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IMPACTS OF BOTTOM TRAWLING ON A DEEP-WATER *OCULINA* CORAL ECOSYSTEM OFF FLORIDA

John K. Reed, Christopher C. Koenig, and Andrew N. Shepard

ABSTRACT

In 1984, a portion of the deep-water *Oculina* coral reef ecosystem off eastern Florida was protected as the *Oculina* Habitat Area of Particular Concern (OHAPC), prohibiting bottom trawls, longlines, dredges, and anchors. Unfortunately, the northern two thirds of the reef system remained open to these gear until 2000 when the OHAPC boundaries were expanded to 1029 km^2. In the 1970s, the *Oculina* reefs were teeming with large spawning aggregations of grouper and snapper. By the early 1990s, commercial and recreational fishing had decimated the fish populations, and the coral had been severely impacted by bottom trawling for rock shrimp. Historical photographic transects, taken in the 1970s with the Johnson-Sea-Link submersibles, provide crucial evidence of the status and health of the reefs prior to heavy fishing and trawling activities. Quantitative analyses of photographic images by point count reveal drastic loss of live coral cover between 1975 and 2001. Six coral reef sites had nearly 100% loss of live coral, whereas only two reefs which were within the boundaries of the original OHAPC since 1984 survived and were not impacted by trawling. Management and conservation plans for deep-sea coral reef ecosystems worldwide must be based on sound scientific understanding as well as adequate surveillance and enforcement; this study will help build a foundation for this understanding.

The deep-water *Oculina varicosa* Lesueur, 1821 coral reef ecosystem is known only off the east coast of Florida. At depths of 70–100 m this azooxanthellate, branching coral produces 1–2 m diameter colonies that coalesce into thicket-like habitats and high-relief bioherms that are similar in structure to deep-water *Lophelia* coral reefs (Reed, 2002a,b; Reed et al., 2005, 2006). The majority of this *Oculina* habitat is known between 27°30´N (Fort Pierce) and 28°30´N (Cape Canaveral) in a zone 2–6 km wide, paralleling the 80°W meridian (Avent et al., 1977; Reed, 1980). Historical accounts in the 1970s and 80s indicate high densities of economically important reef fish including large spawning aggregations of grouper associated with the coral habitat (Gilmore and Jones, 1992; Koenig et al., 2000, 2005; Reed et al., 2005, 2006). In 1984, the South Atlantic Fishery Management Council (SAFMC) designated one third of the known reef system (315 km^2) as the *Oculina* Habitat Area of Particular Concern (OHAPC) to protect the coral habitat from bottom trawling, dredging, longlines, and anchoring. Unfortunately, the northern two thirds of the reef system remained unprotected and was legally open to these mechanically destructive activities. During the 1980s and 90s, bottom trawling within *Oculina* ecosystem was primarily for rock shrimp and brown shrimp and this was the primary cause of major habitat destruction. Also commercial dredging for calico scallops was prominent in the 1970s–1980s but overfishing and destruction of habitat caused the collapse of the industry. By the early 1990s, grouper spawning aggregations, which in the 1970s consisted of hundreds of grouper on each reef, were virtually eliminated primarily by commercial and recreational hook-and-line fishing (Koenig et al., 2000, 2005). This stimulated the SAFMC to ban hook-and-line fishing for grouper in 1994 to test the effectiveness of a fishery reserve. In 2000, the *Oculina* HAPC boundaries were expanded to 1029 km^2 and the

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original HAPC, termed the *Oculina* Experimental Closed Area (OECA), continued the additional ban on bottom fishing (Federal Register, June 2000).

Historical photographic records from submersible surveys of the eastern Florida shelf between 1975 and 1977 provide evidence of the status and health of the deep-water *Oculina* reefs prior to heavy fishing and shrimp trawling activities of the 1980s and 1990s (Avent et al., 1977; Avent and Stanton, 1979; Reed, 1980). The *Oculina* reefs were first discovered during these submersible surveys when twelve east-west photographic transects were haphazardly placed along the shelf-edge break. Over 50,000 35-mm photographs were taken during these submersible transects. Portions of these transects that were over reefs were compared to video transects of the same areas made 25 yrs later in 2001. In this study, random photographic images from both surveys were quantitatively analyzed by point count to determine changes in percent cover of live *Oculina* coral, standing dead coral and coral rubble. This study has resulted in the restoration, protection and archiving of these rare and invaluable photographic images and data, and will provide marine managers and scientists with a quantitative assessment of the health and percent cover of live coral in the 1970s, prior to intense trawling, compared to the same sites today.

Methods and Materials

Historical data from 1975–1977 were based on photographic transects of the benthos at twelve sites from the 30 m isobath to 300 m between Cape Canaveral (28°30´N) and Lake Worth, Florida (26°37´N), using the Johnson-Sea-Link (JSL) human-occupied submersibles (owned and operated by Harbor Branch Oceanographic Institution, HBOI) (Avent et al., 1977; Avent and Stanton, 1979). These east-west transects were spaced ~19 km apart and consisted of 50 submersible dives, totaling 298 km (Fig. 1). During these dives, the deep-water *Oculina* reefs were first discovered and described (Avent et al., 1977; Reed, 1980). Navigation was based on LORAN-A which had an accuracy of ± 150–300 m. Detailed records included written transcripts, and ship and submersible logs documenting coordinates, depth, and physical data throughout the dives. Photographs were taken every 1–2 min with a 35-mm Edgerton-type still camera and flash system (Benthos model 372, Benthos Inc.) that was mounted 29° from vertical, providing average frame coverage of 6.3 m^2 at 3.0 m height and 2.5 m mid-frame width. Viewing angle in water was 54° wide and 42° fore-aft. Area was estimated from camera height and in-water viewing angle of the lens and was verified by flying the sub over a 10-m grid on the bottom. Over 50,000 35-mm photographs were taken with 30-m rolls of Ektachrome film. Each image was coded with time and date which corresponded with the navigation data. Eight of the twelve transects encountered deep-water *Oculina* reefs which were used for this study; these images were recently cut from the original 30-m film rolls, digitized with a Nikon LS2000 Coolscan, enhanced in Photoshop®, and saved as high resolution TIFF files (300 dpi, 3.75 mb file).

Recent data (2001) were collected using the human-occupied Clelia submersible (owned and operated by HBOI). Submersible dives that were in proximity to the historical transects were selected for comparison of reef habitat over a 25-yr period. Color videotapes (Mini-DV digital) were recorded with a pan and tilt videocamera which provided a 72.5° × 57.6° field of view (Sony DX2 3000A, 3 chip 2.6 mm CCD, with Canon J8X6B KRS lens, 6–48 mm zoom, and 0.3 m minimum focus). The downward-looking camera was equipped with four parallel lasers (17.5 cm apart along the edge of the diamond shape) providing scale for quadrat size. Ship navigation was determined with differential global positioning system (Magnavox MX 200 GPS) which is accurate to ± 5 m, and submersible tracks were plotted with the Integrated Mission Profiler (Florida Atlantic University) which links to the ship’s GPS. Still images were derived from randomly selected video frame grabs for quantitative point count analyses.

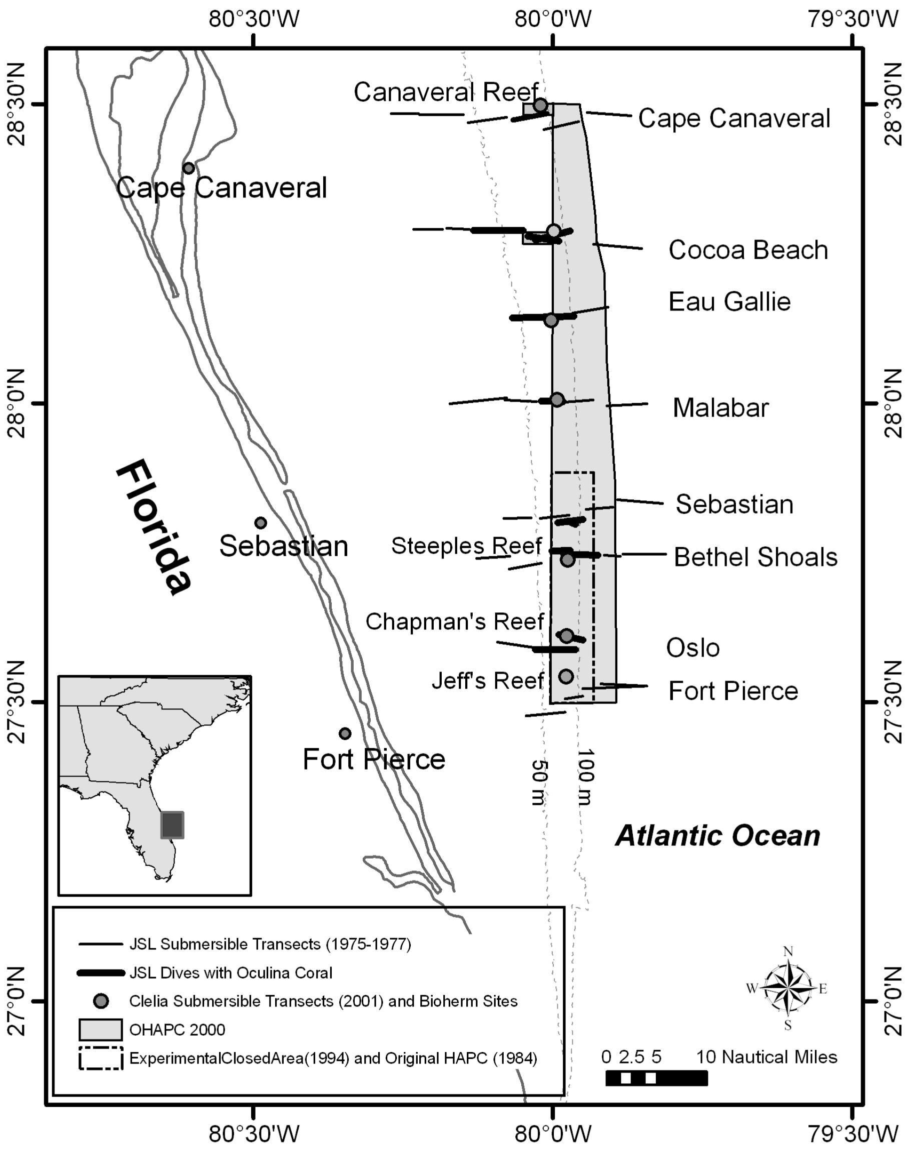

Figure 1. Photographic transect sites and deep-water *Oculina* coral reefs off eastern Florida. Shaded area: 1029 km^2 (300 nmi^2) deep-water *Oculina* Habitat Area of Particular Concern (OHAPC) that was designated in 2000. Dotted boxed area: original boundaries of 315 km^2 (92 nmi^2) OHAPC in 1984 and current boundaries of no-fishing zone of Experimental Closed Area (Marine Protected Area). Photographic transects made from depths of 30–300 m with Johnson-Sea-Link submersible in 1975–1977 (solid lines = individual sub dives; bold line = dives encountering *Oculina* habitat; dots = high-relief *Oculina* reefs and Clelia submersible transect sites in 2001).

Randomly selected historical and recent photographic images from transects that crossed deep-water *Oculina* coral habitat were analyzed for percent cover of three habitat types of *Oculina varicosa* Lesueur, 1821: live coral, dead standing coral, and unconsolidated coral rubble. Each photographic image was overlaid with 100 randomly distributed points to determine percent cover for each habitat type using CPCe software (Kohler and Gill, 2006). The non-parametric Mann-Whitney test was used to determine significant differences between mean coverage estimates from historical and recent transects for all sites except Jeff's Reef. At this site, where considerable coral habitat is still intact, historical and contemporary coverage estimates were more similar and required a more precise statistic to evaluate significant differences. Therefore, for Jeff's Reef we used analysis of variance (ANOVA) with a normalizing arcsine transformation [arcsine(sqrt(x/100))]. Normality was verified after transformation with a Shapiro-Wilk test and multiple comparisons were made with a Fisher's LSD test.

Results

We compare in detail three transect sites that historically showed the highest coverage of live coral between the surveys of 1976–1978 and 2001: Cape Canaveral, Oslo, and Jeff's Reef.

Cape Canaveral Transect (1976).—The Cape Canaveral transect found live *Oculina* within a depth zone of 70–87 m over a distance of 2.4 km (Table 1; Fig. 1). A high-relief *Oculina* bioherm (Canaveral Reef) was found during one dive (JSL II-063) and was described in written transcripts as an 18-m tall coral mound (87 m depth) with 30–45° degree slopes and ~0.35 km width at the base (Fig. 2A). No exposed rock was observed on the slopes or crest of the reef but it appeared to be entirely covered with living and dead *Oculina* coral and sediment. Colonies of live *Oculina* were ~1 m tall (maximum coral colony diameter was 1.7 m in quantified image analyses) on the flanks and the observers estimated 25% live coral cover. Coral colonies along the peak were ~50 cm tall. Some colonies appeared to have been severed into 2 or 3 pieces, possibly by an anchor or cable. A 6-m long, 5-cm diameter cable was found on the bottom near the reef. Dominant fish associated with the reef were snowy grouper *Epinephelus niveatus* (Valenciennes in Cuvier and Valenciennes, 1828), greater amberjack *Seriola dumerili* (Risso, 1810), and smaller reef fish including bank butterflyfish *Prognathodes aya* (Jordan, 1886), blue angelfish *Holacanthus bermudensi*s Goode, 1876, and various damsels and wrasses. West of the bioherm were a series of smaller reefs of moderate to low relief (3–5 m to flat pavement). The dive on the *Oculina* bioherm was divided into four photographic transects (E base, E slope, top ridge, W slope and base). Mean live coral coverage of these transects was the third highest for all sites (mean 19.2%; range 7%–35.1%); standing dead coral was 31.4% and coral rubble 17% (Fig. 3) Maximum coral density for individual photographic quadrats ranged from 32.0%–73.2%.

Cape Canaveral Transect (2001).—In 2001, transects were made at the Canaveral *Oculina* Reef previously mapped in 1976. The submersible dive (Clelia 616) consisted of six transects (W base, N slope, western peak ridge, eastern peak ridge, E slope and base, and SE base). During the 25 yrs between submersible dives, the reef had been reduced to coral rubble (Fig. 2B). Although the 18-m mound still existed, the peaks and flanks on all sides were covered in thick layers of unconsolidated dead coral rubble consisting of pieces ~2–10 cm in length. Some of the dead coral rubble on the upper south and east slopes and peak were somewhat consolidated rubble and well encrusted with demosponges (*Erylus*? sp., *Geodia* sp., Axinellidae) and possibly blue-green algae. Tracks in the coral rubble, apparently made by heavy shrimp trawl doors, appeared as deep, straight grooves (~30 cm deep, 60 cm wide) cut into the coral rubble. A few 1-m colonies of standing dead coral were found at the west base. The only living *Oculina* coral observed was at the southeastern base (82–85 m) where a few 15–60 cm live colonies were observed apparently unattached on sand. The only

Table 1. Comparisons of historical (1975–1982) and recent (2001) estimates of mean percent cover of live colonies of *Oculina varicosa* (OV), standing dead coral (SDC), and coral rubble (CR) on deep-water *Oculina* reefs off eastern Florida. Percent cover estimates are from randomly selected images (quadrats) of photographic transects within the coral habitat at eight transect sites. Statistical differences of percent cover between years at each site are indicated as *** = $P < 0.0001$, ** = $P < 0.001$, * = $P < 0.05$, no symbol = no significant difference ($P \geq 0.05$). Comparisons at Jeff's Reef are for 1977–1996 and 1977–2001.

Transect site	Year	# Quadrats (# transects)	OV Mean (range)	SDC Mean (range)	CR Mean (range)
Cape Canaveral	1976	59 (4)	19.2 (7–35.1)	31.4 (1.8–52.9)	17.0 (11.5–29.7)
	2001	120 (6)	***0.2 (0–0.9)	***1.7 (0–6.6)	***80.5 (26.8–99.7)
Cocoa Beach	1975, '77	24 (3)	3.1 (0.4–5.3)	0.2 (0–0.6)	21.4 (0.5–62.7)
	2001	60 (3)	***0.0 (0)	**0.0 (0)	***75.3 (62.5–93.1)
Eau Gallie	1977	51 (6)	6.6 (0.2–19.1)	5.9 (1.1–15.5)	25.1 (5.2–49.9)
	2001	80 (4)	***0.1 (0–0.3)	18.9 (6.9–32.3)	***78.8 (64.9–91.2)
Malabar	1975	53 (4)	4.2 (1.7–8.8)	3.8 (0.6–7.3)	13.8 (0–51.0)
	2001	not available			
Sebastian	1975, '76	35 (4)	3.2 (0.9–6.9)	3.7 (1.1–6.8)	1.9 (0–5.9)
	2001	40 (4)	***0.1 (0–0.1)	*5.7 (2.7–11.6)	***92.5 (87.3–95.3)
Bethel Shoals	1975	46 (2)	7.1 (6.8–7.4)	12.4 (8.7–16.2)	33.6 (11.9–55.3)
	2001	40 (4)	***0.0 (0)	***5.6 (0.6–20.0)	***92.6 (79.9–98.9)
Oslo (Chapman's)	1977, '82	17 (2)	21.2 (7.0–35.3)	38.2 (27.5–48.8)	40.6 (15.7–65.4)
	2001	80 (5)	11.4 (7.0–22.3)	16.1 (0–27.1)	not available
Jeff's Reef	1977	104 (5)	39.3 (30.6–47.7)	25.8 (20.2–37.8)	25.3 (19.4–31.7)
	1996	70 (5)	***10.3 (8.2–15.0)	***60.2 (36.7–76.7)	25.4 (11.7–53.4)
	2001	100 (5)	***13.4 (7.2–18.8)	*34.0 (26.4–42.3)	***43.4 (34.9–59.6)

large fish were amberjack and a few small reef fish. Since 1976, nearly 100% of the live coral had been lost; mean cover was reduced from 19.2% to 0.2% (Mann-Whitney: $P < 0.0001$) and standing dead coral had dropped from 31.4% to 1.7% ($P < 0.0001$; Table 1, Fig. 3). Concurrently, cover of coral rubble had increased by 64%, from 17% to 80.5% (Mann-Whitney: $P < 0.0001$; Fig. 3C).

Oslo Transect (Chapman's Reef) (1977).—The zone of *Oculina* coral occurred from 65–85 m over a distance of 2.07 km (JSL II-197). Most of the coral was associated with low relief (1–2 m) knolls. Adjacent to this transect an additional dive was made in 1982 on a high relief *Oculina* bioherm named Chapman's Reef (JSL I-1201) which was added to the transect data. This was a steep (30°–45°) sloped feature with 1–2 m live *Oculina* colonies (maximum coral diameter from quantitative image analyses was 1.52 m) forming dense thickets on the slope and peak. No rock outcrops were apparent and the flanks were entirely live coral, coral rubble, and sediment. Quantitative analyses of the two photographic transects showed mean live *Oculina* cover was the second highest of any of the transects (21.2%) and also had large amounts of standing dead coral (38.2%) and unconsolidated coral rubble (40.6%) (Fig. 3). The transect from Chapman's Reef alone had 35.3% mean live coral, 48.8% standing dead coral, and 15.7% coral rubble. Maximum coral density of individual quadrats was 35.6%–47.4% .

Oslo Transect (Chapman's Reef) (2001).—Recent multibeam maps of Chapman's Reef complex show three high-relief *Oculina* banks in close proximity to the historical Oslo Transect. Echosounder transects further showed Chapman's North Reef to be the tallest feature of the three (35 m relief, 57 m at peak, 92 m at north

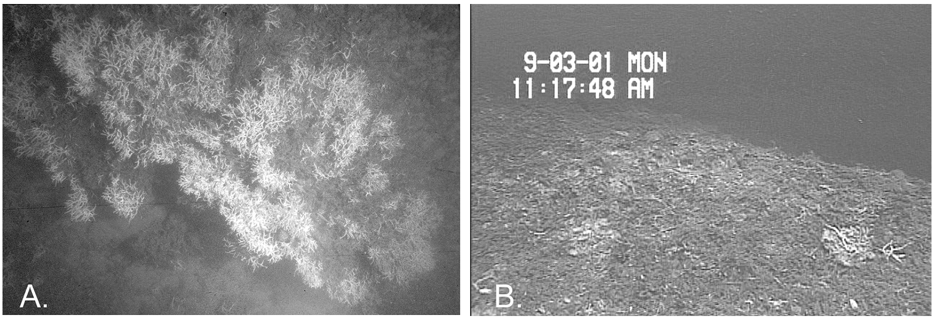

Figure 2. Deep-water *Oculina* bioherm at Cape Canaveral (67 m depth). (A) Historical photo from submersible dive (JSL II-063) in 1976; (B) Same site (Clelia 613) in 2001 reduced to rubble from apparent bottom trawling.

base). The South Reef was 23 m tall and the West Reef was 12 m. Due to inconsistencies between LORAN A and GPS, it is uncertain exactly which of these reefs was surveyed in 1977. In 2001, five photographic transects (Clelia 621) were made on Chapman's Reef West which are described in Koenig et al. (2005). They reported mean live coral cover at 11.4% and mean standing dead coral at 16.1%; coral rubble cover data were not included (Table 1). Because of the limited number of quadrats available from the 1982 dive on Chapman's Reef (9), these data were not statistically compared. However, since 1977 there was a 46% decrease in live coral, a 58% loss of standing dead coral, but the maximum coral diameter remained relatively unchanged (1.52 m and 1.43 m, respectively).

Fort Pierce Transect (Jeff's Reef) (1977).—The original transect site off Fort Pierce consisted of four submersible dives from 30–261 m over 23.3 km; however, no live *Oculina* coral or coral rubble was encountered on this transect. During the same time period a massive live *Oculina* bioherm was discovered just 4 km north of the transect line and is the southern-most living *Oculina* bioherm known. An extensive photographic survey was made by JKR in 1977 on this bioherm (JSL II-164). This 18-m tall bioherm was ~300 m wide and consisted of three E-W oriented ridges (64–70 m minimum depth). Described in Reed (1980), the mound appeared to be entirely coral and sediment and a true bioherm. The 1977 dive was divided into five photographic transects (N, S, E, W flanks, and peak). The east, west, and south slopes and ridges at the peak were covered with massive live *Oculina* coral, 90–150 cm tall. The steep south slope (45°) and south faces of the ridges were covered with dense coral, forming nearly continuous rows of coral bushes. The 30° north slope had more coral rubble, less live coral, and generally smaller colonies of live coral. Dense spawning aggregations consisting of hundreds of scamp *Mycteroperca phenax* Jordan and Swain, 1884 and gag *Mycteroperca microlepis* (Goode and Bean, 1879) grouper were described on this reef and other *Oculina* bioherms in the early 1980s (Gilmore and Jones, 1992). Mean live coral cover was the greatest of all sites (39.3%); standing dead coral was 25.8%, and coral rubble 25.3% (Fig. 3). Maximum coral density from individual quadrats ranged from 46.3%–67.4% and maximum coral diameter was 2.01 m; however, in many cases the corals appeared to grow together into continuous hedges (which exceeded the width of the photograph, ~2.5 m) and it was difficult to ascertain individual colonies.

Fort Pierce Transect (Jeff's Reef) (1996).—In 1996, JKR revisited the reef for the first time in over a decade (JSL II-2800). Video transects were made with similar

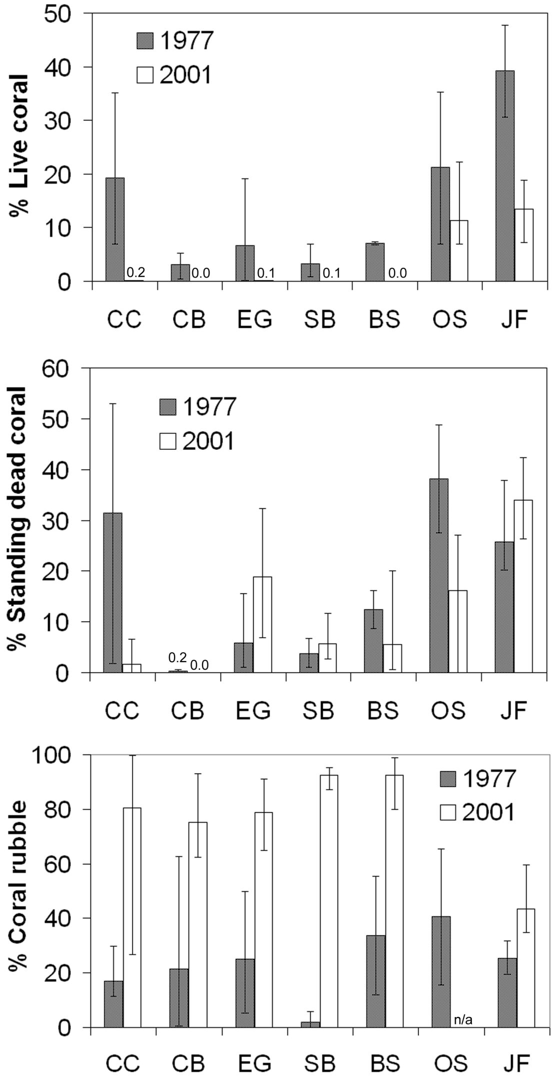

Figure 3. Mean percent (A) live *Oculina* coral, (B) standing dead *Oculina* coral, and (C) *Oculina* coral rubble at submersible transect sites in 1977 (solid bars) and 2001 (open bars) (range bars = range of transect means). CC = Cape Canaveral, CB = Cocoa Beach, EG = Eau Gallie, SB = Sebastian, BS = Bethel Shoals, OS = Oslo (= Chapman's Reef), JF = Jeff's Reef.

methodology and generally in similar locations as the 1977 dive. Five transects were selected for quantitative analyses (N slope, S slope, and top ridges). Mean live coral cover was 10.3%, standing dead coral 60.2%, and coral rubble 25.4%. Maximum coral cover ranged from 12%–36%.

Fort Pierce Transect (Jeff's Reef) (2001).—In 2001, ten video transects were randomly laid out on the reef (Clelia 606). These were divided into the following reef regions (S, W, E, and N slopes, and top ridges). Maximum coral density ranged from 20.4%–55.0%. Mean live coral cover decreased significantly (ANOVA: $P < 0.0001$, Table 1) by 30% between 1977 (39.3%) and 1996 (10.3%), but showed no significant

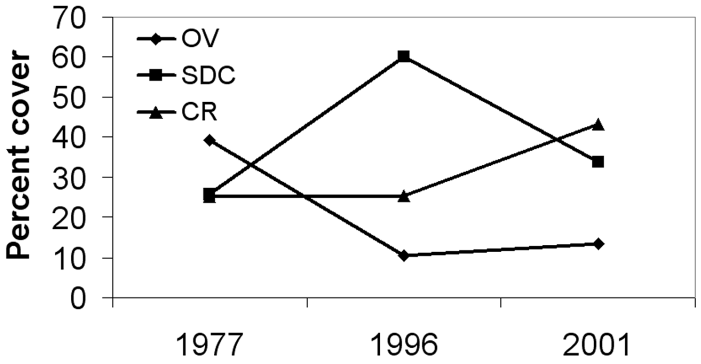

Figure 4. Mean percent cover of live *Oculina* coral (OV), standing dead *Oculina* coral (SDC), and *Oculina* coral rubble at Jeff's Reef bioherm in 1977, 1996, and 2001.

change between 1996 and 2001 (13.4%; ANOVA: $P > 0.05$). Mean standing dead coral cover was significantly different among all 3 yrs (ANOVA: $P < 0.01$) ranging from a low of 25.8% in 1977 to 60.2% in 1996 then down to 34% in 2001. Concurrently, mean coral rubble was similar in 1977 and 1997 (25.3%, 25.4%), but increased to 43.4% in 2001 (ANOVA: $P < 0.001$; Fig. 4).

Four other sites, Cocoa Beach, Eau Gallie, Sebastian, and Bethel Shoals, which had relatively lower live coral cover (mean < 10%) during the 1976–1978 transects also showed nearly 100% coral loss by 2001. The Malabar site also had low live coral cover (4.2%) in 1975 but was not resurveyed in 2001.

Cocoa Beach Transect.—During the historical dives (1975–1977), live *Oculina* was found at this site within a zone extending 6.80 km at depths of 67–82 m that included numerous low to high relief (6–18 m) *Oculina* mounds and ridges. Quantitative analyses showed a mean of 3.1% live coral cover, 0.2% standing dead coral, 21.4% coral rubble, and 37.4% rock pavement and ledges (Fig. 3). Quantitative analyses of the 2001 video transects revealed 0% cover of live coral, 0% standing dead coral, and 75.3% coral rubble. Since 1975 there was 100% loss of live coral (Mann-Whitney: $P < 0.0001$), 100% loss of standing dead coral (Mann-Whitney: $P < 0.001$), and 54% increase in coral rubble (Mann-Whitney: $P < 0.0001$; Table 1).

Eau Gallie Transect.—In 1977, the zone of live coral extended 3.13 km at depths of 59–87 m. At least eight individual moderate relief reefs at depths of ~76 m were found with thickets of live *Oculina*. Within the coral zone, the mean live coral cover was 6.6%, standing dead coral 5.9%, coral rubble 25.1%, and rock pavement and ledges 30.1%. Individual quadrats of the densest coral growth averaged 29.9% and ranged up to 58.3% live coral cover. In 2001, an 18-m tall *Oculina* bioherm was the primary feature of the video survey at this site. The bioherm was 0.37 km wide E-W and consisted of a series of mounds that extended 1.1 km N-S. The submersible dive was divided into four video transects (W, E, and S slopes, and top ridge). The bioherm was entirely covered with thick layers of unconsolidated coral rubble and sediment except for a few 30–90 cm standing dead corals and a few 20–50 cm live colonies. Some colonies were wrapped in monofilament fishing line. The only large fish noted were one gag grouper and a few greater amberjack; no scamp grouper were present. Since 1977 at the Eau Gallie site, mean live coral cover had been almost completely eliminated from 6.6% to 0.1% (Mann-Whitney: $P < 0.0001$), standing dead coral showed no significant change (from 5.9% to 18.9%; Mann-Whitney: $P > 0.05$), and dead coral rubble has increased more than 3-fold from 25.1% to 78.8% (Mann-Whitney: $P < 0.001$; Fig. 3, Table 1).

SEBASTIAN TRANSECT.—Historical dives (1975–1977) encountered live *Oculina* coral in a zone extending 4.61 km at depths of 54.9–85.0 m. Overall, relatively little live coral and no large bioherms were observed on these dives. The mean live *Oculina* cover was 3.2%, standing dead coral 3.7%, and coral rubble 1.9%. The 2001 dive found a zone of dead coral rubble extending at least 1.6 km in length. The bottom was low relief ridges of dead rubble and sparse standing dead coral. The only living coral observed were two 15 cm colonies. Mean live coral cover was 0.1%, standing dead coral 5.7%, and coral rubble 92.5%. Since 1976 there has been nearly 100% loss of live coral (Mann-Whitney: $P < 0.0001$), a significant increase in standing dead coral (Mann-Whitney: $P < 0.05$), and coral rubble had increased by 90.6% (Mann-Whitney: $P < 0.0001$; Fig. 3, Table 1).

BETHEL SHOALS TRANSECT (STEEPLES REEF).—In 1975, two submersible dives encountered *Oculina* coral over a linear distance of 3.7 km at depths of 61–81 m. Patch reefs consisting of large 1.5 m diameter live *Oculina* were present on low relief (0.5–2.5 m) mounds and ridges. Visual observations estimated 5%–10% live coral on these reefs. No large, high relief bioherms were encountered. Mean live *Oculina* coral was 7.1%, standing dead coral 12.4%, and coral rubble 33.6% (Fig. 3). Maximum coral coverage of individual quadrats ranged from 13.1%–33.0%. Additional dives were also made near the Bethel Shoals transect in the late 1970s where two large bioherms were encountered; these were termed the Steeples or the Thompson-Reed Reefs- TR8 and TR9. Although quantitative photographic transects were not made, written transcripts of dive observations indicated that one mound (TR8) had 25-m relief and 1–2 m live *Oculina* colonies were abundant on the south slope and peak. Interestingly, just 0.37 km to the north was a smaller bioherm (TR9, 12.8 m relief) that was entirely dead coral rubble. In 2001, a submersible dive conducted detailed transects over the Steeples (TR8); the south and north slopes and peak were covered with nearly 100% dead *Oculina* coral rubble. The upper south slope had some 30 cm standing dead coral and coral rubble consolidated with encrusting sponges. The live coral showed a significant 100% loss since 1976 from 7.1% to 0% (Mann-Whitney: $P < 0.0001$), and standing dead coral also decreased from 12.4% to 5.6% (Mann-Whitney: $P < 0.0001$) while coral rubble increased a total of 59% from 33.6% to 92.6% (Mann-Whitney: $P < 0.0001$; Fig. 3, Table 1).

DISCUSSION

OCULINA HABITAT: CHANGES FROM 1970S TO RECENT.—The historical transects ended in 1977 but additional dives continued at many of the reef sites through 1985 for various projects including geology, taxonomy, and ecology. No noticeable reef or coral death was evident from the mid 1970s to the mid 1980s. Very few dives occurred between 1985 and 2001 due to lack of funding. Although there are discrepancies of up to 350-m between LORAN-A coordinates of the 1970s and recent GPS coordinates, at least four of the bioherms (Cape Canaveral, Steeples, Chapman's, Jeff's Reefs) are precisely the same features compared in the 1970s and 2001 transects. In some cases, the reef was revisited during the transformation from LORAN-A to LORAN-C to GPS. Unfortunately, by 2001, most of the deep-water *Oculina* ecosystem had shown severe or complete loss of standing coral habitat when compared to the 1975–1977 photographic transects. By 2001, only two high-relief bioherm sites had extensive amounts of live coral remaining (Chapman's Reef and Jeff's Reef). Except for these two reefs, all 2001 transect sites had < 0.1% live coral remaining. Overall, the loss of mean live coral cover at each transect site was dramatic and statistically significant, varying from 3% to 26%. In addition, the percent loss of live coral was nearly 100% (range 98.4%–100%) for each site except Chapman's Reef and Jeff's Reef (46.2, 66.4%, respectively). Concurrently, four of the seven sites showed a decrease in standing dead coral, and all showed an increase in percent cover of unconsolidated dead coral rubble. Significant declines in both standing live coral and standing dead coral together with the concurrent increase of coral rubble further indicate that mechanical disruption was the probable cause of the decline.

Only Jeff's Reef had an interim survey in 1996. Using the JSL submersible, video transects were conducted on all sides of the reef in similar locations to the 1977 transects. An alarming and significant drop in percent cover of mean live coral occurred between 1977 (39.3%) and 1996 (10.3%). Between 1996 and 2001, however, there was no significant change in live coral. Concurrently, the percent of standing dead coral coverage also increased significantly from 1977 (25.8%) to 1996 (60.2%). At Jeff's Reef, it appears that the live coral coverage dropped dramatically over the 20 yrs from 1977 to 1996 concurrent with increase in standing dead coral. This strongly implies that impacts other than trawling or mechanical damage were also involved in the decline of *Oculina*. Additional analyses were made for the Jeff's Reef transects to define the loss of live coral. In order to determine whether there was any change in the percent live coral on standing coral colonies (both live and standing dead), data were standardized to include only quadrats that had standing coral and were assessed for percent live coral [(number of point counts of live coral / number live coral + number standing dead coral) × 100]. Although the pattern is similar to the overall mean loss of live coral, there is a statistically significant gain in live coral from 1996 to 2001 (ANOVA: $P < 0.0001$; Fig. 5). This gain in live coral (per standing coral) is coincident with the closure of the original OHAPC boundaries (OECA) to bottom fishing. Although coincidental, this may indicate an actual improvement in coral and habitat health; that is, the coral is regrowing on the standing dead coral as long as it is not mechanically impacted by trawls, bottom longlines, anchors, or fishing weights.

Recent ROV dives (2001–2005) have documented extensive live bottom habitat within the OHAPC, in addition to *Oculina* coral habitat (Reed et al., 2005), that consists of limestone pavement, ledges, and boulders with associated epibenthic fauna (sponges, hydroids, gorgonians) and fish. Based on new multibeam maps, over 100 high-relief (12–18 m tall) bioherms have been recently discovered, mostly adjacent to but outside the current OHAPC boundaries from Eau Gallie to Cape Canaveral. ROV dives have confirmed that most of these, if not all, have been reduced to coral rubble. However, these bioherms support various live bottom habitats. The upper flanks and peaks of these bioherms have dense coral rubble, which in some cases have consolidated from thick encrusting sponges and other fouling organisms, and some sparse standing dead coral is evident. These provide minor relief (15–30 cm) for many small reef fish such as yellowtail reeffish**,** *Chromis enchrysura* Jordan and Gilbert, 1882, and bank butterflyfish, *Prognathodes aya* (Jordan, 1886). On many of the bioherms, sparse, scattered individual colonies of live *Oculina* and small thickets of live coral were discovered, usually near the base of the reefs. Also the northern

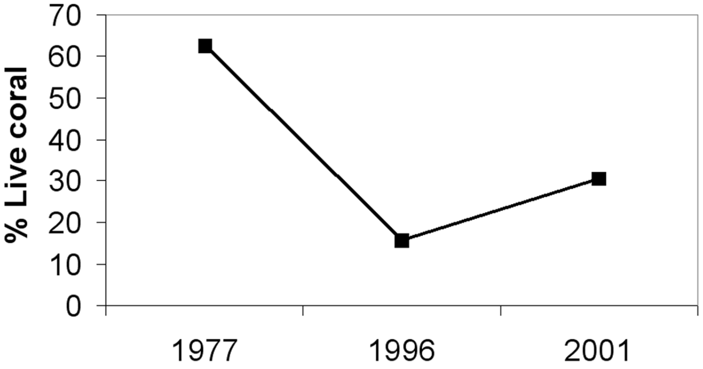

Figure 5. Comparison of percent live *Oculina* coral on all standing coral colonies (both live and standing dead colonies) at Jeff's Reef [(number of point counts of live coral / number of point counts of live coral + number of point counts of standing dead coral) × 100]. Between year comparisons were statistically different for all years including a gain of live coral between 1996 and 2001 (ANOVA: $P < 0.0001$).

base of many of the bioherms has exposed limestone ledges and boulders (1 m relief), which now provide the primary habitat for the larger fish such as scamp and snowy grouper.

Habitat Loss: Effects on the Ecosystem.—The *Oculina* biogenic refuge consists primarily of standing live and dead coral habitat. As long as the coral is standing, the living space within the colony branches supports dense and diverse communities of associated invertebrates (Reed et al., 1982, 2002a,b; Reed and Mikkelsen, 1987). However, once reduced to unconsolidated coral rubble, little living space is left except for the boring infauna (Reed, 1998). When the standing coral habitat is lost due to mechanical damage or natural causes, effects on the ecosystem are dramatic. The decline in fish populations, primarily gag and scamp grouper, on the *Oculina* reefs over that past 20 yrs is well documented (Gilmore and Jones, 1992; Koenig et al., 2000, 2005). This may be attributed to both habitat loss and overfishing. Population densities of the dominant basses [roughtongue bass *Pronotogrammus martinicensis* (Guichenot, 1868) and red barbier *Hemanthias vivanus* (Jordan and Swain, 1885)], dominant groupers [scamp, gag, and speckled hind *Epinephelus drummondhayi* Goode and Bean, 1878), and pelagic species (greater amberjack and almaco jack *Seriola rivoliana* Valenciennes in Cuvier and Valenciennes, 1833) all showed positive association with intact coral habitat (either sparse or dense live coral) compared to unconsolidated coral rubble habitat (Koenig et al., 2005). Scamp grouper density in intact coral habitat was significantly greater than other habitats (sparse live coral or rubble). Only one commercially important species (snapper, *Lutjanus* spp.) was primarily associated with the coral rubble habitat.

A hypothetical trophic model of the *Oculina* coral ecosystem shows the plausible interactions of the various invertebrate and fish species that are associated with the coral habitat (George et al., 2007). Standing live and dead coral provide refuge within the branches for diverse invertebrate communities including polychaete worms, mollusks, crustaceans, sponges, and octocorals. These consist of various suspension feeders, detritivores, carnivores and corallivores (Reed, 2002a), which are prey for smaller reef fish and up the food chain to larger benthic and pelagic fish. The economically important grouper complex, including gag and scamp grouper and speckled hind, are closely associated with the standing intact coral habitat (Gilmore and Jones, 1992; Koenig et al., 2005). The whole system, in turn, is also linked to physical factors such as food, nutrients, and plankton from the Florida Current (Gulf Stream) and upwelling events which provide influx of cold nutrient rich water (Reed, 1983). Therefore, significant loss of habitat, particularly intact live and dead standing coral, could feasibly bring dramatic and possibly catastrophic shifts in the ecosystem. As seen with the grouper complex that is associated with the intact coral, the loss of standing coral habitat could result in the loss of several commercially important species that use the *Oculina* ecosystem as spawning and feeding grounds. Some species such as gag grouper utilize inshore mangrove and grassbed habitat as juveniles then move to the deeper high relief reefs once they are sexually mature (Gilmore and Jones, 1992). Also the effects of overfishing are unknown for the *Oculina* ecosystem. Even if the *Oculina* coral is kept intact, how will the lack of top predators affect the whole reef system? Such a loss could cause dramatic shifts in the entire community structure of smaller food prey and ultimately affect the coral itself. Similar ecological concerns are evident for deep-sea coral reefs worldwide where direct and indirect effects of trawling have changed benthic community abundance and composition, degraded species diversity, and resulted in the loss of corals and sponges which have a keystone role in providing habitat for a large number of other organisms (Fosså et al., 2002; Gage et al., 2005).

Impacts from Fishing and Trawling.—From analyses of these photographic transects over a 25 yr period, it is clear that many if not most of the reef sites have shifted from a predominately live coral habitat to coral rubble. Although this has occurred throughout the OHAPC, the only remaining intact reefs of significant size are in the southern portion that has been protected within the boundaries of the original OHAPC since 1984, in which bottom trawls, bottom longlines, dredges, fish traps, and anchoring are all prohibited. Only recently have surveillance and enforcement been sufficient to deter illegal fishing and trawling within the *Oculina* reef ecosystem. Since 2000, when the boundaries of the OHAPC were expanded northward to Cape Canaveral, shrimp bottom trawlers have been caught poaching within the boundaries of the original OHAPC (OECA) and in the vicinity of Chapman's Reef and Jeff's Reef, the only remaining live, high-relief reefs. Also throughout the OHAPC, recent dives with ROVs have documented reefs wrapped with fishing lines, piles of bottom longlines, discarded trawl nets, and anchor lines (Reed et al., 2005). Since the 1970s, bottom trawling within the *Oculina* ecosystem has been primarily for rock shrimp and brown shrimp and this may be the primary cause of major habitat destruction. Also commercial dredging for calico scallops was prominent in the 1970s–1980s but overfishing and destruction of habitat caused the collapse of the industry. Photographic transects in the 1970s showed deep mounds of living scallops, but these tended to be in sandy/shelly bottom in shallower water west the *Oculina* reefs and were not likely the cause of impacts to the majority of *Oculina* bioherms.

Worldwide, bottom trawling has severely impacted deep-sea coral reef habitat and continues to be a major concern and threat (Rogers, 1999; Butler and Gass, 2001; Morgan et al., 2003; Barnes and Thomas, 2005; Mortensen et al., 2005). Bottom trawling causes severe mechanical damage as evident on deep-water *Lophelia* reefs in the northeast Atlantic (Rogers, 1999; Fosså et al., 2002), hard bottom habitats off the southeastern United States (Van Dolah et al., 1987), and deep-water seamounts off New Zealand and Tasmania (Jones, 1992; Koslow et al., 2001). In a research experiment, a single pass of a bottom trawl removed 1000 kg of *Primnoa* coral off Alaska and resulted in the detachment of 27% of the corals (Krieger, 2001). ROV surveys of extensive deep-water *Lophelia* coral reefs off Norway found that 30%–50% of the reefs were damaged from fishing gear; at some sites almost all corals were crushed or dead (Fosså et al., 2002). Heavily fished seamounts off Tasmania have up to 90% coral loss and 83% less biomass than unfished sites (Koslow et al., 2001). Unfortunately, damage to deep-sea coral reefs has dramatically changed with larger vessels, advent of new gear such as roller trawls, and an increase in navigation technology such as precision depth recorders and inexpensive geo-positioning electronics which allows specific areas and even spawning aggregations to be targeted (Morgan et al., 2005).

Conclusions

The long term prospects for the deep-water *Oculina* coral ecosystem remain tentative at best. Certainly, mechanical damage from bottom trawling has occurred and is extensive. Between 1977 and 2001, six of the coral reef transects in this study had nearly 100% loss of live coral cover (range 98.4%–100%) whereas only two reefs which were within the original OHAPC since 1984 have survived. Significant declines in both standing live coral and standing dead coral with the concurrent increase of coral rubble suggest that mechanical disruption was the cause of the decline. Certainly, trawling continues to be the primary threat to the ecosystem as evident from recent photographs of trawl nets found on the bottom, destroyed reefball modules, the documented destruction of the Cape Canaveral *Oculina* bioherm, and evidence of trawl scars in the rubble (Reed et al., 2005).

But positive efforts are showing results. Legislation now prohibits anchors and destructive fishing gear, such as bottom trawls, dredges, and longlines throughout the entire 1029 km^2 OHAPC (NOAA, 2000). Since this legislation was enacted several illegal trawlers have been intercepted and fined by the U.S. Coast Guard. Recent legislation also requires shrimp-trawling vessels operating in the area to have an active vessel monitoring system (VMS) aboard which allows vessels to be tracked continuously by satellite. Since the ban on bottom hook-and-line fishing within the boundaries of the OECA was enacted in 1994, there was a statistically significant gain in live coral from 1996 to 2001 at one of the remaining *Oculina* bioherm sites. We are hopeful that this is actual improvement in coral and habitat health and that the coral is regrowing as long as it is not mechanically impacted by trawls, bottom longlines, anchors or fishing weights. In addition, the deep-water *Oculina varicosa* Lesueur, 1821 coral has been nominated as an endangered species (Hirshfield et al., 2005). The indefinite ban on bottom fishing for grouper within the OECA boundaries may enhance recovery of spawning aggregations of these commercially important species. Management must prevent future disruption of the bottom within the current OHAPC to allow coral larval settlement on the rubble and extensive hard bottom areas, promote recovery of healthy reefs, and allow credible monitoring programs to proceed. Unparalleled research opportunities are possible to document the effectiveness of deep-water coral reserves. The *Oculina* bioherms and coral habitat occur both within and outside of the OHAPC, relatively close to shore and at depths that are much more accessible than most other deep coral ecosystems. Further research is needed on deep-water coral reproduction, recruitment, mortality, disease, trophic models, bentho-pelagic pathways, and physical processes. In addition, adequate surveillance and enforcement along with severe penalties are necessary to protect and conserve the *Oculina* reefs as well as other deep-water coral reserves for future generations.

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Literature Cited

Avent, R. M. and F. G. Stanton. 1979. Observations from research submersible of megafaunal distribution on the continental margin off central eastern Florida. Harbor Branch Foundation Tech. Rep. 25, Harbor Branch Oceanographic Institution, Ft. Pierce. 40 p.

_________, M. E. King, and R. H. Gore. 1977. Topographic and faunal studies of shelf-edge prominences off the central eastern Florida coast. Int. Rev. Ges. Hydrobiol. 62: 185–208.

Barnes, P. W. and J. P. Thomas. 2005. Benthic habitats and the effects of fishing. American Fisheries Society, Bethesda. 890 p.

Butler, M. and S. Gass. 2001. How to protect corals in Atlantic Canada. Pages 156–165 *in* J. Martin Willison, J. Hall, S. Gass, E. Kenchington, M. Butler, and P. Doherty, eds. Proc. 1st Int. Symp. Deep-sea Corals. Ecology Action Center. Halifax.

Fosså, J. H., P. B. Mortensen, and D. M. Furevik. 2002. The deep water coral *Lophelia pertusa* in Norwegian waters: distribution and fishery impacts. Hydrobiologia 471: 1–12.

Gage, J. D., J. M. Roberts, J. Hartley, and J. Humphery. 2005. Potential impacts of deep-sea trawling on the benthic ecosystem along the Northern European continental margin: a review. Am. Fish. Soc. Symp. 41: 503–517.

George, R., T. Okey, J. Reed, and R. Stone. 2007. Ecosystem-based fisheries management of seamount and deep-sea coral reefs in U.S. waters: conceptual models for proactive decisions. Pages 9–30 *in* R. Y. George and S. D. Cairns, eds. Conservation and adaptive management of seamount and deep-sea coral ecosystems. Rosenstiel School of Marine and Atmospheric Science, University of Miami. Miami. 324 p.

Gilmore, R. G. and R. S. Jones. 1992. Color variation and associated behavior in the epinepheline groupers, *Mycteroperca microlepis* (Goode and Bean) and *M. phenax* Jordan and Swain. Bull. Mar. Sci. 51: 83–103.

Hirshfield, M. F., S. Roberts, and D. Allison. 2005. Oceana's efforts to protect deep-sea coral in the United States. Pages 1141–1149 *in* R. A. Freiwald and J. M. Roberts, eds. Cold-water corals and ecosystems. Springer-Verlag Berlin Heidelberg.

Jones, J. B. 1992. Environmental impact of trawling on the seabed: a review. N. Z. J. Mar. Freshwat. Res. 26: 59–67.

Koenig, C. C., F. C. Coleman, C. Grimes, G. Fitzhugh, K. Scanlon, C. Gledhill, and M. Grace. 2000. Protection of fish spawning habitat for the conservation of warm-temperate reef-fish fisheries of shelf-edge reefs of Florida. Bull. Mar. Sci. 66: 593–616.

__________, A. N. Shepard, J. K. Reed, F. C. Coleman, S. D. Brooke, J. Brusher, and K. M. Scanlon. 2005. Habitat and fish populations in the deep-sea *Oculina* coral ecosystem of the western Atlantic. Am. Fish. Soc. Symp. 41: 795–805.

Kohler, K. E. and S. M. Gill. 2006. Coral point count with Excel extensions (CPCe): a visual basic program for the determination of coral and substrate cover using random point count methodology. Comput. Geosci. 32: 1259–1269.

Koslow, J. A., K. Gowlett-Holmes, J. Lowry, T. O'Hara, G. Poore, and A. Williams. 2001. Seamount benthic macrofauna off southern Tasmania: community structure and impacts of trawling. Mar. Ecol. Prog. Ser. 21: 111–125.

Krieger, K. J. 2001. Coral (Primnoa) impacted by fishing gear in the Gulf of Alaska. Pages 106–117 *in* J. H. M. Willison, J. Hall, S. Gass, E. Kenchington, M. Butler, and P. Doherty, eds. Proc. 1st Int. Symp. Deep-Sea Corals. Ecology Action Centre, Halifax.

Morgan, L. E., P. Etnoyer, A. Scholz, M. Mertens, and M. Powell. 2005. Conservation and management implications of deep-sea coral and fishing effort distributions in the Northeast Pacific Ocean. Pages 1171–1187 *in* R. A. Freiwald and J. M. Roberts, eds. Cold-water corals and ecosystems. Springer-Verlag Berlin Heidelberg.

Mortensen, P. B., L. Buhl-Mortensen, D. Gordon, Jr., G. Fader, D. McKeown, and D. Fenton. 2005. Effects of fisheries on deepwater gorgonian corals in the Northeast Channel, Nova Scotia. Am. Fish. Soc. Symp. 41: 369–382.

National Oceanic and Atmospheric Administration. 2000. Final rule, Amendment 4 to the Fishery Management Plan for Coral, Coral Reefs, and Live/Hard Bottom Habitats of the South Atlantic Regions (Coral FMP). Federal Register, Vol. 65, No. 115, June 14, 2000.

Reed, J. K. 1980. Distribution and structure of deep-water *Oculina varicosa* coral reefs off central eastern Florida. Bull. Mar. Sci. 30: 667–677.

________. 1983. Nearshore and shelf-edge *Oculina* coral reefs: The effects of upwelling on coral growth and on the associated faunal communities. Pages 119–124 *in* M. Reaka, ed. The ecology of deep and shallow coral reefs. Symposia Series for Undersea Research, Vol. 1, NOAA.

________. 1998. Bioerosion and sediment production on Florida's deep-water *Oculina* coral Banks. Abstract, 2nd Inter. Bioerosion Workshop, Harbor Branch Oceanographic Institution, Fort Pierce. 62 p.

________. 2002a. Deep-water *Oculina* coral reefs of Florida: biology, impacts, and management. Hydrobiologia 471: 43–55.

________. 2002b. Comparison of deep-water coral reefs and lithoherms off southeastern U.S.A. Hydrobiologia 471: 57–69.

________ and P. M. Mikkelsen. 1987. The molluscan community associated with the scleractinian coral *Oculina varicosa*. Bull. Mar. Sci. 40: 99–131.

________, D. Weaver, and S. A. Pomponi. 2006. Habitat and fauna of deep-water *Lophelia pertusa* coral reefs off the Southeastern USA: Blake Plateau, Straits of Florida, and Gulf of Mexico. Bull. Mar. Sci. 78: 343–375.

________, R. H. Gore, L. E. Scotto, and K. A. Wilson. 1982. Community composition, structure, areal and trophic relationships of decapods associated with shallow- and deep-water *Oculina varicosa* coral reefs. Bull. Mar. Sci. 32: 761–786.

________, A. Shepard, C. Koenig, K. Scanlon, and G. Gilmore. 2005. Mapping, habitat characterization, and fish surveys of the deep-water *Oculina* coral reef marine protected area: a review of historical and current research. Pages 443–465 *in* R. A. Freiwald and J. M. Roberts, eds. Cold-water corals and ecosystems. Springer-Verlag Berlin Heidelberg.

Rogers, A. D. 1999. The biology of *Lophelia pertusa* (Linnaeus, 1758) and other deep-water reef-forming corals and impacts from human activities. Int. Rev. Ges. Hydrobiol. 84: 315–406.

Van Dolah, R. F., P. H. Wendt, and N. Nicholson, 1987. Effects of a research trawl on a hard-bottom assemblage of sponges and corals. Fish. Res. 5: 39–64.

ADDRESSES: (J.K.R.) *Harbor Branch Oceanographic Institution (HBOI), 5600 U.S. 1, North, Fort Pierce, Florida 34946.* (C.C.K.) *Department of Biological Science, Florida State University, Tallahassee, Florida 32306*. (A.N.S.) *NOAA Undersea Research Center, University of North Carolina at Wilmington, 5600 Marvin Moss Lane, Wilmington, North Carolina 28409.* CORRESPONDING AUTHOR: (J.K.R.) *Email: <jreed@hboi.edu>.*