reef gaps in outer and inner reefs. The growth history of the middle reef is incompletely understood, but surficial ages obtained so far range from 4.2 to 3.7 cal BP.

The inner reef is the most variable and discontinuous of the three reef tracts and is, in most areas, a complicated amalgamation of patch reefs that can be fused to form longer structures, with individual patch reefs frequently remaining identifiable. It crests at ~8 m below sea level and generally consists of *A. palmata* framework. The inner reef begins south of the middle reef off North Dade County at N25°40′ and extends northward to Hillsboro Inlet at N26°15′ in Broward County where it disappears under the shoreline that in this region changes trend. It is between 2 and 3 m thick and rests either on coquina (Broward County) or laminated soilstone crusts (South Broward and Miami-Dade Counties). Ages obtained from the inner reef range from 5.9 to 6.2 cal BP.

The nearshore ridge complex extends from N25°51′ in Miami-Dade County to N26°15′ (Hillsboro Inlet) and consists of shoreline deposits with visible karst features. Sediment in cores varied in coarseness from shell hash to coarse sand and had variable siliclastic content. The sediment was interpreted as cemented beach, or immediately nearshore deposits, consisting of a mixture of reworked Pleistocene Anastasia Formation and Holocene deposits. A possibly wave-cut feature exists at 6 m below sea level with a relief of 1.5 m on the outer ridge. The sea-level curve of Toscano and Macintyre (2003) would put erosion of that cliff at 3.5–6.5 cal BP, which would make it a possible shoreline for the period when the inner reef was alive and accreting. Lidz et al. (2003, 2006) also describe a nearshore rock ledge and scarp that could be an equivalent structure in the Florida Keys. In Palm Beach County, the substrate of the nearshore ridges is covered by colonies of tube-building polychaete (*Phragmatopoma*) worms (commonly known as "worm rock"), which considerably expand the complexity of this habitat and supports a diversity of macroalga, small stony corals, boring sponges, worm rock, and tunicates.

Banks et al. (2007) proposed a conceptual model of development of this reef system that included stepwise aggradation and backstepping in response to sea-level history. The basis of any reefal accretion is believed to be submarine sand dunes that originally formed during the oxygen isotope substage-5e highstand (approximately 125 BP). At that time, the SE Florida shelf experienced higher wave-energy due to the submergence of the Bahamas Banks with consequently less buffering of waves. These sand shoals fell dry during subsequent lowstands and became indurated. In the early Holocene, as sea level rose, the sand shoals near the shelf became the locus of accretion of the outer reef. Lighty et al. (1978) noted that it initiated as a fringing reef and transitioned to an extensive shelf-edge barrier reef as rising sea level submerged the back reef shelf margin during its growth from >10.2 cal BP and its demise at 8 cal BP (Lighty 1977). The middle reef is situated possibly on the shoreline that might

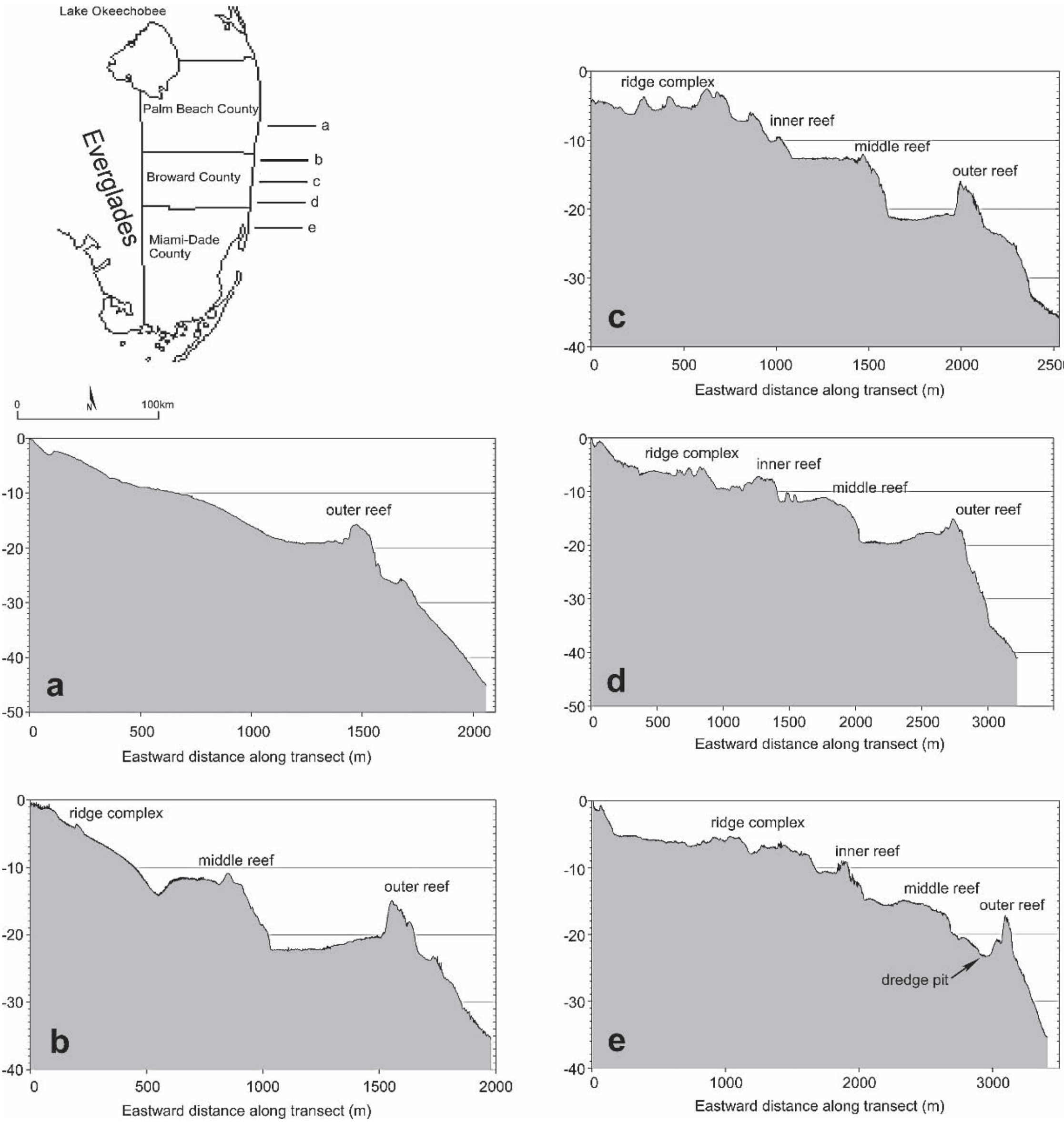

FIG. 5.9. Cross-sections of the ridge complex and reef tracts offshore of Southeast Florida. Bathymetry is extracted from a Lidar dataset of Broward County (Banks et al. 2007)

have been coeval with formation of the outer reef. A further rise in sea level led to the initiation of the inner reef. The available inner reef ages (~6 cal BP) are almost 2 KY younger than the uppermost outer reef (Lighty 1977). At least from the outer to the inner reef, true reef backstepping had occurred. The surface of the middle reef is at 4.3–3.7 cal BP another 2 KY younger than the inner reef, at least on its surface and may thus have initiated sooner and persisted longer. Banks et al. (2007) propose the following backstepping sequence: growth of the outer reef from ~12–8 cal BP at which time a beach and beach-ridge system existed at the later locus of the middle reef; backstepping to the locations of the present middle and inner reefs during transgression. The initiation sequence of middle and inner reefs is still unresolved, but one would assume that the deeper middle reef initiated first. An ecological differentiation seems to have existed: *Acropora palmata* framework on the shallower inner reef, and massive, less environmentally sensitive corals (*Montastraea* spp. *Diploria* spp., *Siderastrea* spp.) on the middle reef. Causes for termination of inner reef accretion are unclear but cannot be linked to the rate of sea level rise since at the time of demise it was 2–3 mm $year^{-1}$ (Toscano and Macintyre 2003), far less than the maximum reef-accretion rate of 14 mm $year^{-1}$ (Buddemeier and Smith 1988).

Despite being largely unexplained, the demise of SE Florida *Acropora* is interesting insofar as it was apparently not unique to South Florida. Hubbard et al. (2005) found a Caribbean-wide gap in *A. palmata* reef building at around the same time (~6–5.2 cal BP). Parallels to the modern *Acropora* crisis in the Florida Keys and Caribbean become obvious. In each case, the cause or causes remain elusive.

5.3.2 Benthic Habitat Mapping

Walker et al. (2008) created maps of the nearshore benthic habitats from 0 to 35 m depth by employing a combined-technique approach which incorporated high resolution laser bathymetry, aerial photography, acoustic ground discrimination (AGD), video groundtruthing, and limited subbottom profiling (Fig. 5.10a–c). Features were classified based on their geomorphology and benthic fauna using similar criteria to NOAA Caribbean biogeography mapping including a similar classification scheme. *In situ* data, video camera groundtruthing, and AGD were used to help substantiate the classification of the habitat polygons.

Acoustic ground differentiation, which evaluates the shape of sound waves bounced off the seafloor from which different categories of wave shapes are classified that correspond to different habitats, was also used to further discriminate the sea floor based on the density of organisms (Moyer et al. 2005; Riegl et al. 2005). These data supplemented the geomorphology-based layer to include not only mapping between features (inner, middle, and outer reefs), but also the variability of habitat within these features (Walker et al. 2008).

This combined technique approach ensured high accuracy by utilizing the data with highest resolution (LADS bathymetry) as the base and supplementing it with lower resolution data of different information content. The maps yielded user and producer accuracies comparable to the photo-interpreted NOAA Caribbean maps (near 90%).

5.4 Biogeography of Southeast Florida Reefs

The biogeographic setting of the SE Florida reef system is a complex of potentially interconnected habitats and the confluence of oceanic (clear, oligotrophic water; stable temperature) and continental (higher temperature variability, land run-off, human impacts, submarine groundwater discharge) influences. The Florida current delivers planktonic larvae from the upstream sources (Yeung and Lee 2002) in the Florida Keys and Tortugas (tropical, insular) and the estuaries and lagoons of Biscayne Bay and Florida Bay (subtropical, continental). Estuaries within the southeast continental region with tidal inlet connectivity to the reef system include northern Biscayne Bay with seagrass and mangroves, mangrove habitat in Broward County, and mangrove and sea grass habitats in the Lake Worth Lagoon of Palm Beach County. The western Bahamas Banks lie only approximately 80 km eastward of SE Florida but are separated by the deep water and rapid currents of the Florida Straits.

Studies on the extent and direction of gene flow or connectivity among reefs in the SE Florida biogeographic region are limited to work on amphipods and ophiuroids by Richards et al. (2007). Genetic connectivity was studied along 355 km of the Florida Keys and SE Florida reef tract (Fig. 5.11) from assessment of gene flow in three commensal invertebrate species displaying contrasting reproductive strategies. The three species, two amphipods (*Leucothoe kensleyi* and *Leucothoe ashleyae*) and a brittle star (*Ophiothrix lineata*), are all commensal within the branching vase sponge *Callyspongia vaginalis* (Fig. 5.12). The brittle star is a broadcast spawner, whereas the amphipods brood their young and lack planktonic larvae. Although *O. lineata* is a broadcast spawner, it possesses an apparently rare form of development in ophiuroids where embryos develop inside a fertilization membrane for 6–8 days before emerging

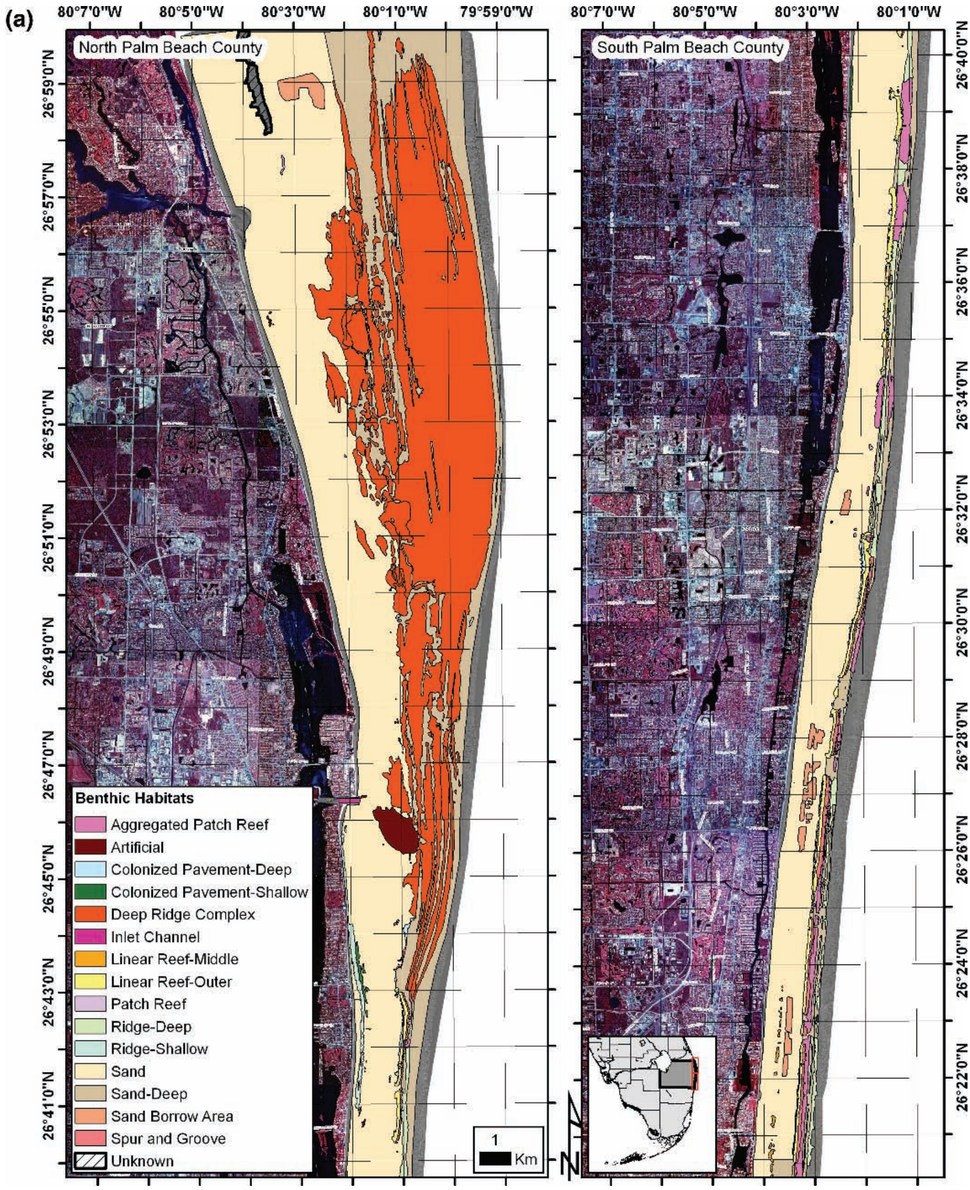

FIG. 5.10. Habitat maps for the Continental SE Florida reef tract based on a combined method approach using laser bathymetry, acoustic ground discrimination, visual groundtruthing (Walker et al. 2008). (**a**) Palm Beach County

as miniature crawl-away juveniles (V.P. Richards, unpublished data). This mode of development suggests that its embryos are passive propagules and exposure to currents for up to 8 days should give *O. lineata* enhanced dispersal abilities. These contrasting reproductive strategies led to expectations of strong gene flow (high connectivity) among reefs for the broadcasting brittle star, but low connectivity for the brooding amphipods.

Findings suggest that reproductive life history is not always a reliable predictor of genetic connectivity. Commonplace within reefs are positive species interactions such as commensalism and mutualism (i.e., facilitation), which have substantial influence

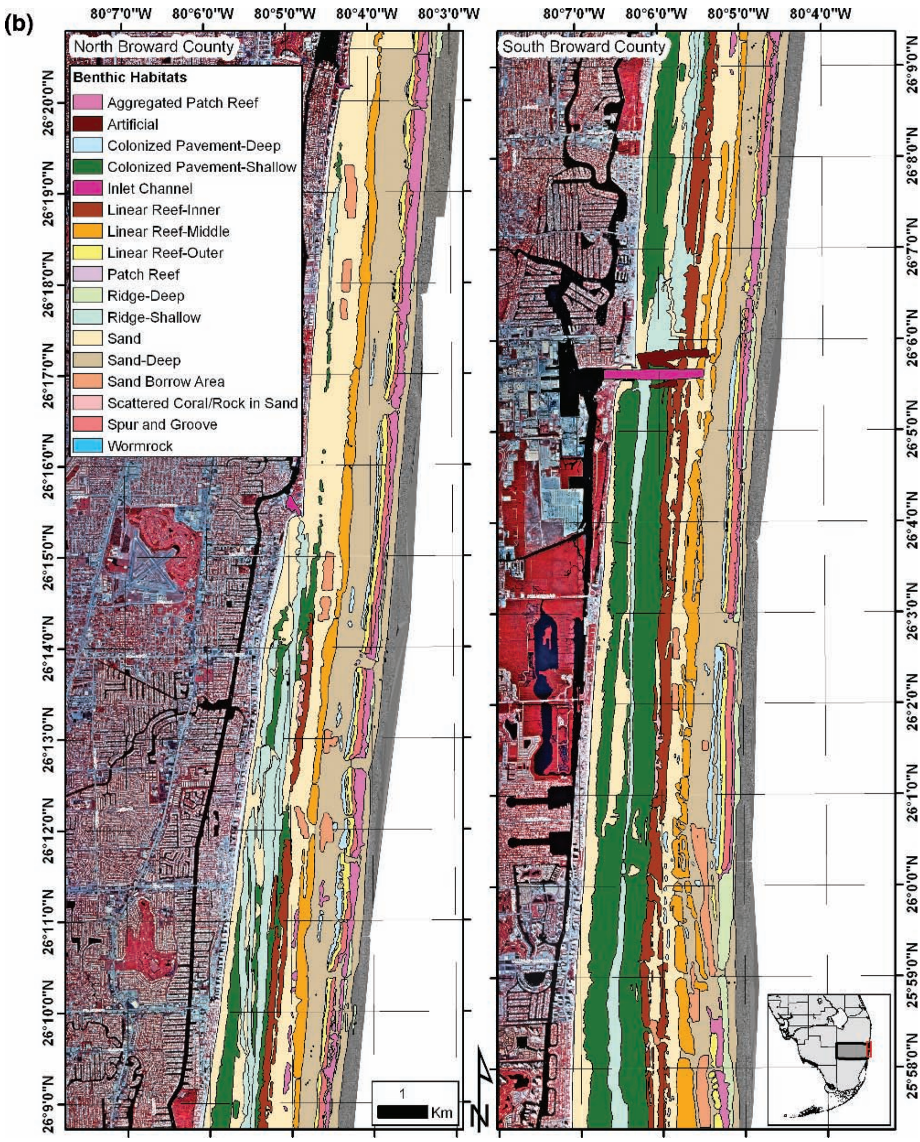

FIG. 5.10. (continued) (**b**) Broward County

on the structure and function of these communities (Bruno et al. 2003). The dynamics of connectivity among reef populations is complex, and factors such as shallow coastlines, deep expanses of open water, and interaction among species involved in facilitation also need to be considered.

Measures of genetic differentiation among populations showed high levels of connectivity overall along the Florida reef tract for all three species (i.e., there was no significant difference in the distribution of haplotypes among populations; Fig. 5.13). The Ft Lauderdale population of *L. ashleyae* did not follow this general pattern and represented the only instance of restricted gene flow along the SE Florida coastline (see Richards et al. 2007 for further discussion on possible reasons for this exception). Paradoxically, only the brittle star showed a statistically significant pattern of genetic isolation by geographic distance along the Florida reef tract (i.e., individuals from

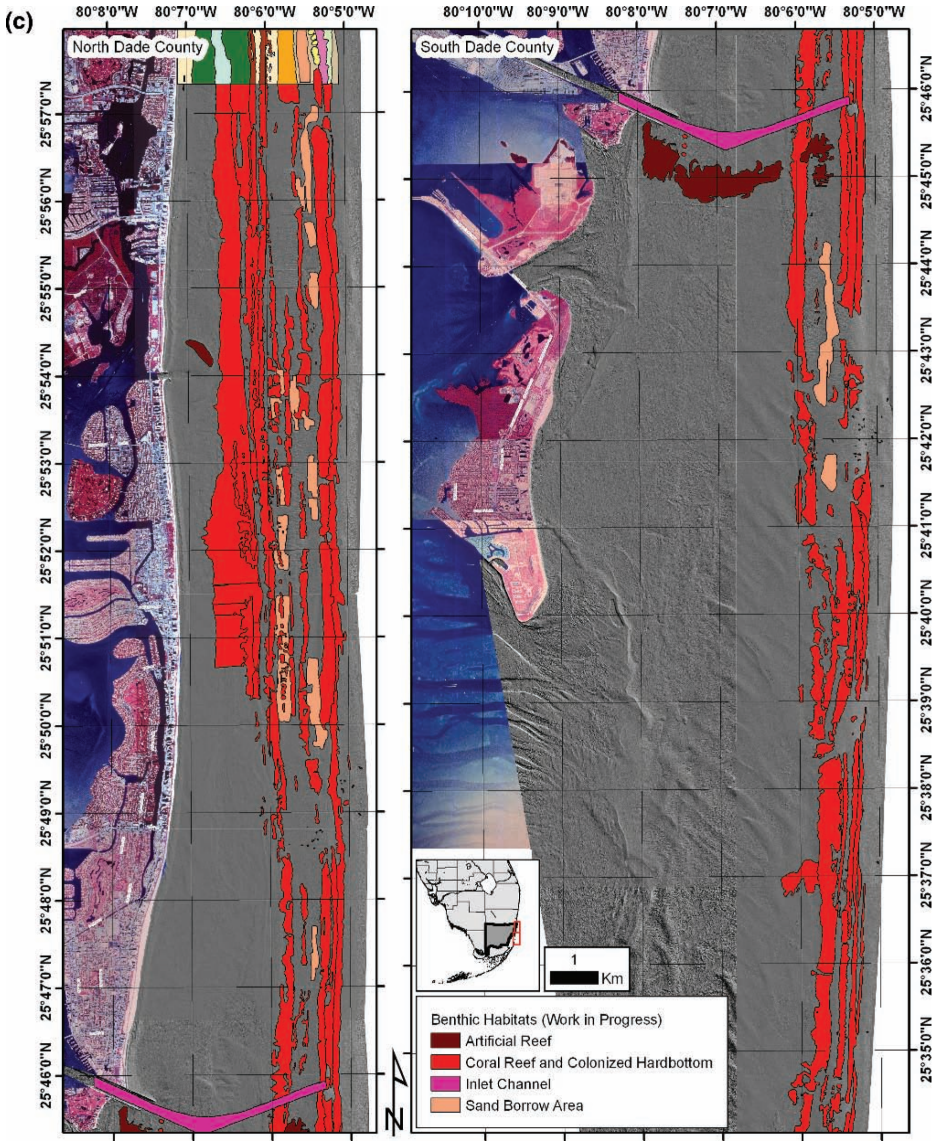

FIG. 5.10. (continued) (**c**) Miami-Dade County (modified from Walker et al. 2008 by permission of Journal of Coastal Research)

neighboring populations were more closely related to each other than individuals from more distant populations).

The high levels of connectivity detected for both amphipod species along the Florida reef tract were unexpected given their lack of planktonic larvae and raises the question of how they are able to disperse so effectively along the SE Florida coastline. If the amphipods (which usually only attain an adult size of <5.0 mm) were dispersing via crawling or occasional short-range swimming bursts, a pattern of genetic isolation by distance would exist. The lack of this signal suggests that another dispersal mechanism is operating. A possible

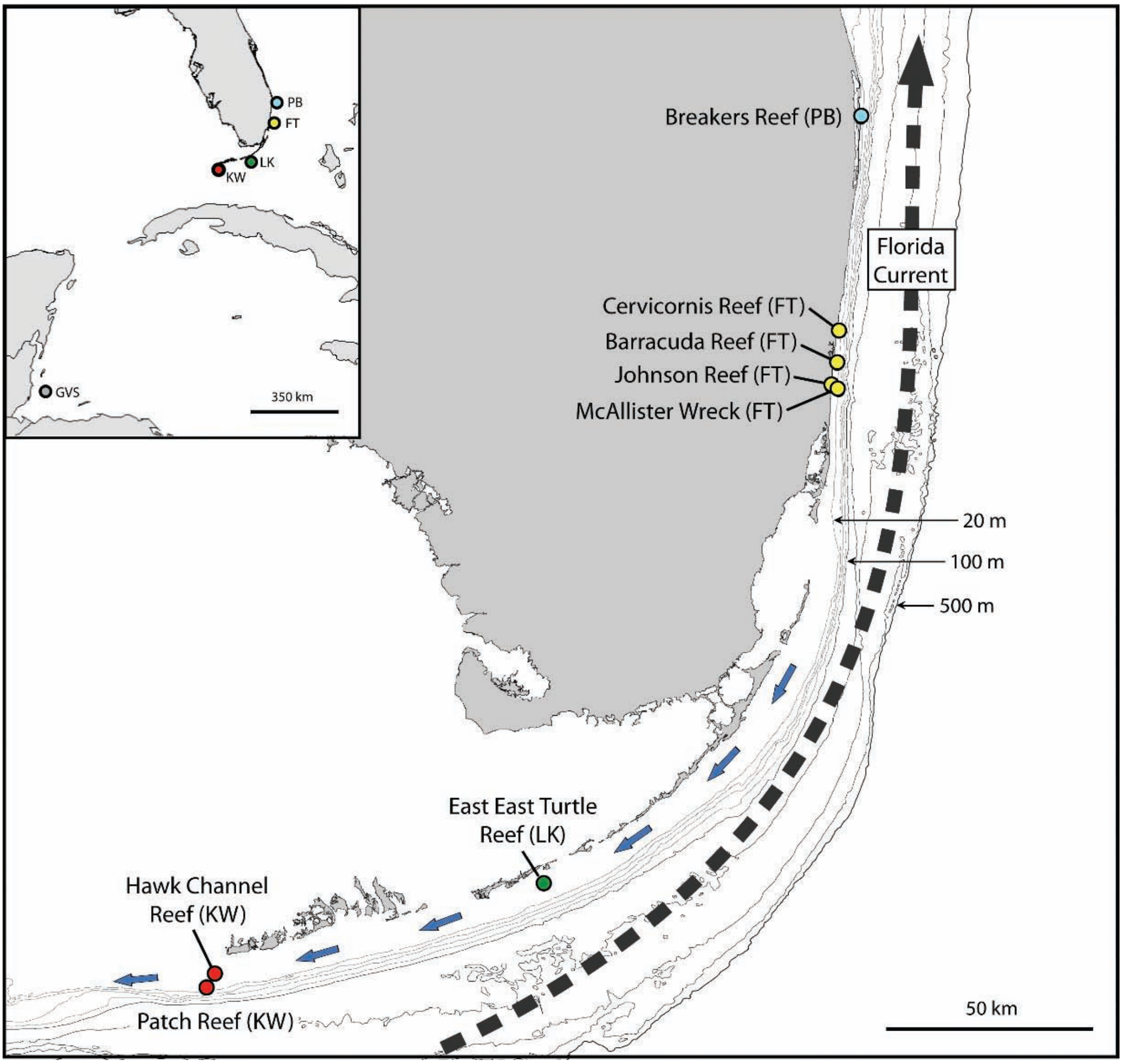

Fig. 5.11. Map showing individual collection sites for the study of genetic connectivity along the SE Florida coastline (color scheme corresponds to Fig. 5.13.). Blue arrows depict a counter current flowing through Hawk Channel (after Yeung and Lee 2002). Inset shows the four major collection locations relative to the collection site in Belize: PB, Palm Beach; FT, Ft Lauderdale; LK, Long Key; KW, Key West; GVS, Glover's Reef. Depth contour data from http://www.ngdc.noaa.gov/mgg/ibcca

explanation is one where the amphipods are being dispersed along the reef tract inside sponge fragments generated during strong storms and hurricanes. Asexual fragmentation is an important dispersal mechanism for many branching sponge species (Wulff 1991), and the type of severe storms and hurricanes often experienced along the SE Florida coastline are capable of detaching and transporting numerous sponge species considerable distances as demonstrated in other reef environments by Wulff (1985, 1995a, b). Thus, at least a portion of SE Florida's benthos may have recruited by simply tumbling along the linear drowned reef systems.

An estimate of migration indicated that the amphipods were migrating up and down the SE Florida coastline with approximately equal frequency, a result consistent with random, bi-directional

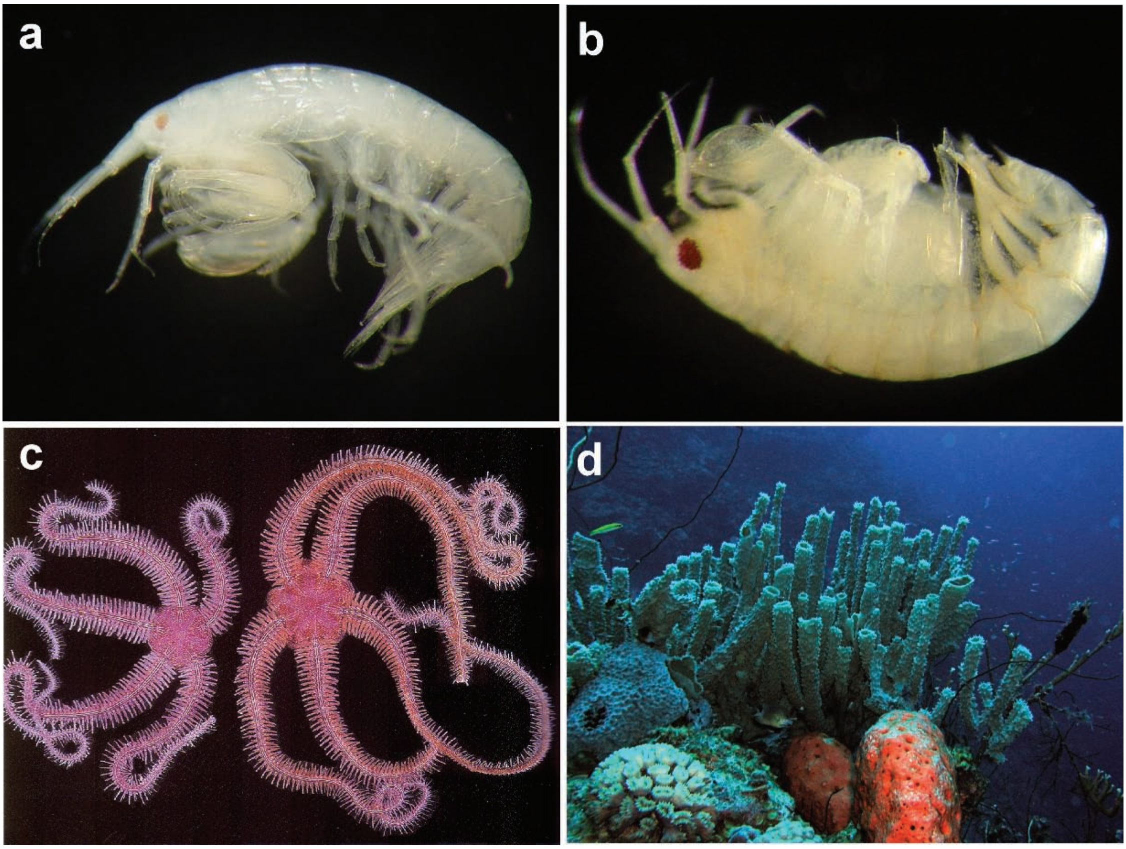

Fig. 5.12. Richards et al. (2007) used the amphipods: **(a)** *Leucothoe kensleyi*; **(b)** *L. ashleyae*; **(c)** brittle star, *Ophiothrix lineata*, which are all commensals with: **(d)** the sponge, *Callyspongia vaginalis,* to study gene flow among reefs in the Southeast Florida biogeographic region. (Photos by: **a**, **b** Vince Richards; **c** scanned with permission from Hendler et al. 1995)

transport mediated by storms. In notable contrast, the brittle star showed a strong southerly migration bias in the Florida Keys. Although the strong northerly flow of the Florida Current is assumed to be an important dispersal agent along the Florida coastline; instead, the well characterized counter current (Fig. 5.11) that runs southwest through Hawks Channel in the Florida Keys (Lee and Williams 1999; Yeung and Lee 2002) may be the dominant dispersal agent for *O. lineata* embryonic propagules in this region. The southerly bias to *O. lineata* migration was not evident along the Broward and Palm Beach county coastlines, where migration occurred with high frequency in both directions. This complex pattern may result from the dynamic counter currents and eddies created as the Florida current intrudes over the shelf break (Lee and Mayer 1977; Shay et al. 2002; Soloviev et al. 2003).

Richards et al. (2007) also tested the hypothesis that deep water acts as a barrier between populations by examining the connectivity between Florida and Belize. Because *O. lineata* embryo propagules are non-swimming, their dispersal can be assumed to be passive and, therefore more likely to be influenced by physical oceanographic factors. Consequently, the deep water between Florida and Belize and entrapment in eddy currents over the Meso-American Barrier Reef System (Sheng and Tang 2004) are factors that could affect dispersal. Furthermore,

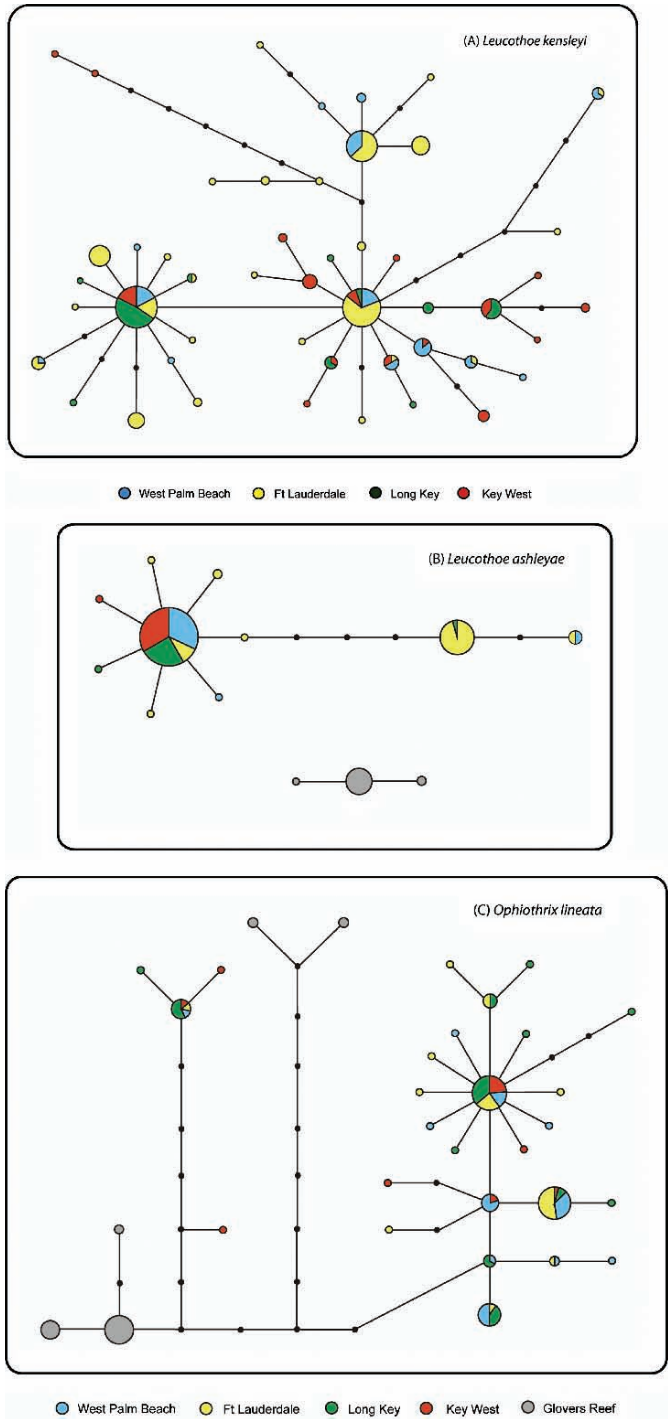

FIG. 5.13. Statistical Parsimony networks depicting the relationship among different mitochondrial COI haplotypes for (A) *Leucothoe kensleyi*, (B) *Leucothoe ashleyae*, and (C) *Ophiothrix lineata*. Colored circles = individual haplotypes; small black circles = haplotypes that hypothetically should exist in the population, but were not sampled; connecting lines = one base pair mutation. Circle size for each haplotype is proportional to its frequency of occurrence and all three networks have the same scale. Different colors correspond to the five major geographic sampling regions (see Fig. 5.11). Due to the large genetic distance between the Florida and Belize *L. ashleyae* haplotypes (79 base pair mutations), there is no statistical support for any connection point between them. Consequently, connection of these haplotypes in the same network is precluded. Networks were created using the software package TCS version 1.13 (Clement et al. 2000)

the strong genetic isolation by distance signal detected across all locations suggests that geographic distance is also an important factor influencing connectivity patterns in this species. The results for *L. ashleyae* represent a dramatic contrast in dispersal ability dependant on the physical environment: high gene flow along a shallow coastline despite a brooding reproductive strategy, with absence of gene flow between populations separated by deep water resulting in potential cryptic speciation.

Richards also sampled the amphipods, *Leucothoe kensleyi* and *L. ashleyae* in Bimini, Bahamas which is 95 km from the Florida coast, yet separated by deep, high current velocity water. Although the geographic distance from Fort Lauderdale to Bimini is less than a third the distance from Palm Beach to Key West, the genetic distance was much higher, so these amphipods are strongly connected along shallow coastlines, yet show no connectivity across very short distances of deep water.

The finding of high levels of genetic connectivity for three species within the Florida reef tract (Figs. 5.10 and 5.12) has important implications for the management and conservation of Florida reefs. Northern reefs receive considerably less management attention than reefs in the south (Causey et al. 2002), and are likely being adversely impacted by extensive urban development in this region (Lapointe 1997; Finkl and Charlier 2003). The continued decline of the northern reefs could impact southern reefs, as a reduction in gene flow from the north could reduce genetic diversity in the southern reefs rendering them less adaptable to environmental perturbation.

5.5 Patterns in Reef Community Structure

Although the continental SE Florida reefs have a fauna similar to the Florida Keys, Bahamas and Caribbean, the community structure is different (Moyer et al. 2003). The only major reef building coral missing from SE Florida is *Acropora palmata*, although isolated colonies do exist (Banks, personal observation). Recent claims that *Acropora* occurrences in Broward county are indicative of ocean warming (Precht and Aronson 2004) require further verification, since widespread rubble of the species in question indicates that these corals have already previously had a repeated, but ephemereal presence in the area over the last centuries. Aside from a dominance of bare substratum, relative cover is dominated by macroalgae or octocorals, while scleractinian cover is low. Isolated patches of higher coral cover can be found on the ridge complex offshore central Broward County where one site, dominated by massive corals, has approximately 16% cover and another area is covered by large colonies of *Acropora cervicornis* with 34% cover.

5.5.1 Region-Wide Benthic Community Structure

A summary of relative bottom cover data for SE Florida is given in Table 5.5. Methodological and sample size differences likely contribute to variations in cover among studies. Based on the averages of data collected by Blair and Flynn (1989), Thanner et al. (2006), and Gilliam et al. (2007) overall faunal density is dominated by porifera (15.7/m^2), followed by octocorals (7.7/m^2) and scleractinia (2.5/m^2). A list of all reported species of macroalgae, sponges, octocorals and stony corals reported is provided in Table 5.13.

Macroalgal cover is generally lower in SE Florida than in the Florida Keys and Tortugas (Beaver et al. 2005; FWCC 2005). Foster et al. (2006) found that *Dictyota* spp. and *Halimeda* spp. were the dominant algal species. Abundance of macroalgae can be seasonal or vary over different time scales.

Paul et al. (2005) reported that the cyanobacteria *Lyngbya confervoides* and *L. polychroa* (Fig. 5.14) covered extensive areas of reef offshore Broward County in recent years, particularly 2003. Extensive blooms subsided in 2005 and 2006, although shorter time scale boom/bust cycles are apparent. Tichenor (2005) reported a persistent bloom on the outer reef offshore of Palm Beach County. Causes of these blooms are unknown although he attributed them to treated wastewater discharge from an outfall pipe up-current of his

TABLE 5.5. Average relative bottom cover for ridge complex and reef tracts of Southeast Florida. FWCC (2006) data averaged over 2003–2004 and based on three sites per county (fourth site in Broward is large stand of *Acropora cervicornis*). Two Broward sites have unusually high stony coral cover (one, 40% cover *A. cervicornis* and one, 12% cover of massive corals on ridge complex). Values in parentheses do not include these high cover sites. Data from other studies are averaged over all sites for each county.

	Palm Beach County	Broward County			Miami-Dade County
	(3)	(1)	(3)	(2)	(3)
Bare substrate	70%	10%	73% (80%)	54%	73%
Macroalgae	1%	66%	4% (4%)	15%	9%
Octocoral	20%	12%	8% (12%)	16%	12%
Porifera	7%	8%	2% (4%)	8%	3%
Scleractinia	1%	2%	13% (0%)	5%	1%
other	1%	2%	1% (0%)	3%	2%

(1) Foster et al. (2006)
(2) Moyer et al. (2003)
(3) FWCC (2006)

study site. Foster et al. (2006) included presence/absence data of *Lyngbya* spp. during their studies and found significant occurrences on all reef tracts but not on the ridge complex. The fine filamentous morphology of this genus probably contributes to an underestimated cover based on point count of images, therefore not contributing significantly to macroalgal cover estimates.

In spring, 2007, a macroalgae bloom comprised of *Cladophora liniformis*, *Enteromorpha prolifera*, *Centroceras clavulatum* (Fig. 5.7) (identification by Brad Bedford, Harbor Branch Oceanographic Institute) occurred. Other species may have been present but were not identified. These macroalgae formed a thick mat on sand bottom and reef in northern Broward and southern Palm Beach Counties. The cause has not been identified.

All datasets (Goldberg 1973; Moyer et al. 2003; Gilliam et al. 2007; Foster et al. 2006) consistently showed that octocorals dominate faunal cover on SE Florida reefs (Table 5.6), although porifera dominated in abundance. Forty-eight species were reported by Foster et al. (2006) and the dominant groups were *Eunicea/Muricea* spp. and *Briareum asbestinum*. Thanner et al. (2006) reported similar dominant taxa in Miami-Dade County. Octocoral cover on SE Florida reefs is similar to that in the Florida Keys (Beaver et al. 2005; Gilliam et al. 2007).

The dominant sponges are the basket sponge, *Xestospongia muta*, *Anthosigmella varians* and *Spheciospongia vespariuum*. 43 species of scleractinian have been reported for SE Florida (Moyer et al. 2003; Foster et al. 2006; FWCC 2006; Goldberg 1973), including the Indo-Pacific azooxanthellate coral, *Tubastrea coccinea* (Fenner and Banks 2004). Cover is low and most colonies are of small size, typically less than 50 cm. SE Florida has lower species richness and cover than Florida Keys and Tortugas (1.5% versus >5% coverage; Beaver et al. 2005; FWCC 2006). *Montastraea cavernosa* is dominant in terms of cover, although *Siderastrea siderea* is numerically the most abundant. This species recruits frequently but does not usually reach large sizes. Similar dominance of *M. cavernosa* has been reported for other high latitude reefs (Bermuda and Brazil; Laborel 1966; Castro and Pires 2001) and reefs in turbid settings like windward Barbados (Lewis 1960). Loya (1976) found a correlation between the abundance of *M. cavernosa* and heavy turbidity and sedimentation, and the SE Florida reefs can certainly be called a usually turbid environment. Species of the *Montastraea annularis* complex are all present in SE Florida but, in contrast to the Caribbean, are not dominant (Knowlton 2001; Moyer et al. 2003).

Moyer et al. (2003) reported significant north/south variation in benthic community structure on the ridge complex and outer reefs. In general, diversity increased from north to south in Broward County. A number of factors could account for this, including temperature variations, planktonic larval supply, substrate characteristics, and wave energy. Planktonic larval supply is transported northward by the Florida Current from the Florida Keys and Caribbean provinces, thus the observed S-N gradient may indicate attenuation of larval supply towards the north. Studies that could verify such a hypothesis are lacking. Substrate differences may also affect community structure. Vertical relief of the ridge complex declines towards the north, eventually reaching <1 m. This seems to be accompanied by decreasing live benthic cover and increased sponge dominance. In the south, where relief is greater than 1 m, the benthic fauna is dominated by octocorals and the zoanthid, *Palythoa caribbaeorum*. Combined with

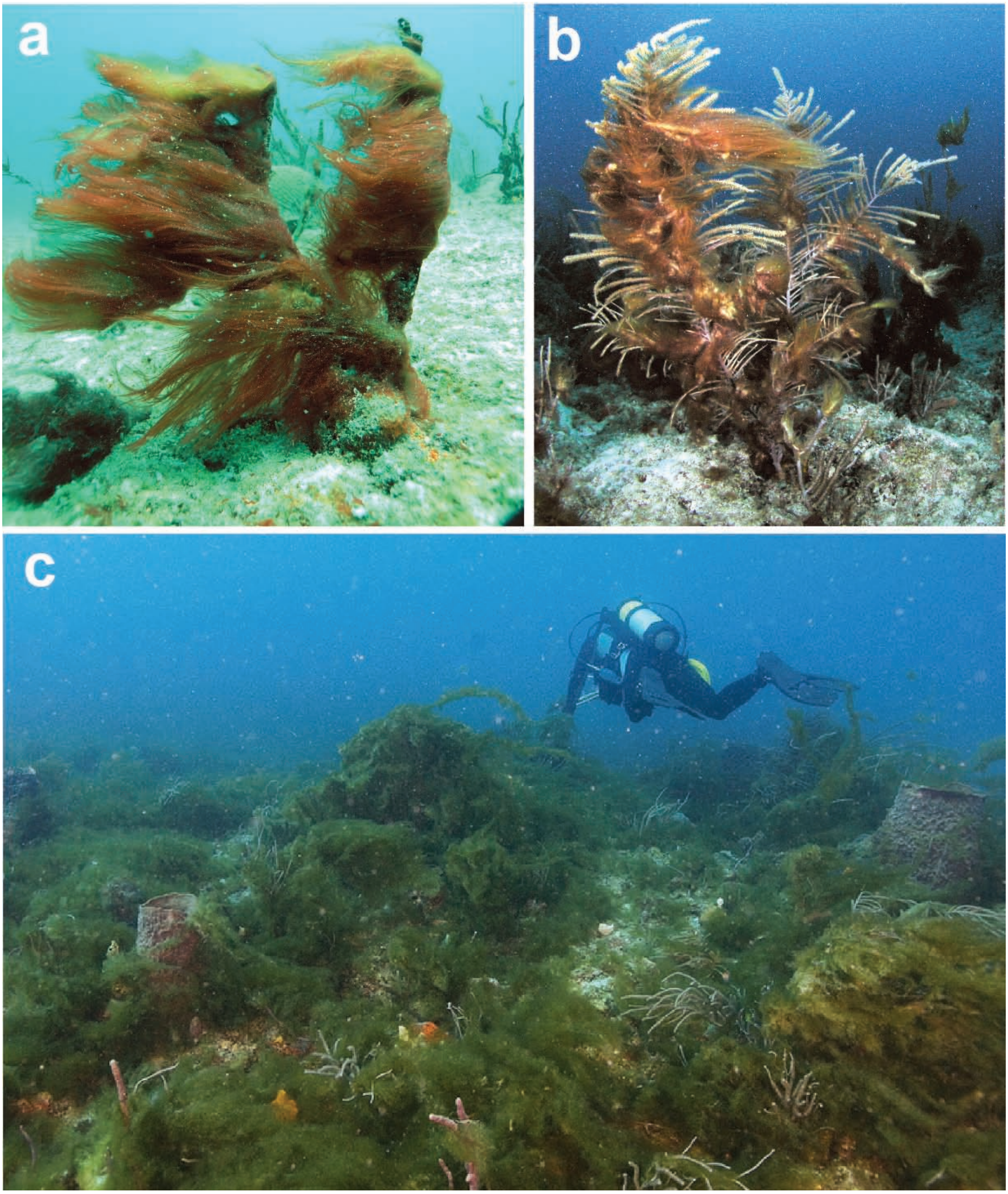

FIG. 5.14. (**a**, **b**) The cyanobacteria, *Lyngbya confervoides* and *L. polychroa* formed persistent blooms on the reefs in 2003 and smothered many reef organisms, particularly branching octocorals, such as *Pseudopterogorgia* spp. (**c**) Extensive blooms of *Cladophora liniformis*, *Enteromorpha prolifera*, *Centroceras clavulatum*, and others bloomed on inter-reef sand plains and reef tracts of northern Broward County and southern Palm Beach County in the spring of 2007. (Photos by: **a**, **b** Karen Lane; **c** Jeff Torode)

lower relief, the northern areas also receive higher wave energy, since the protection of the Bahamas banks decreases less towards the north. Wind waves from the north and northeast are generally higher in the northern portions of SE Florida which may results in more sediment suspension and turbidity in the northern nearshore.

The cover by scleractinians and octocorals showed no significant temporal changes in the 1997–2005 monitoring dataset obtained by Gilliam et al. (2007), but sponges declined significantly in 2000/2001 and stabilized after that. Concomitant sedimentation monitoring showed high rates at all sites in the winter of 2001 which may have contributed to sponge mortality.

5.5.2 Cross-Shelf Patterns in Benthic Community Structure

The reef cross sections shown in Fig. 5.9 illustrate the depths of the reef tracts and ridge complex. In addition to depth, variation in substrate composition and morphology among reef tracts can impact benthic composition. Among other factors, the porosity of the limestone on the narrow shelf may allow groundwater to seep up onto the reef (Finkl and Charlier 2003) potentially exposing the community to groundwater-borne pollutants. In general, environmental conditions on the ridge complex and possibly the inner reef are more variable than on the middle and outer reefs due to less depth and proximity to shore. Moyer et al. (2003) found that benthic communities on the middle and outer reefs were similar but both differed from the inner reef communities (Figs. 5.15 and 5.16).

Foster et al. (2006) investigated the effect of depth, bottom slope, rugosity and sediment thickness on the structure of benthic communities. Similar to Moyer et al. (2003), they found the community on the ridges and inner reefs to differ from the middle and outer reefs (Tables 5.7 and 5.8). Living benthic substrate cover increased from onshore to offshore. Table 5.9 shows lowest scleractinian density on the inner reef when sites with high *Acropora cervicornis* and anomalously high coral cover were removed (Gilliam et al. 2007). Overall, octocoral and sponge densities are lowest on the ridge complex and inner reef, which might be a direct response to increased wave energy. Kinzie (1973) and Yoshioka and Yoshioka (1991) suggested that wave energy may influence octocoral populations by detachment of colonies. While living cover clearly differed, species richness of hard and soft corals and sponges among reef tracts was relatively constant.

Vargas-Angel et al. (2003) reported extensive patches of flourishing *Acropora cervicornis* approximately 400–800 m offshore on the ridge complex in Broward County in 3–7 m depth. The area of the patches ranged from ~0.1 to 0.8 ha. Coral cover was 5–28% within reef patches with 87–97% of the cover by *A. cervicornis*. In 2002 they reported Type I White Band Disease (WBD) in all thickets but no bleaching. The WBD was more common at the center of the patches than the periphery where cover was lower. These populations were found to be fertile and to spawn each summer (Vargas-Angel et al. 2003; Vargas-Angel et al. 2006).

5.5.3 Fish Community Structure

5.5.3.1 Miami-Dade and Broward Counties

In total, over 350 fish species have been recorded from Broward and Miami-Dade Counties. However, this total is certainly an underestimate and could substantially increase if piscicide (e.g., rotenone) collections of cryptic fishes were conducted (Ackerman and Bellwood 2000; Willis 2001; Collette et al. 2003).

Generally, the fish assemblages associated with hardbottom reef communities in SE Florida resemble those found throughout the Florida Keys, Greater Caribbean, and Gulf of Mexico. All the common families are represented (Labridae, Pomacentridae, Haemulidae, Gobiidae, etc.; Fig. 5.17). Nonetheless, given the northern latitude at which these reef communities exist, temperate fish (*Orthopristis chrysoptera* [Haemulidae]) can be commonly observed in winter months. The Broward County reef fish community exhibits cross-shelf variation in fish assemblage structure correlated with changes in depth. The deeper, outer reef sites harbor higher fish densities and more species than the shallower inner reef sites (Ferro et al. 2005).

Nearshore hardbottom (<300 m from the shoreline; colonized pavement) fish assemblages show considerable differences in assemblage structure

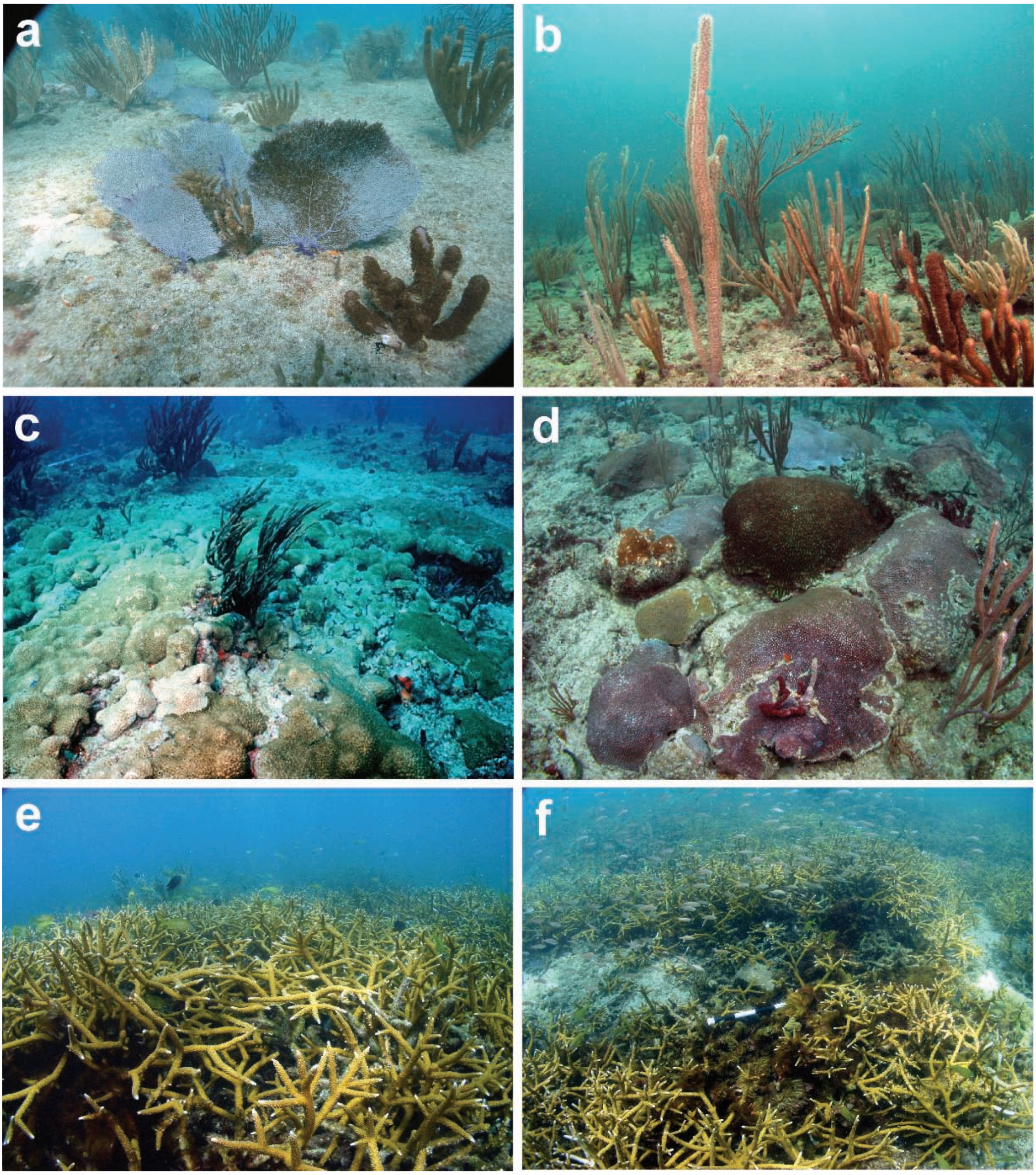

Fig. 5.15. Photos of ridge complex communities illustrate: (**a**) and (**b**) typical flat pavement-like substrate and abundance of octocorals; (**c**) the encrusting zoanthid, *Palythoa caribaeorum*, is common on the ridge complex and inner reef; (**d**) patches of relatively high stony coral cover are occasionally found on back- and foreslopes; (**e**) and (**f**) relatively large, monotypic patches of *Acropora cervicornis* are found offshore central Broward County (Photos by: **a**, **e**, **f**, Kenneth Banks; **b**, **c**, **d**, David Gilliam, Susan Devictor)

when compared to the more offshore sites on the inner, middle, and outer reefs. Typically, the inner reef is dominated by juvenile grunts (Haemulidae) (Jordan et al. 2004), whereas wrasses (Labridae) and damselfishes (Pomacentridae) dominate the middle and outer reefs. Due to its close proximity to shore and shallow depths (<7 m), the nearshore hardbottom habitat is ephemeral with movements

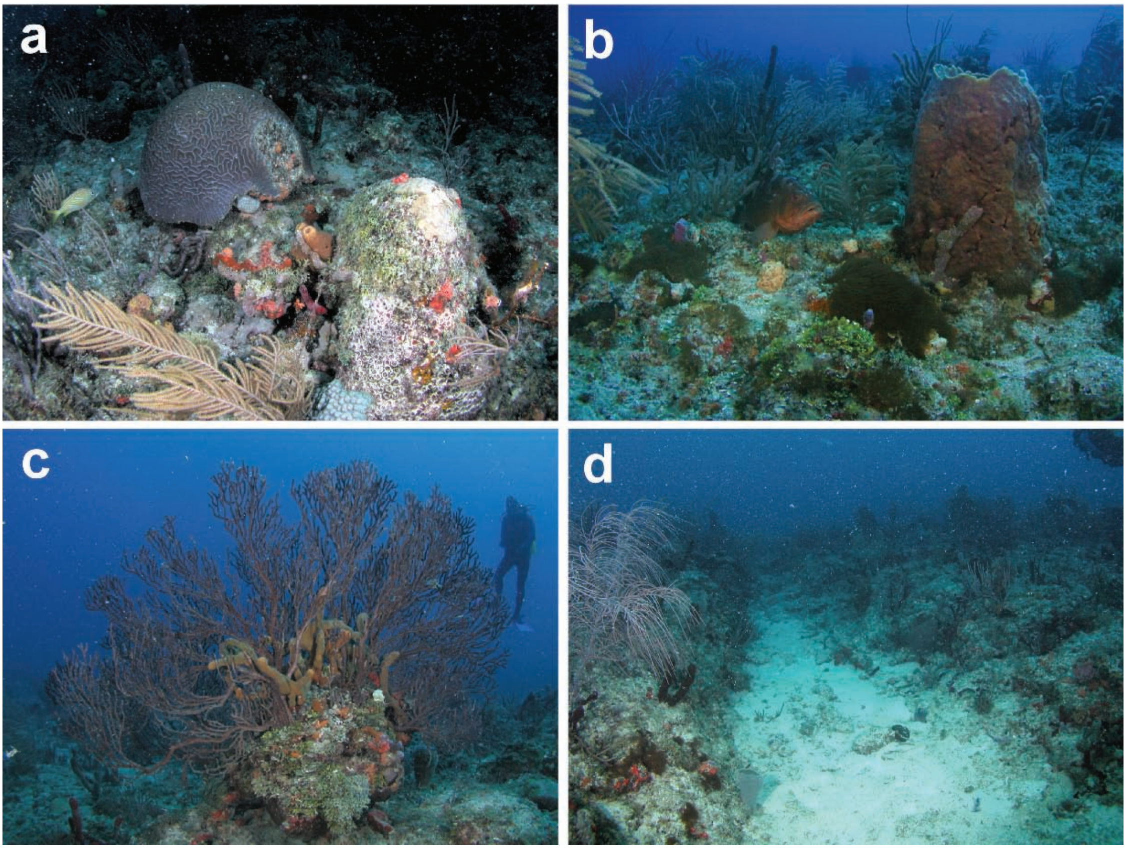

FIG. 5.16. Photos of the outer reef illustrate: (**a**) typical diversity of sponges, octocorals and scleractinians; (**b**) the massive sponge, *Xestospongia muta*, is common on all reef tracts in Southeast Florida; (**c**) the alcyonacean, *Icilligorgia schrammi* is common on the outer reef and areas of high rugosity on the middle reef; (**d**) reef-perpendicular sand channels commonly incise the outer reef (Photos by David Gilliam, Susan Devictor)

TABLE 5.6. Average relative faunal cover for ridge complex and reef tracts of Southeast Florida. FWCC (2006) data averaged over 2003–2004 and based on three sites per county (fourth site in Broward is large stand of *Acropora cervicornis*). Two Broward sites have unusually high stony coral cover (one, 40% cover *A. cervicornis* and one, 12% cover of massive corals on ridge complex sites). Values in parentheses do not include these high cover sites. Data from other studies are averaged over all sites for each county.

	Palm Beach County		Broward County		Miami-Dade County
	(3)	(1)	(3)	(2)	(3)
Octocoral	68%	48%	34% (75%)	50%	65%
Porifera	23%	34%	10% (22%)	25%	16%
Scleractinia	4%	8%	53% (2%)	16%	6%
other	5%	10%	3% (1%)	9%	13%

(1) Foster et al. (2006)
(2) Moyer et al. (2003)
(3) FWCC (2006)

of large amounts of sediments during major storm events (Walker 2007). Nevertheless, when compared to other natural reef habitats in the area, this low-relief hardbottom contains disproportionately high densities of juvenile fishes (Lindeman and Snyder 1999; Baron et al. 2004; Jordan and Spieler 2006). The ephemeral nature of the nearshore hardbottom and its high proportion of juveniles (with their intrinsic recruitment variability) are likely responsible for the large annual population fluctuations recorded for this dynamic habitat (Jordan and Spieler 2006). Additionally, anthropogenic impact appears to be intense in this habitat. For example, recent (2005–2006) beach renourishment activities (deposition of sand to widen beaches) buried approximately 30,000 m^2 of nearshore hardbottom along a 9-km segment of coastline. Although the habitat loss was mitigated by deploying large boulder artificial reefs (total area ~8.9 acres),

TABLE 5.7. Average relative bottom cover for ridge complex and reef tracts of Broward County. FWCC (2006) data averaged over 2003–2004 and based on three sites per county (fourth site in Broward is large stand of *Acropora cervicornis*). Two Broward sites have unusually high stony coral cover (one, 40% cover *A. cervicornis* and one, 12% cover of massive corals on ridge complex sites) and are not included in the average values.

	Ridge complex d < 6 m			Inner reef d = 6–10 m			Middle reef d = 10–20 m			Outer reef d = 15–30 m		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Bare substrate	15%	72%	–	12%	53%	–	8%	46%	–	4%	43%	–
Macroalgae	68%	4%	–	73%	17%	–	70%	22%	–	60%	18%	–
Octocoral	7%	11%	–	6%	12%	–	10%	17%	–	23%	25%	–
Porifera	3%	3%	–	4%	7%	–	10%	10%	–	12%	10%	–
Scleractinia	3%	8%	4%	2%	3%	1%	1%	4%	2%	1%	4%	2%
Other	4%	2%	–	3%	8%	–	1%	1%	–	0	1%	–

(1) Foster et al. (2006)
(2) Moyer et al. (2003)
(3) FWCC (2006)

TABLE 5.8. Average relative faunal cover for ridge complex and reef tracts of Broward County. FWCC (2006) data averaged over 2003–2004 and based on three sites per county (fourth site in Broward is large stand of *Acropora cervicornis*). Two Broward sites have unusually high stony coral cover (one, 40% cover *A. cervicornis* and one, 12% cover of massive corals on ridge complex sites) and are not included in the average values.

	Ridge complex d <6 m			Inner reef d = 6–10 m			Middle reef d = 10–20 m			Outer reef d = 15–30 m		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Octocoral	41%	46%	–	40%	40%	–	45%	53%	–	64%	63%	–
Porifera	18%	13%	–	27%	23%	–	45%	31%	–	33%	25%	–
Scleractinia	18%	25%	4%	13%	10%	–	5%	13%	2%	3%	10%	2%
Other	24%	8%	–	20%	27%	–	5%	3%	–	0	3%	–

(1) Foster et al. (2006)
(2) Moyer et al. (2003)
(3) FWCC (2006)

TABLE 5.9. Average faunal density for ridge complex and reef tracts of Broward County. FWCC (2006) data averaged over 2003–2004 and based on three sites per county (fourth site in Broward is large stand of *Acropora cervicornis*). Two Broward sites have unusually high stony coral cover (one, 40% cover *A. cervicornis* and one, 12% cover of massive corals on ridge complex sites) and are not included in the average values.

	Ridge complex d <6 m	Inner reef d = 6–10 m			Middle reef d = 10–20 m				Outer reef d = 15–30 m			
	(1)	(1)	(2)	Average	(1)	(2)	(3)	Average	(1)	(2)	(3)	ave
Octocoral	5.9	9.8	3.0	6.5	4.9	4.0	9.5	8.5	8.9	11.5	12.9	11.1
Porifera	7.7	7.5	4.9	6.2	12.6	3.3	50.8	22.2	8.6	3.3	43.3	14.0
Scleractinia	2.4	1.0	4.0	2.5	2.6	3.5	2.2	2.8	2.7	1.4	2.8	2.3

(1) Gilliam et al. (2007)
(2) Blair and Flynn (1989)
(3) Thanner et al. (2006)

preliminary results show that, while these mitigation boulders harbor juveniles at densities similar to the nearshore hardbottom, the percent contribution of juveniles to the total fish assemblage was substantially lower. That is, more adult-stage fishes and a higher piscivore density were found on the boulders, possibly affecting the natural predation rate on neighboring natural substrate (S. Freeman, personal communication 2007).

Reef fish community studies in Miami-Dade County are limited to work by Thanner et al. (2006) who compared benthic and fish communities on artificial and natural reefs offshore northern Miami-Dade County. They found that the middle reef was strongly dominated by Gobiidae, while the outer reef was dominated by Pomacentridae with Scaridae and Labridae closely following. They reported 44 and 48 fish species on the middle and outer reefs, respectively.

As previously mentioned, Broward County has sites with unusually high densities of *Acropora cervicornis* for SE Florida (Section 5.1). The corresponding fish assemblages are also unique to the area. High densities of both juveniles (mainly *Haemulon flavolineatum* [Haemulidae]) and piscivores have been recorded at the *A. cervicornis* thickets (Gilliam et al. 2007). Given the size of the juveniles present, it is likely that this habitat acts as refuge for early juvenile and subadult haemulids. Despite the attraction of juvenile fishes, the natural meshwork created by the branching coral appears to limit larger piscivores from entering.

Also characteristic of Broward County reef fish assemblages are its conspicuously low densities of legal-size groupers and snappers (variable for different species). Ferro et al. (2005) analyzed data from 667 point-counts in Broward County and found only two grouper (Serranidae) of legal size. When compared to reefs in the Upper Florida Keys (Dixie Shoals), Broward County fish assemblages have a substantially lower density of groupers. Point-counts from Dixie Shoals exhibited an abundance of groupers that was four times greater than surveys from Broward County. At Dixie Shoals, on average, two commercially and recreationally important groupers were seen per point-count survey; while in Broward County even single grouper was infrequently seen (Table 5.10). Although legal-sized grouper were recorded during only two of 667 surveys, large grouper exist in Broward County waters albeit at a lower frequency than in the Florida Keys, as evidenced by low commercial landings (Johnson et al. 2007).

Remotely operated vehicle (ROV) surveys along deep habitat at 50–120 m depth (Bryan 2006) revealed little hardbottom. What existed had low vertical relief (<1 m). Of the 27 species recorded from ROV surveys on the 50–120 m depth natural substrate, nine were absent from the more extensive, shallow reef survey.

TABLE 5.10. Grouper (Serranidae) abundances from point-count surveys in Broward County, Florida and Dixie Shoals (Florida Keys).

Species	Broward County abundance	Dixie Shoals abundance
Cephalopholis cruentata (Graysby)	127	40
Cephalopholis fulva (Coney)	2	20
Epinephelus adscensionis (Rock hind)	4	2
Epinephelus guttatus (Red hind)	8	2
Epinephelus morio (Red grouper)	232	5
Mycteroperca bonaci (Black grouper)	0	16
Mycteroperca interstitialis (Yellowmouth grouper)	1	1
Mycteroperca phenax (Scamp)	8	1
Mycteroperca venenosa (Yellowfin grouper)	1	8
Number of point-count surveys	**667**	**47**
Grouper per point-count survey	**0.57**	**2.02**

In addition to its natural hardbottom, Broward County has an abundant and diverse range of artificial reefs deployed with the intention of enhancing fishing and scuba diving activities. Vessel-reefs consisting of ship hulls intentionally scuttled for recreational fishing and diving use at ~21 m depth (Arena et al. 2007) have significantly higher fish abundance and species richness than natural hardbottom, as well as different species composition and trophic structure. Planktivores dominated the vessel-reef fish assemblages (53% versus 27% of total abundance on the nearby natural hardbottom). The higher planktivore densities recorded on vessel-reefs may have been due to entrainment of planktonic food resources as a result of laminar flow disruptions from the tall vertical profiles of the structures (Arena et al. 2007). Vessel-reefs also harbored several species not seen during natural hardbottom surveys (*Lutjanus buccanella* [Lutjanidae] and *Epinephelus niveatus* [Serranidae]) (Arena et al. 2004). Bryan (2006) conducted ROV surveys on three vessel-reefs located between depths of 50–120 m. Anthiinae (mostly *Pronotogrammus martinicensis* [Serranidae]) numerically dominated vessel-reefs and were likely the forage base of the numerous, large, piscivorous fishes inhabiting these same vessel-reefs. Unlike at shallow vessel-reefs, herbivorous fishes were absent from the deep vessel-reefs (Bryan 2006).

Besides the many vessel-reefs in SE Florida, several hundred artificial reef modules (~1 m^3 in size) have been deployed for use as: replicate units for scientific studies examining reef fish colonization and predation, habitat mitigation, and restoration tools. Gilliam (1999) compared fish recruitment on caged and uncaged artificial reef modules at 8 m depth and showed that seasonal density-dependent predation is one of several factors affecting the structure of the associated fish assemblages. Nearshore (8 m) sites had a lower disparity

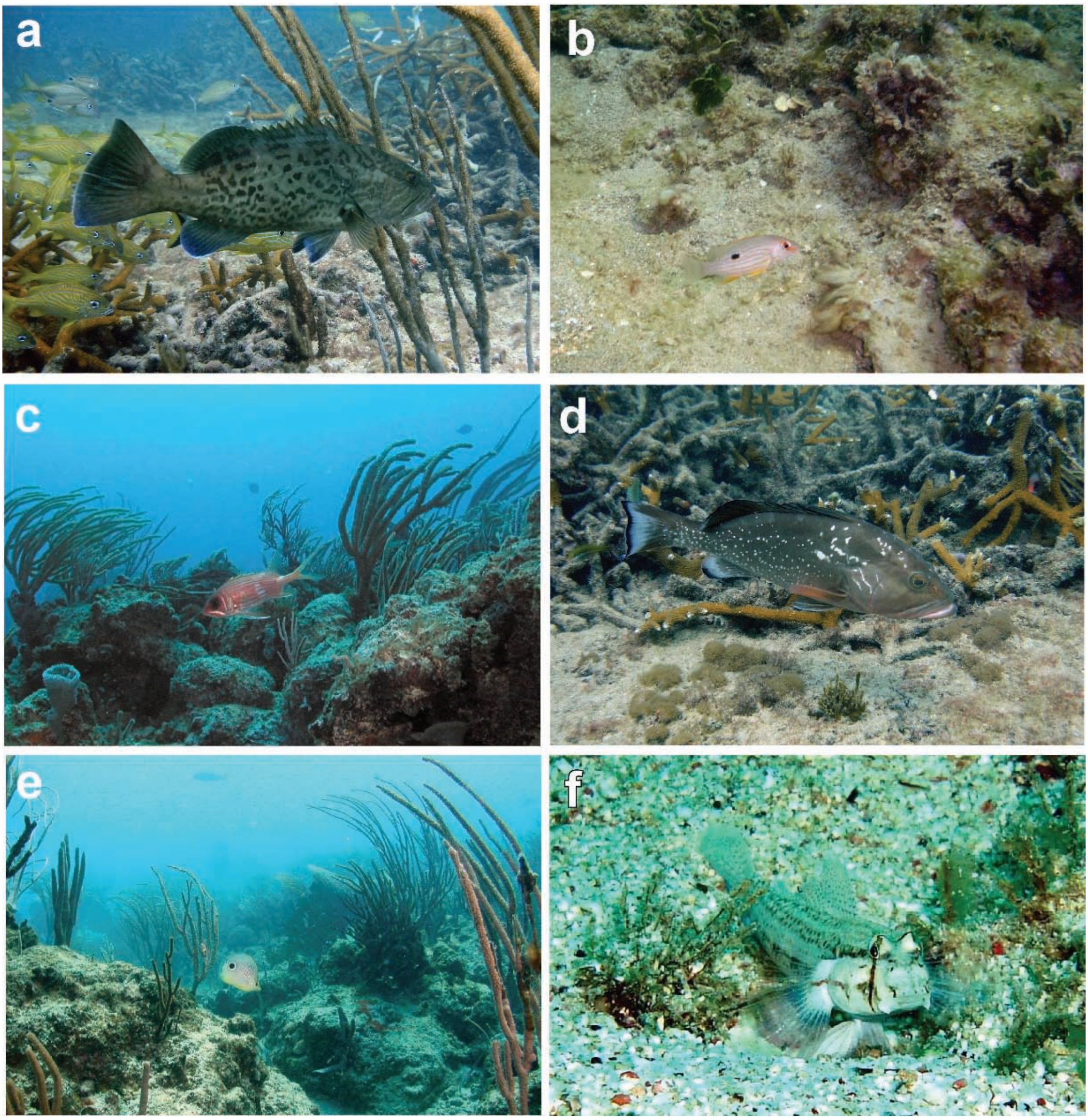

FIG. 5.17. (**a**) Gag grouper (*Mycteroperca microlepis)* at staghorn coral thicket. (**b**) Juvenile lane snapper (*Lutjanus synagris*) on nearshore hardbottom. (**c**) Longspine squirrelfish (*Holocentrus rufus*) on outer reef. (**d**) Red grouper (*Epinephelus morio*) at staghorn coral thicket. (**e**) Foureye butterflyfish (*Chaetodon capistratus*) on outer reef. (**f**) Goldspot goby (*Gnatholepis thompsoni*). (Photos by: **a**–**e** L. Jordan, **f** by K. Kilfoyle)

in newly settled Haemulidae abundance between caged and uncaged modules suggesting predation pressure to be lower in the nearshore environment. This supports the notion that nearshore hardbottom habitats are nurseries for juvenile fishes (L. Jordan, personal communication 2007).

5.5.3.2 Palm Beach County

A total of 2,440 fish surveys conducted at 109 sites in Palm Beach County (PBC) between 1993 and 2007 documented 400 species of fish. Of these, seven were sightings of exotic species found only on offshore reefs. Comparison of species reported for north versus south Palm Beach County found 300 species in common. 43 species were recorded in the north and not in the south compared to 56 additional species recorded in the south but not the north. The most frequently sighted species differed markedly. Table 5.11 lists the top 20 species documented for both north and south PBC. Markedly different assemblages reflect the differing reef habitats between north and south Palm Beach County. Only five of the most common species are shared between the north and the south (porkfish, sergeant major, bluehead, French grunt, and bluestriped grunt).

Comparison of species reported from nearshore reefs for north versus south PBC (Table 5.12) found

TABLE 5.11. The 20 most frequently sighted fish species in North and South Palm Beach County (courtesy REEF database).

Family	Family	Common name	Scientific name	N freq.	S freq.
Surgeonfish	Acanthuridae	Ocean Surgeon	*Acanthurus bahianus*	33.20%	70.80%
Surgeonfish	Acanthuridae	Doctorfish	*Acanthurus chirurgus*	87.50%	59.20%
Surgeonfish	Acanthuridae	Blue Tang	*Acanthurus coeruleus*	47.30%	86.70%
Butterflyfish	Chaetodontidae	Foureye butterflyfish	*Chaetodon capistratus*	19.50%	69.70%
Butterflyfish	Chaetodontidae	Spotfin Butterflyfish	*Chaetodon ocellatus*	24.50%	70.20%
Butterflyfish	Chaetodontidae	Reef Butterflyfish	*Chaetodon sedentarius*	32.50%	70.60%
Grunt	Haemulidae	Black Margate	*Anisotremus surinamensis*	61.70%	62.50%
Grunt	Haemulidae	Porkfish	*Anisotremus virginicus*	91.60%	89%
Grunt	Haemulidae	Tomtate	*Haemulon aurollneatum*	54.20%	66.10%
Grunt	Haemulidae	French Grunt	*Haemulon flavolineatum*	78.30%	77.80%
Grunt	Haemulidae	Sailor's Choice	*Haemulon parra*	66.80%	48.90%
Grunt	Haemulidae	Bluestriped Grunt	*Hemulon sciurus*	66.40%	77.60%
Spadefish	Ephippidae	Atlantic Spadefish	*Chaetodipterus faber*	73.30%	36.50%
Chub	Kyphosidae	Bermuda/Yellow chub	*Kyphosus sp.*	69.50%	36.50%
Wrasse	Labridae	Spanish Hogfish	*Bodianus rufus*	38%	75%
Wrasse	Labridae	Slippery Dick	*Halichoeres bivittatus*	67.50%	33.30%
Wrasse	Labridae	Yellowhead Wrasse	*Halichoeres garnoti*	30%	67.30%
Wrasse	Labridae	Bluehead Wrasse	*Thalassoma bifasciatum*	79.60%	58%
Snapper	Lutjanidae	Schoolmaster	*Lutjanus apodus*	68.50%	31.60%
Snapper	Lutjanidae	Gray Snapper	*Lutjanus griseus*	66.80%	50.70%
Snapper	Lutjanidae	Lane Snapper	*Lutjanus synagris*	63.30%	23.60%
Goatfish	Mullidae	Spotted goatfish	*Pseudupeneus maculatus*	33.60%	78.90%
Angelfish	Pomacanthidae	Queen Angelfish	*Holacanthus ciliaris*	64.60%	48.70%
Angelfish	Pomacanthidae	Rock Beauty	*Holacanthus tricolor*	25.80%	74.50%
Angelfish	Pomacanthidae	French Angelfish	*Pomacanthus paru*	85%	88.10%
Damselfish	Pomacentridae	Sergeant Major	*Abudefduf saxatilis*	85.90%	86.20%
Damselfish	Pomacentridae	Beaugregory	*Pomacentrus leucostictus*	73.90%	32.40%
Damselfish	Pomacentridae	Bicolor Damselfish	*Pomacentrus partitus*	52.40%	82.30%
Parrotfish	Scaridae	Redband Parrotfish	*Sparisoma aurofrenatum*	29.50%	67.70%
Parrotfish	Scaridae	Yellowtail Parrotfish	*Sparisoma rubripinne*	64.20%	21.70%
Parrotfish	Scaridae	Stoplight Parrotfish	*Sparisoma viride*	28.50%	79.30%
Drum	Sciaenidae	High-Hat	*Equetus acuminatus*	71%	63.40%
Barracuda	Sphyraenidae	Great Barracuda	*Sphyraena barracuda*	73.80%	26%

"N freq." is the sighting frequency for north Palm Beach County
"S freq." is the sighting frequency for south Palm Beach County

TABLE 5.12. Top 20 nearshore species listed for both North and South Palm Beach County with sighting frequencies.

Family	Family	Common name	Scientific name	N freq.	S freq.
Surgeonfish	Acanthuridae	Ocean Surgeon	*Acanthurus bahianus*	10.90%	47.30%
Surgeonfish	Acanthuridae	Doctorfish	*Acanthurus chirurgus*	96.70%	73.60%
Surgeonfish	Acanthuridae	Blue Tang	*Acanthurus coeruleus*	28%	47.30%
Jack	Carangidae	Bar Jack	*Caranx ruber*	50.20%	73.60%
Snook	Centropomidae	Snook	*Centropomus undecimalis*	95%	5.20%
Anchovies	Engraulidae			89%	26.30%
Spadefish	Ephippidae	Atlantic Spadefish	*Chaetodipterus faber*	94.90%	10.50%
Mojarra	Gerreidae	Yellowfin mojarra	*Gerres cinereus*	76.70%	57.80%
Grunt	Haemulidae	Black Margate	*Anisotremus surinamensis*	62.60%	71%
Grunt	Haemulidae	Porkfish	*Anisotremus virginicus*	94.30%	60.50%
Grunt	Haemulidae	French Grunt	*Haemulon flavolineatum*	86%	50%
Grunt	Haemulidae	Sailor's Choice	*Haemulon parra*	80.30%	52.60%
Chub	Kyphosidae	Bermuda/Yellow chub	*Kyphosus sp.*	88.40%	39.40%
Wrasse	Labridae	Slippery Dick	*Halichoeres bivittatus*	81.10%	73.60%
Wrasse	Labridae	Bluehead Wrasse	*Thalassoma bifasciatum*	83%	60.50%
Snapper	Lutjanidae	Schoolmaster	*Lutjanus apodus*	91.90%	5.20%
Snapper	Lutjanidae	Gray Snapper	*Lutjanus griseus*	76.70%	50%
Snapper	Lutjanidae	Lane Snapper	*Lutjanus synagris*	86.60%	52.60%
Filefish	Monacanthidae	Orangespotted Filefish	*Cantherhines pullus*	10%	55.20%
Angelfish	Pomacanthidae	French Angelfish	*Pomacanthus paru*	96.10%	42.10%
Damselfish	Pomacentridae	Sergeant Major	*Abudefduf saxatilis*	97.60%	94.70%
Damselfish	Pomacentridae	Beaugregory	*Pomacentrus leucostictus*	92.50%	52.60%
Damselfish	Pomacentridae	Cocoa Damselfish	*Pomacentrus variabilis*	50.90%	68.40%
Parrotfish	Scaridae	Yellowtail Parrotfish	*Sparisoma rubripinne*	97.70%	60.50%
Drum	Sciaenidae	High-Hat	*Equetus acuminatus*	87.80%	50%
Porgy	Sparidae	Silver Porgy	*Diplodus argenteus*	95.30%	65.70%
Barracuda	Sphyraenidae	Great Barracuda	*Sphyraena barracuda*	92.90%	42.10%

"N freq." is the sighting frequency for north Palm Beach County
"S freq." is the sighting frequency for south Palm Beach County

163 species in common. 92 species were recorded in the north and not in the south compared to only 26 additional species recorded in the south but not the north. The most frequently sighted species recorded for nearshore reefs shared 11 species in common in the top 20 species recorded. In Fig. 5.3 the top 20 species documented for both north and south PBC nearshore reefs are listed with sighting frequencies.

In north Palm Beach County, 343 species of fish were recorded. Of these, 255 were recorded at nearshore sites and 285 were recorded offshore. In south PBC, 356 species were recorded, and of these, 189 species were recorded in the nearshore, 171 recorded at the second reef, and 351 recorded offshore. As would be expected, there is an increase in species richness on the more rugose offshore tracts compared to the inshore tracts (Ettinger et al. 2001).

5.6 Environmental Factors Influencing Reef Biology

In addition to water depth and topographic variations, cooling of surface waters during severe winter cold fronts can be a major environmental control on the distribution of corals with depth. Offshore southern Miami-Dade County, shallow reefs nearest to tidal passes (points of cool water discharge) have the least developed reef communities (Burns 1985). The relatively high latitude of the SE Florida reef system (N25°34′ northward to N26°43′, a distance of 125 km) exposes the SE Florida reefal biota to

Table 5.13. List of species reported for Southeast Florida ridge complex and reefs.

Macroalgae Cyanobacteria	Scleractinia/Milliporina/ Zoanthidia	Octocorallia	Porifera
Dictyota bartayressi	*Acropora cervicornis*	*Briareum asbestinum*	*Agelas clathrodes*
Dictyota spp.	*A. palmata*	*Diodogorgia nodulifera*	*A. conifera*
Galaxaura obtusata	*Agaricia agaricites*	*Ellisella barbadensis*	*A. wiedermyeri*
Halimeda discoidea	*A. fragilis*	*Erythropodium caribaeorum*	*Amphimedon compressa*
H. opuntia	*A. humilis*	*Eunicea calyculata*	*Anthosigmella varians*
Jania adherens	*A. lamarcki*	*E. clavigera*	*Aplysina cauliformis*
Lyngbya confervoides	*Astrangia solitaria*	*E. fusca*	*A. fistularis*
L. polychroa	*Cladocora arbuscula*	*E. laciniata*	*A. fulva*
Padina spp.	*Colpophyllia natans*	*E. laxispica*	*A. lacunosa*
	Dendrogyra cylindrus	*E. palmeri*	*Callyspongia plicifera*
	Dichocoenia stokesii	*E. pinta*	*C. vaginalis*
	Diploria clivosa	*E. succinea*	*Chondrilla nucula*
	D. labyrinthiformis	*E. tourneforti*	*Cinachyra* spp.
	D. strigosa	*Gorgonia ventalina*	*Cliona celata*
	Eusmilia fastigiata	*Iciligorgia schrammi*	*C. delitrix*
	Favia fragum	*Lophogorgia cardinalis*	*Diplastrella megastellata*
	Isophyllia sinuosa	*Muricea laxa*	*Dysidea* spp.
	Leptoseris cucullata	*M. muricata*	*Ectyoplasia ferox*
	Madracis decactis	*M. pendula*	*Haliclona* spp.
	M. mirabilis	*Muriceopsis petila*	*Holopsamma helwigi*
	M. pharensis	*Nicella schmitti*	*Iotrochota birotulata*
	Manicia areolata	*Plexaura flexuosa*	*Ircinia campana*
	Meandrina meandrites	*Plexaurella dichotoma*	*I. felix*
	Millepora alcicornis	*P. fusifera*	*I. strobilina*
	Montastraea annularis f. annularis	*P. grisea*	*I. variablis*
	M. annularis f faveolata	*P. pumila*	*Microciona juniperina*
	M. annularis f franksii	*Pseudoplexaura crucis*	*Monachora barbadensis*
	M. cavernosa	*Pseudopterogorgia acerosa*	*M. unguifera*
	Mussa angulosa	*P. americana*	*Mycale laevis*
	Mycetophyllia danaana	*P. elisabethae*	*Myrmekioderma styx*
	M. lamarckiana	*P. navia*	*Niphates digitalis*
	M. aliciae	*P. rigida*	*N. erecta*
	Oculina diffusa	*Pterogorgia citrina*	*Ophiactis* spp.
	Palythoa caribaeorum	*P. guadalupensis*	*Pellina carbonaria*
	Phyllangia americana	*P. citrina*	*Pseudaxinella lunaecharta*
	Porites astreoides	*P. guadalupensis*	*Pseudoceratina crassa*
	P. porites	*Swiftia exserta*	*Ptilocaulis* spp.
	Scolymia cubensis		*Spheciospongia vesparium*
	S. lacera		*Strongylacidon* spp.
	Siderastrea radians		*Tedania ignis*
	S. siderea		*Ulosa ruetzleri*
	Solenastrea bournoni		*Verongula rigida*
	S. hyades		*Xestospongia muta*
	Stephanocoenia intersepta		
	Stylaster rosea		
	Tubastrea coccinea		

Based on data from Blair and Flynn (1989), Foster et al. (2006), Gilliam et al. (2007), Gilliam (personal communication 2006), Goldberg (1973), Kosmynin (personal communication 2006)

low air temperatures during the passage of winter cold fronts. At the northern and southern end of the reef system air temperatures of 14°C and 15°C, respectively, have been reported. The durations of temperature minima are usually short (hours) and water temperatures are moderated by the large mass of warm water of the Florida Current. In a regional sense, the influences of cold air are confounded by

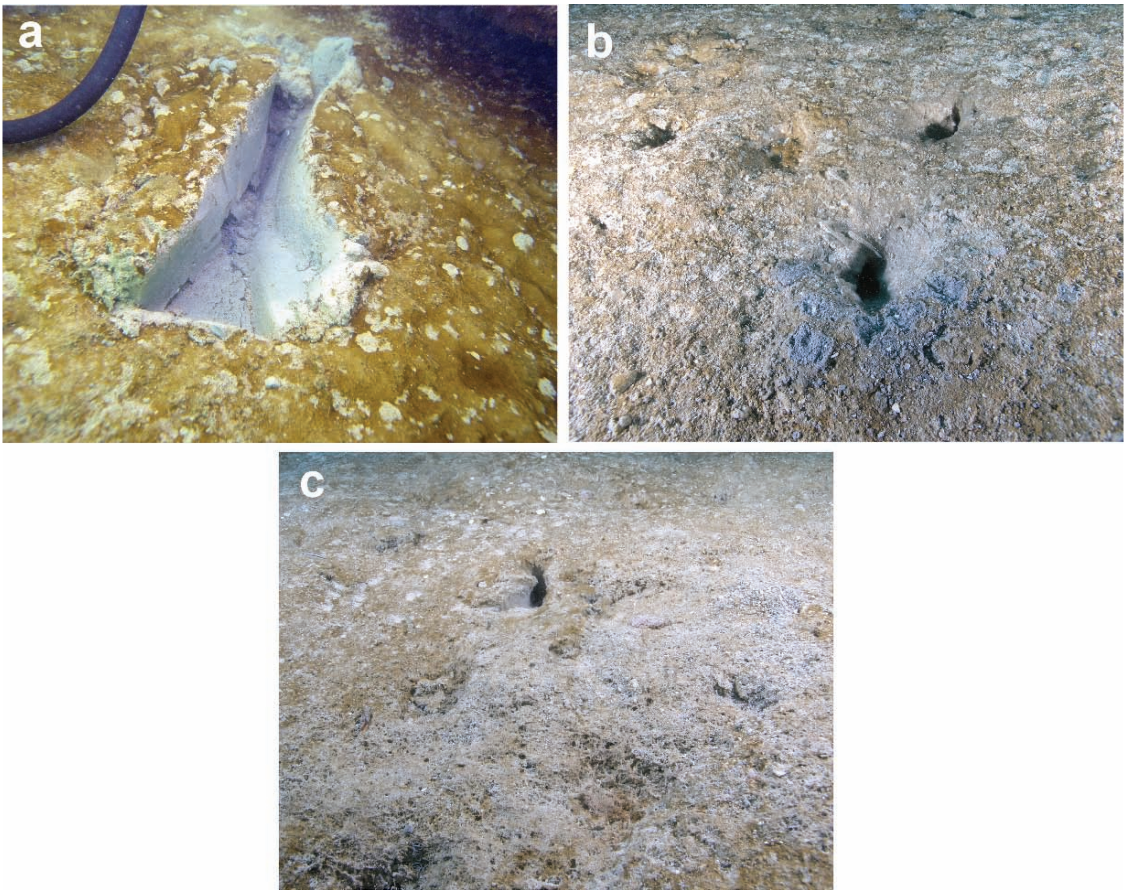

FIG. 5.18. Persistent deposits of silt/clay size sediments were found in sediment depressions and topographic lows on the reef tract and **a, b** and **c** inter-reef sand plains following the passages of hurricanes, Charley, Frances, Ivan, and Jeanne, in 2004 (Photos by: **a** Vladimir Kosmynin; **b**, **c** Kenneth Banks)

the proximity of the Florida Current to the shelf, i.e., closer to shore in the north and farther in the south. Such air temperature minima are near the lower tolerance limit for many reef-associated biota with scleractinia in Florida having a reported lethal limit at 14°C (Porter et al. 1982). Persistence of cold air can have deleterious consequences for many reef associated organisms. In the Florida reef tract, even further south, Roberts et al. (1982) documented water temperatures of 12.6–16.0°C at a depth of 4.3 m for 8 days in January 1977 (24°56′ N) and Lee (in Burns 1985) reported surface temperatures of 13.3°C (25°13′ N) and 15.2°C (25°01′ N) in January 1981. During summer 2003 water temperatures were 5–7°C lower than air temperatures at the northern end of the region (Aretxabaleta et al. 2006) due to upwelling caused by a complex interaction between local and remote atmospheric forcing and open ocean effects which apparently caused mortality of fish and sea-turtles (local media reports).

Lowest average monthly temperatures were in January 2001 with values of 18.3°C (Fig. 5.4e). Average maximum monthly water temperatures in this time period exceeded 29°C in the summers of 2001 and 2002 (Fig. 5.4f). Elevated water temperatures can induce coral bleaching and while bleaching of some stony corals, octocorals, and *Palythoa caribbeorum* colonies has been observed, mass bleaching events have not occurred since the El Nino of 1997–98. Roberts et al. (1982) reported cold-water disturbances in Florida Bay in January 1977 with temperatures below 16°C sustained for 8 days (minimum recorded water temperature was 12.6°C). Burns (1985) attributed the lack of acroporids on the shallow fore-reef, the increase in total coral cover with depth and the greater abundance of *Montastraea annularis* in the deepest zones in the upper Florida Keys as a result of cooling of surface waters during severe winter cold fronts. Water temperatures in SE Florida were likely similar or lower than the low temperatures recorded in the Florida Keys in 1977 (Roberts et al. 1982). Thus, aperiodic chilling processes have a limiting influence on reef community development throughout the Florida Keys Reef Tract but probably even more so at the higher latitude reefs of SE Florida.

Sedimentation and turbidity can affect reef organisms by shading, burial of epibiota, and burial of substrate necessary for recruitment and survival of epibiota. The responses of organisms to shading and temporary burial are complicated by adaptation. Telesnicki and Goldberg (1995) documented depressed photosynthesis:respiration ratios and mucous production in the corals *Dichocoenia stokesii* and *Meandrina meandrites* due to elevated turbidity.

Gilliam et al. (2007) have used sediment traps to measure sedimentation on all reef tracts in Broward County since 1997. Their data indicate that the inner reef typically has the highest rate of sedimentation, as well as largest grain size, followed by the middle reef and then the outer reef. This trend is a result of increasing depth and therefore decreasing wave energy. This was illustrated in 2005 when severe sea conditions during hurricane Katrina (25 August 2005) resulted in the highest sedimentation rates measured in that year. FWCC (2006) reported burial of fixed monitoring sites on the ridge complex offshore Palm Beach County in 2005. The cause was unknown, although hurricanes Jeanne and Frances in 2004 may have contributed to substantial sand movement in the shallow ridge complex area.

In 2004, after the Gulf of Mexico and Atlantic coasts of Florida were impacted by four hurricanes (Charlie, Frances, Ivan, and Jeanne), widespread accumulation of silt/clay size sediment was observed on nearshore hardbottom from Cape Canaveral to Fort Lauderdale (Kosmynin and Miller 2007). This material filled sand depressions on the inter-reef sand plains and buried patches of nearshore hardbottom and persisted through at least the winter of 2007 (Fig. 5.18). The origin is unknown but Kosmynin and Miller (2007) hypothesized that hurricane generated waves and currents transported silt/clays shoreward from deeper parts of the continental shelf.

5.7 Human Impacts and Conservation Issues

The proximity of the SE Florida reef tract to a highly urbanized coastal zone contributes a number of human-related stressors to the reef communities. Water pollution, over-fishing, coastal construction activities, vessel anchoring and grounding, as well as ballast water discharge impact the region's reefs. While balancing economic growth with environmental protection is challenging, the economic value of the coral reefs is considerable. Johns et al. (2003) determined the economic contribution by recreational users of artificial and natural reefs (fishers, divers, snorkelers, visitors viewing reefs from glass-bottomed boats) over the period June 2000 to May 2001 to have been US$2.3 billion in sales and US$1.1 billion in income. 36,500 full and part-time jobs were related to the recreational use of the reefs.

5.7.1 Water Quality

Water quality monitoring in SE Florida is limited to inland waters (Trnka and Logan 2006; Caccia et al. 2005; Torres et al. 2003; Carter 2001). Long-term data does not exist for ocean waters, however the Broward County Environmental Protection Department began a coastal water quality monitoring program in 2005 (Craig 2004). Three study sites were established around Port Everglades Inlet where nutrients, chlorophyll, salinity, dissolved oxygen, and pH are measured monthly.

Lapointe (1997) provided evidence that macroalgal blooms on the reefs offshore Palm Beach County were caused by nitrogen from land-based sewage. Finkl and Charlier (2003) and Finkl and Krupa (2003) estimated that nutrient loading of nitrogen and phosphorus from inland agriculture to the

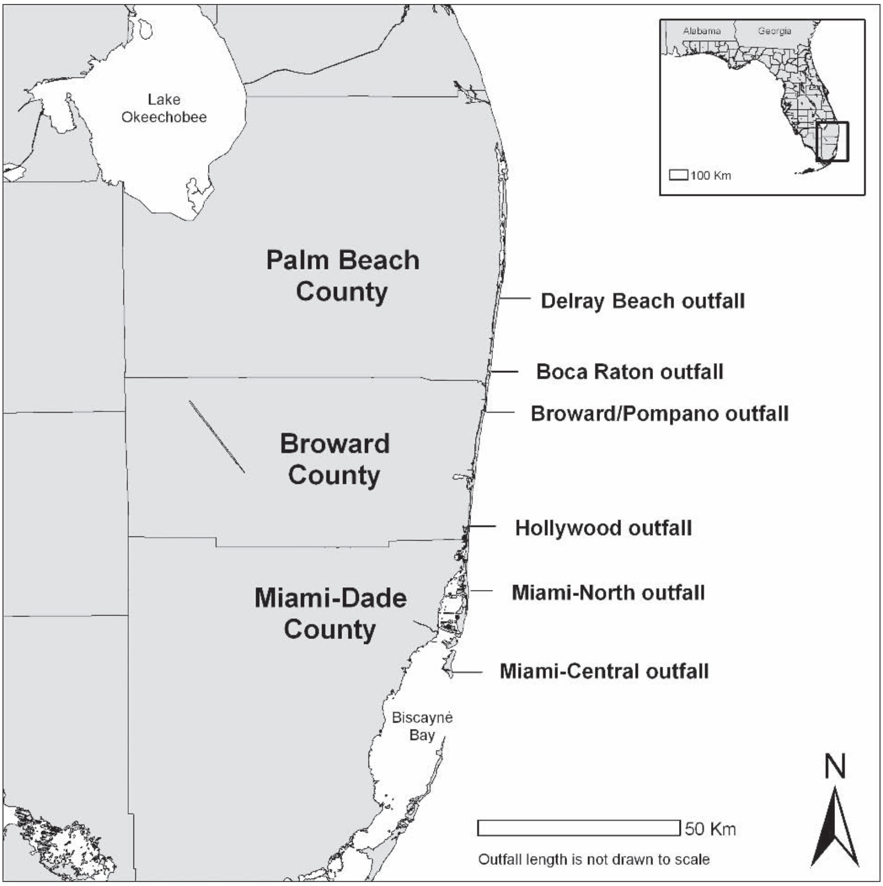

FIG. 5.19. General location of treated human wastewater outfall pipes in Southeast Florida that discharge effluent on lower foreslope of the outer reef

coastal waters offshore of Palm Beach County via surface water discharge are 2,473 and 197 MT/year, respectively, and via submarine groundwater discharge (SGD) 5,727 and 414 MT/year, respectively. They projected that even if nutrient loading to groundwater was to be stopped immediately, effects would still persist 5–8 decades into the future due to slow groundwater flow. Fauth et al. (2006) used cellular diagnostics to detect signs of nutrient-related stress in *Porites astreoides* offshore Broward County when compared to samples from the Bahamas. 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.

5.7.2 Coastal Construction

Before 2000, coastal construction activities in SE Florida were primarily related to installation of cross-shelf wastewater outfall pipes and dredging projects for inlet channel maintenance and beach restoration. The proximity of the reef tracts and hard bottom communities to the coast increases the potential for impacts from any dredging or other coastal construction activities.

Six wastewater pipes cut through the reef tracts in SE Florida (Fig. 5.19), which were constructed at a time when there was little awareness of reef resources or concern for the environment in general. The pipes were placed in deep trenches cutting through the reef. An overburden of boulders or articulated concrete block mats was used for protection where pipes traversed sand. The discharge points for the pipes are on the lower foreslope of the outer reef.

Seven navigational inlets exist in SE Florida (Fig. 5.1). North Lake Worth Inlet (locally called Palm Beach Inlet), Port Everglades Inlet and Government Cut service seaports and are maintained for large vessel traffic. South Lake Worth Inlet (also called Boynton Inlet), Boca Raton Inlet, Hillsboro Inlet, and Haulover Inlet are limited to use by smaller vessels due to depth constraints or bridge height clearances. Although all of the inlets are jettied, littoral transport of sand from the north results in in-filling of the inlet channels with ebb or flood shoals. Maintenance dredging usually involves removing this sand to down-drift beaches or to deepwater Offshore Dredge Material Disposal Sites (ODMDS) (EPA 2004). A number of harbor deepening projects have been proposed in recent years as a result of a trend toward larger, deeper draft commercial ships. Since the inlet channels cross the reef tracts, large areas of reef will be removed. Physical damage to reef and hardbottom in the vicinity of dredging activity can occur from slack tow cables scraping the bottom, sedimentation resulting from tug boat propeller thrust in shallow water, and vessel anchors. Potential impacts to reefs from these dredging projects are primarily related to suspended sediments and turbidity. While the larger grain size sediments settle out rather quickly, the finer grain material may remain suspended for long periods of time. Subsequent advection by ebb tidal flows can lead to exposure of the surrounding reefs to turbidity and sediment deposition.

Another common type of dredging project in SE Florida is for the restoration of eroded beaches. Beach erosion is a problem because inlet jetties interrupt the transport of quartzose sands from the north causing sand starvation downdrift. In addition, coastal development has narrowed the beach zone, preventing the beach from absorbing wave energy. Regular nourishing of the beaches began in the early 1970s and continues to the present day. Eroded beaches are filled with sand dredged from between reef tracts and are generally re-nourished on 10–15-year intervals. Cutter-head and hopper

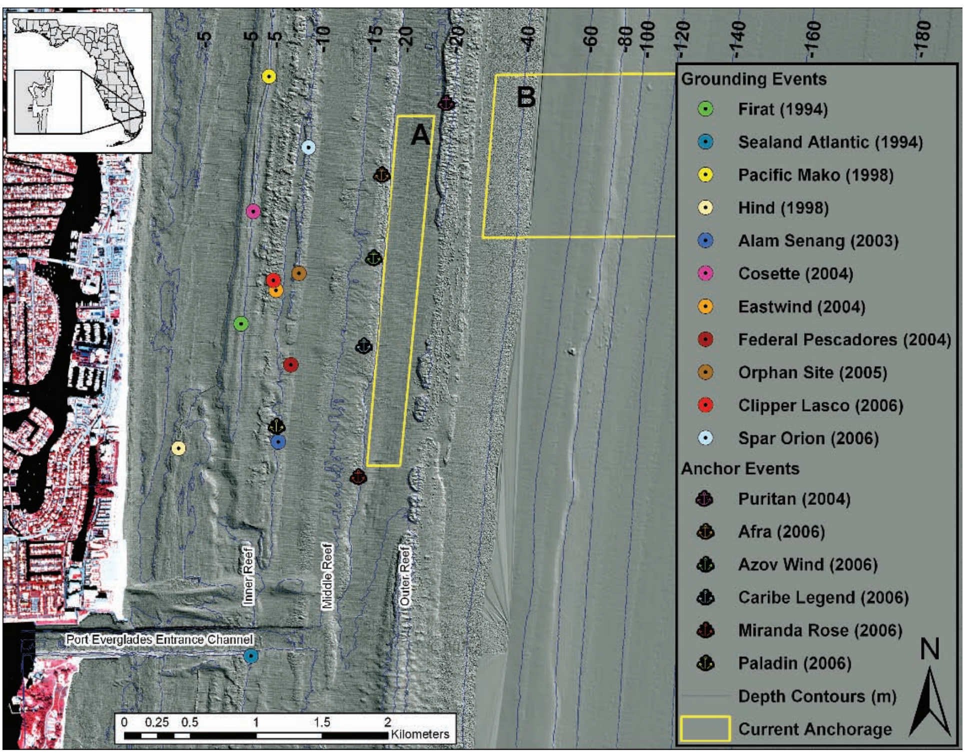

FIG. 5.20. Position of shipgroundings near Port Everglades, Broward County. Most groundings are related to the proximity of the middle reef to the shallow anchorage A

dredges used for beach nourishment are large vessels and must maneuver in small areas when dredging around reefs. The result is an increased risk of physical impacts from cutter-heads and drag arms hitting the reef and tow cables of support vessels dragging over the reef. As in the case for inlet dredging, sedimentation and turbidity are also problematic. Nearshore hardbottom is often directly buried during beach filling or during the adjustment of the beach profile after filling.

Rapid population growth in the SE Florida region has resulted in an increased demand for energy and communications infrastructure. A number of linear, cross-shelf natural gas pipelines and communications cables are planned or have been constructed.

Three natural gas pipelines have been proposed for SE Florida. Initial plans were to use horizontal directional drilling (HDD) to create pilot holes under the reef tracts which would subsequently be enlarged to the necessary diameters for pipeline installation. Because of the risk of frac-outs (leakage of drilling muds through the porous substrate underlying the reefs) and other potential impacts from the release of drilling muds, HDD was abandoned in favor of tunneling under the coastal shelf. This technology is well developed and minimizes risks to the reefs.

Communications cables are laid directly on the sea floor and although their diameters are small (24 cm), their lengths and numbers can result in significant primary physical reef impacts. Since cable-laying vessels have to come into shallow waters for the installation there is a high risk of impact from propeller wash and tow cable scrapes. ATT's installation of two fiberoptic telecommunications cables resulted in dislocated scleractinian and octocoral colonies, as well as physical damage to many remaining colonies. Re-cementing of stony coral colonies and mitigation were required (PBS&J 1999).

Environmental protection measures used during coastal construction projects has progressed greatly in recent years because of a greater conservation ethic by the public and increased awareness of the resources present. In a recent beach restoration project completed by Broward County, environmental protection and monitoring costs for the project were approximately 20% of the total construction costs. The average for similar projects is approximately 10% (Chris Creed, personal communication). The availability of high resolution bathymetry and advances in positioning technology and remote, real-time monitoring of vessels' position allow the establishment of transit corridors for vessels to minimize vessel-related impacts.

The increased extent and duration of reef impact monitoring associated with coastal construction projects has resulted in an increased knowledge of the reef-associated communities, however, understanding of long-term impacts of these projects remains unclear. Highly urbanized SE Florida presents a number of stressors to reef communities so it is difficult to find suitable experimental control for monitoring. The recent use of molecular and organismal level techniques to determine stress before impacts occur at the community level may be a portent of the future monitoring of project impacts. Vargas-Angel et al. (2006) used histological techniques to determine sedimentation induced stress on corals and calibrated a visual method of determining organismal stress. Fauth et al. (2006) used enzymatic biomarkers in the stony coral, *Porites astreoides*, coupled with analysis of community structure and healing of lesions to look for possible impacts of wastewater outfall pipes and inlet discharges. These techniques using multiple levels of monitoring could be expanded to examine impacts from coastal construction.

5.7.3 Ship Groundings and Anchor Damage on Reefs

Commercial shipping into the ports at Palm Beach, Port Everglades, and Miami is an important part of the economy of SE Florida and increased 150% between 1964 and 2002 (Andrews et al. 2005). The proximity of reefs to the navigational inlets and commercial ship anchorages leads to a high risk for ship groundings and anchor damage with subsequent reef damage. This reaches an extreme around Port Everglades Inlet where a relatively shallow (d = 20 m) anchorage lies in sand offshore of the middle reef tract. Between 1993 and 2007, eleven ships have grounded on reefs inshore of this anchorage, impacting over 40,000 m^2 (Fig. 5.20) and, fortunately, vessel owners have been relatively responsive in carrying out reef restoration. Efforts among federal, state and local government agencies to eliminate the shallow anchorage are underway in order to reduce impacts and a study of alternative anchorages has been completed (Moffatt and Nichol 2006).

Anchoring of ships outside the designated anchorage and even small boat anchors pose other problems. The number of recreational boats in SE Florida increased by 500% from 1964 to 2002 (Andrews et al. 2005). There is no documentation of the extent of resulting reef damage. To lessen anchor damage by small boat, over 100 moorings were installed in Broward County. Reef impacts due to concentration of reef users around moorings are currently being investigated by Klink et al. (2006).

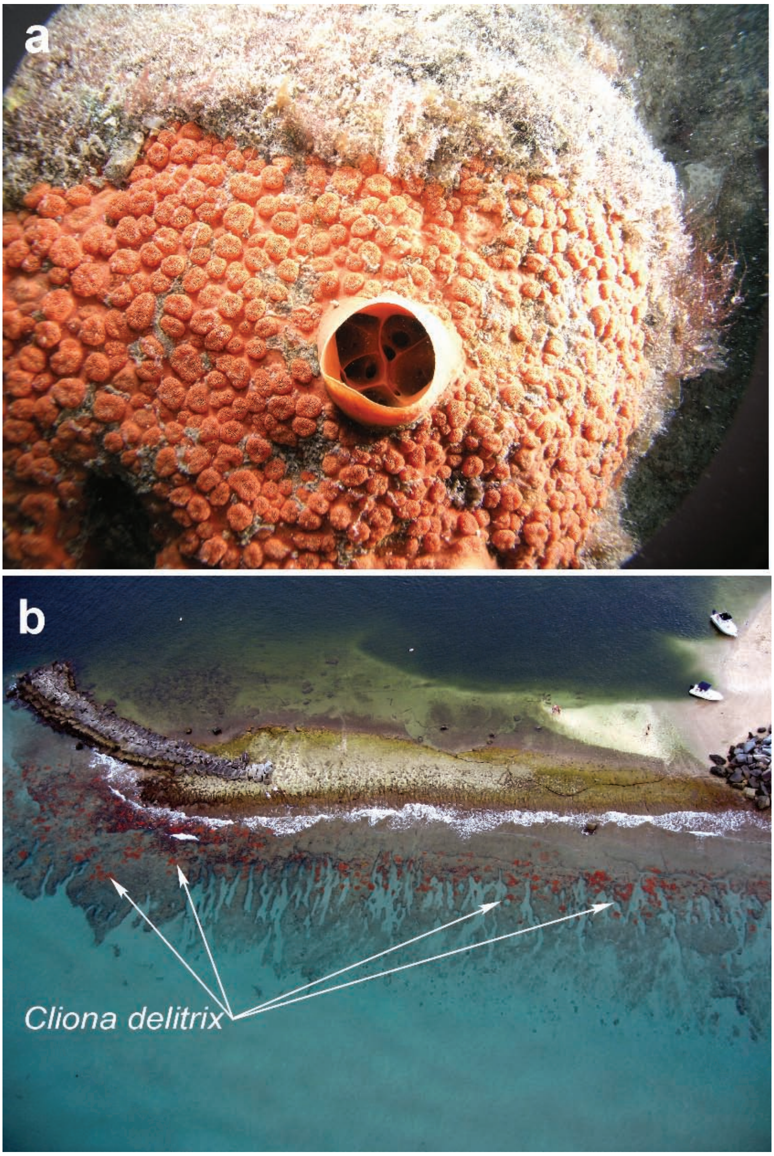

FIG. 5.21. **a** The boring sponge, *Cliona delitrix*, occurs extensively offshore Southeast Florida and may indicate human sewage contamination of the coastal waters (Ward-Paige et al. 2005). **b** Aerial photo of the hardbottom adjacent to the north jetty at Hillsboro Inlet shows high coverage of *C. delitrix* that may correlate with tidal plume contamination (Photos by: **a** K. Banks; **b** D. Behringer)

5.7.4 Climate Change

Increases in sea temperature, sea level rise and, possibly, increasing levels of ultraviolet radiation due to global climatic change may affect coral reefs in SE Florida. Locally or regionally, changes in tropical cyclone patterns may directly impact the coral communities, and changes in rainfall patterns may affect sedimentation, salinity, nutrient and pollutant inputs (Edwards 1995). Rainfall data for 1890–2000 show that there has been a decline in rainfall since the 1960s for unknown reasons, and global climate models predict a reduction of precipitation for South Florida ultimately resulting in decreased runoff (SFWMD 1996). This may, in itself, be beneficial to reef biota. For example, Dodge and Helmle (2003) found that lower salinities (relative to normal seawater) slowed coral growth rates (see also Section 5.2.4). However, a region's landscape (urbanization) can influence rainfall (Pielke et al. 1999) so the prediction of future rainfall levels is complicated by other factors, including water use patterns by an ever increasing local population.

While many local climatic changes occur on relatively smaller time scales, global events such as eustatic sea level rise and atmospheric warming occur on much larger time scales. Sea level rise is of great concern for low elevation coastal regions, such as SE Florida. The Intergovernmental Panel on Climate Change (IPCC 2007) reported that global sea level rise for the period 1961–2003 averaged 1.8 mm/year (1.3–2.3) and increased to 3.1 (2.4–3.8) mm/year over 1993–2003. Wanless (1989) reported that since 1932 tide gauge records from Key West and Miami show relative sea level rise in South Florida has accelerated and more recent rates are 3–4 mm/year. Titus (1995) estimated that by the year 2050 eustatic sea level will likely rise at least 15 cm (2.7 mm/year) and there is a 10% probability that it will rise 30 cm (5.4 mm/year). Others (Buddemeier and Smith 1988) estimate future rates of 15 ± 3 mm/year as probable over the next century. Such high rates could impact corals directly by shifting them to a deeper, lower light position in the water column. Acroporid reefs would drown under these conditions since their sustained reef accretion rates are only about 10 mm/year. Since SE Florida's reefs are already non-framebuilding relicts in which reef-building biota are small and the reef-associated biota dominate space, one would assume them not to be as sensitive to climatic changes in the shorter term. However, secondary impacts, such as increased sedimentation and turbidity from coastal flooding and erosion, would degrade water quality and could affect reef growth.

5.8 Present Status of Reef Health

It is difficult to compare the health of the reefs of SE Florida with extant Acroporid coral dominated reefs in other areas of the western Atlantic and Caribbean. The Acroporids ceased dominating cover in SE Florida 5–7 cal BP (Lighty 1978; Banks et al. 2007). Most of the declines reported in other areas have been a result of loss of *Acropora* spp. to white band disease (Gardner et al. 2003). White band disease has been reported in 1.8% of the cover of the *Acropora cervicornis* thickets offshore of Broward County described by Vargas-Angel et al. (2003).

The Caribbean-wide decrease of *Diadema antillarum* was also experienced in SE Florida where Goldberg (1973) reported this sea-urchin to have been abundant offshore Boca Raton. In contrast, FWCC (2006) reported none at 10 SECREMP sites from Palm Beach to Miami-Dade Counties. Six were seen at for sites in 2004 and 15 at six sites in 2005. Recovery therefore seems to be lagging.

Ward-Paige et al. (2005) surveyed clionid sponges on the Florida Keys reef tract and found a relationship with sewage contamination. In SE Florida FWCC (2006) reported *Cliona delitrix* at all sites, except at the *A. cervicornis* thickets. *Montastraea cavernosa*, the regionally most abundant scleractinian, was most affected by this sponge. Diver observations by one of us (KB) indicate that *C. delitrix* is abundant throughout Broward County, particularly on the ridge complex and inner and middle reefs (Fig. 5.21).

In SE Florida harmful algal blooms of *Caulerpa brachypus* have occurred extensively offshore Palm Beach County during the past decade (Lapointe et al. 2006). In February 2007, *Caulerpa brachypus* spread into northern Broward County. Paul et al. (2005) reported extensive blooms of the cyanobacteria, *Lyngbya confervoides* and *L. polychroa*, on the reefs offshore of Broward County. These blooms have had a significant impact on reef-associated organisms by smothering and out-competing recruits of sessile benthos (Lapointe 1997). For example, at a study site of Gilliam et al. (2007) on the inner reef, significant coverage of *Lyngbya* spp. in 2003 had affected most erect octocorals and their densities declined steadily from 2003–2005. Also sponge density dropped from ~13/m^2 in 2002 to ~6/m^2 in 2003. Some subsequent recovery increased numbers in 2004 to ~8/m^2. Scleractinian cover did not appear to be impacted by *Lyngbya* spp.

The incidence of coral bleaching and disease has been relatively low in SE Florida since 2004, when data were first collected. In 2004, 19 diseased coral colonies were identified in the 10 study sites. In 2005, 21 diseased colonies were identified, 10 of which had apparently been infected in 2004. Nine of those were *Siderastrea siderea* with dark spot syndrome and had recovered by 2005. White complex disease was more prevalent in 2005 (FWCC 2006). No totally bleached coral colonies were observed although partial bleaching was more common than disease.

5.9 Conclusions

The SE Florida reef system consist of relict, early Holocene *Acropora palmata* framework reefs and indurated sand ridges that still maintain a rich, typically Caribbean, but non-framebuilding fauna today. The dominant hard corals are *Montastrea* spp. but living space cover by hard corals is overall low (<6%). Rich alcyonacean communities of typically Caribbean composition cover the majority of benthic space, allowing high benthic space cover. Three shore-parallel reefs (inner, middle, outer) are separated by sandy plains. The middle and outer reefs generally harbor denser benthic cover, dominated by sponges and alcyonacean soft corals. The inner reef is generally more sparsely settled, but has some large patches of dense *Acropora cervicornis* growth, which represents the northern latitudinal distribution limit for these corals The fish communities are typically Caribbean and similar in composition to the Florida Keys, but changes in community composition are observed in Palm Beach County. Heavy recreational fishing pressure has reduced size classes and population densities of groupers and snappers. Threats to the area's reefs are pollution, coastal construction and dredging projects. Recently, benthic cyanobacteria and algae blooms have caused heavy mortality among alcyonacean and hard corals. The local economic value of these reefs is in the range of \$2.3 billion in sales and \$1.1 billion in income per year. 36.500 jobs rely on the use of the reefs.

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