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Long-Term Monitoring at East and West Flower Garden Banks:

2022 Annual Report

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Cover photo: A French angelfish (*Pomacanthus paru*) swims over the coral reef at Flower Garden Banks National Marine Sanctuary. Photo: G.P. Schmahl/NOAA

About the National Marine Sanctuaries Conservation Series

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 620,000 square miles of ocean and Great Lakes waters. The 16 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our nation's maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than one square mile to almost 583,000 square miles. They serve as natural classrooms and cherished recreational spots, and are home to valuable commercial industries.

Because of considerable differences in settings, resources, and threats, each national marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The National Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the National Marine Sanctuary System. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific or historical research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and social sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website.

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Report Availability

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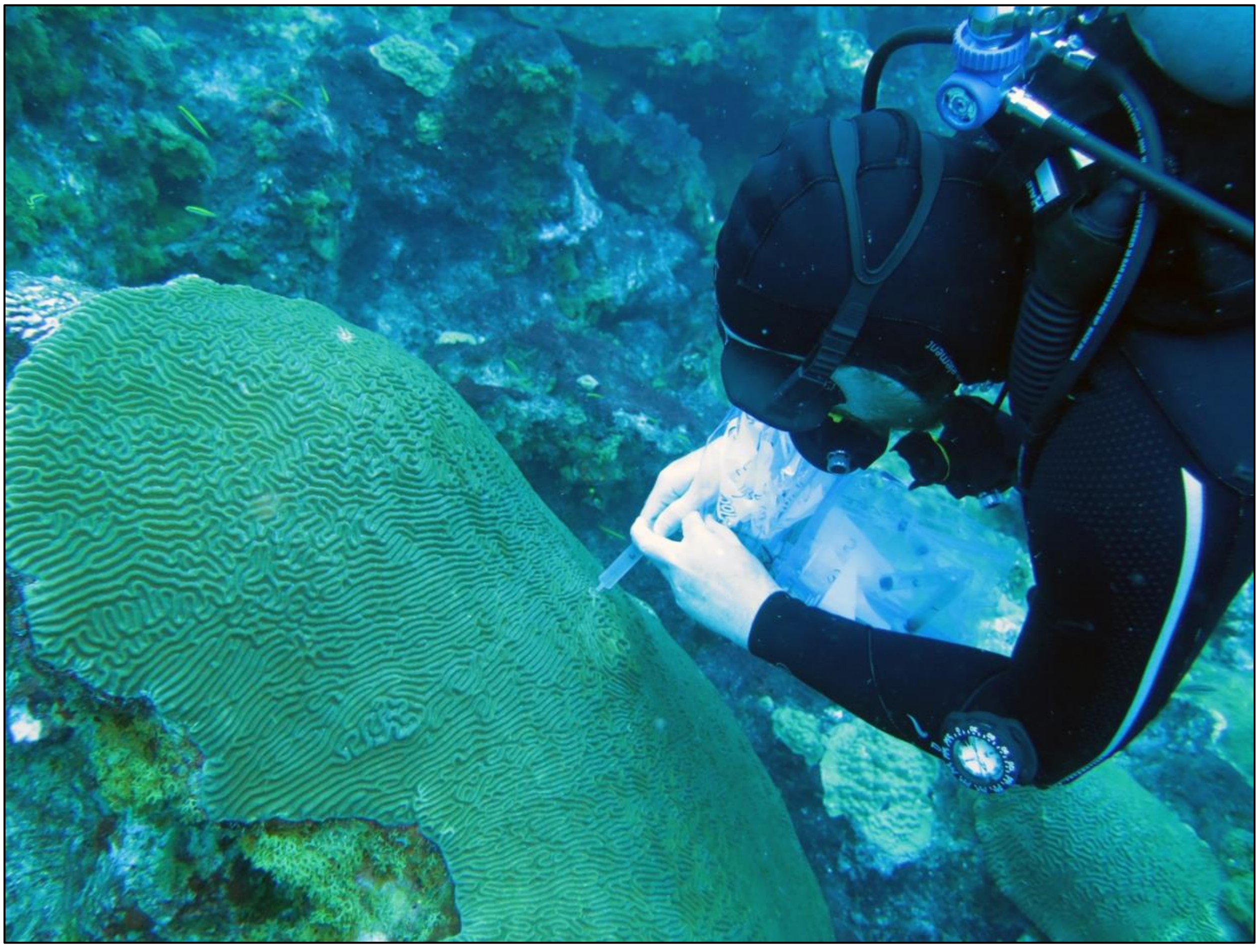
Abstract

This report summarizes fish and benthic community observations and water quality data collected from East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB) in 2022, along with 33 years of historical monitoring data. EFGB and WFGB are part of Flower Garden Banks National Marine Sanctuary (FGBNMS), located in the northwestern Gulf of Mexico. The annual long-term monitoring program began in 1989 and is funded by FGBNMS and the Bureau of Ocean Energy Management, with support from the National Marine Sanctuary Foundation. In 2022, mean coral cover was 54% within the EFGB one-hectare study site and 57% within the WFGB one-hectare study site. Mean macroalgae cover was 29% within the EFGB study site and 37% within the WFGB study site. Since 1989, mean coral cover has increased significantly at WFGB and remained stable at EFGB. Mean macroalgae cover has increased significantly at both banks since 1999. Mean coral cover within repetitive photostations has increased significantly since 1989 at both banks. The *Orbicella* spp. complex, listed as threatened under the Endangered Species Act, accounted for the majority of the coral cover within the study sites. Reef-wide stratified random photo transects were added to the monitoring program in 2022, but more data are needed for a trend analysis. The reef fish community was comprised primarily of the families Labridae and Pomacentridae. Biomass was uniformly distributed between large and small individuals, and piscivores had the greatest mean biomass at both EFGB and WFGB. No manta rays, non-native regal demoiselles, or invasive lionfish were observed in the reef visual census surveys; however, they were documented within the sanctuary on other research expeditions in 2022. During 2022, water temperatures did not exceed 30 °C and coral bleaching at both banks was less than 2% at the time of surveys. A significant monotonic increasing trend in seawater temperature was detected at both banks from 1990 to 2022, indicating ocean temperatures have risen at FGBNMS over the past three decades. The results of this report highlight the importance of long-term monitoring efforts by providing one of the longest records of coral reef health in the Gulf of Mexico and Caribbean region.

Key Words

benthic community, coral ecosystem, coral reef, fish community, long-term monitoring, Flower Garden Banks National Marine Sanctuary, Gulf of Mexico, marine protected area, water quality, coral disease

Chapter 1:
Long-Term Monitoring at East and West Flower Garden Banks



A scuba diver collects mucus from a brain coral colony on the coral reef cap at East Flower Garden Bank. Photo: Michelle Johnston/NOAA

Habitat Description

The coral-reef-capped East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB), located within Flower Garden Banks National Marine Sanctuary (FGBNMS), are part of a discontinuous arc of reef environments along the outer continental shelf in the northwestern Gulf of Mexico (Bright et al., 1985; Figure 1.1). These reefs occupy elevated salt dome formations located approximately 190 km south of the Texas and Louisiana border, containing several distinct habitats ranging in depth from 16–166 m (Rezak et al., 1985; Schmahl et al., 2008; Figure 1.1).

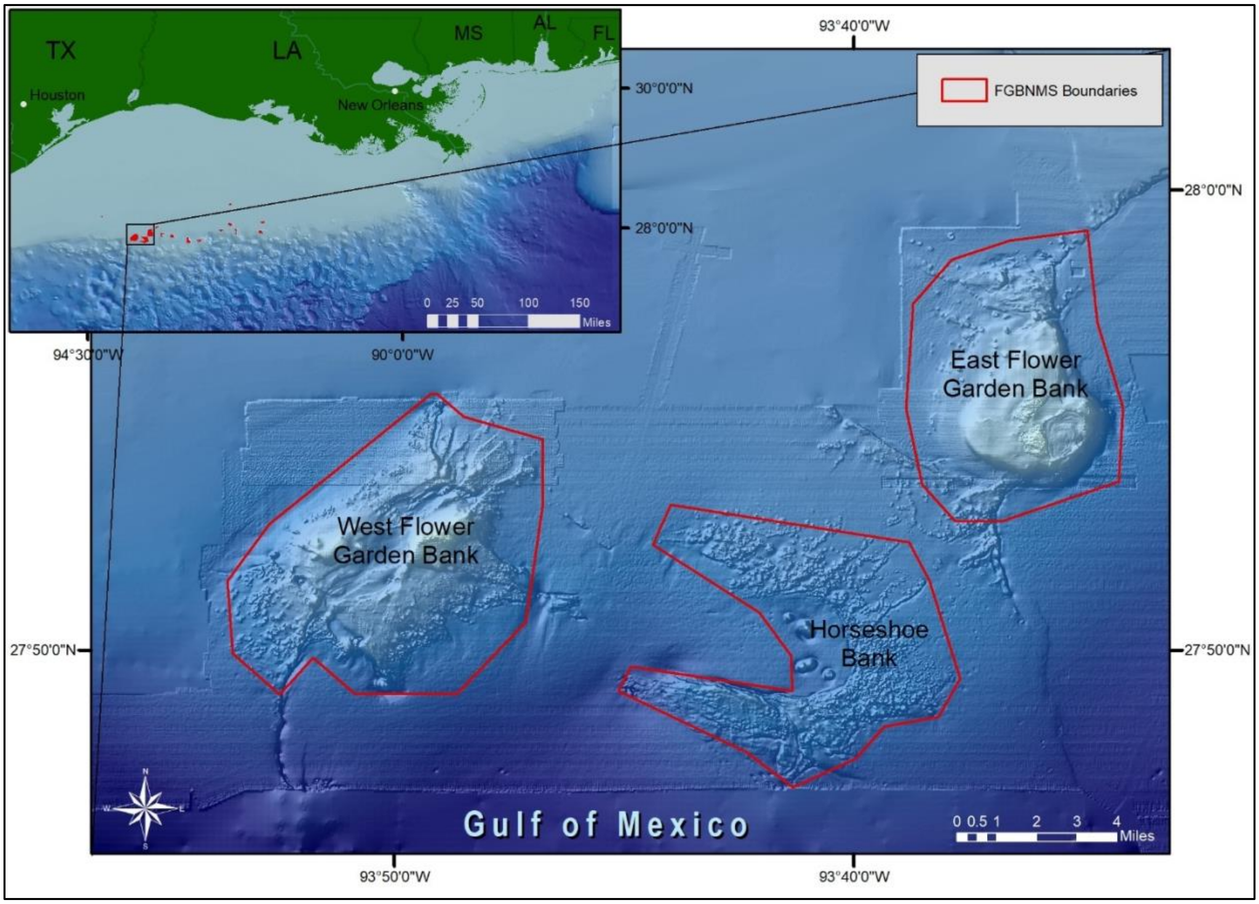


Figure 1.1. Map of EFGB, WFGB, and Horseshoe Bank with an inset of the Gulf Coast states and other FGBNMS boundaries along the continental shelf of the northwestern Gulf of Mexico. Horseshoe Bank is not part of the study area, but is now part of FGBNMS. Image: Marissa Nuttall/CPC

The caps of the banks are approximately 20 km apart and within the photic zone, where conditions are ideal for colonization by shallow water species of corals, algae, invertebrates, and fish that are also found in the Caribbean region (Goreau & Wells, 1967; Schmahl et al., 2008; Clark et al., 2014; Johnston et al., 2016a). The shallowest portions of each bank are topped by well-developed coral reefs in depths ranging from 16–50 m. Although the coral species found on the reef caps of the banks are the same as those on Caribbean reefs, octocorals are absent in shallow habitats, and scleractinian corals of the genus *Acropora* are exceedingly rare. These differences are likely due to remoteness, depth, and the latitude of the banks; FGBNMS is near the northernmost limit of the coral and is distanced from source populations by several hundred kilometers (Bright et al., 1985; Continental Shelf Associates, 1989).

FGBNMS was designated in 1992 (15 C.F.R. Part 992 § 922.120) by the National Oceanic and Atmospheric Administration (NOAA) under the National Marine Sanctuaries Act. The sanctuary was expanded in 1996 to include Stetson Bank, and expanded once again in 2021 to include an additional 14 reefs and banks along the continental shelf of the northwestern Gulf of Mexico (86 Fed. Reg. 4937).

Long-Term Monitoring Program History

Since the 1970s, due to concerns about potential impacts from offshore oil and gas development, the Department of Interior (initially through the Bureau of Land Management, then the Minerals Management Service, and now the Bureau of Ocean Energy Management [BOEM]) has supported monitoring at EFGB and WFGB to determine if the reefs are impacted by nearby oil and gas activities (Figure 1.2).

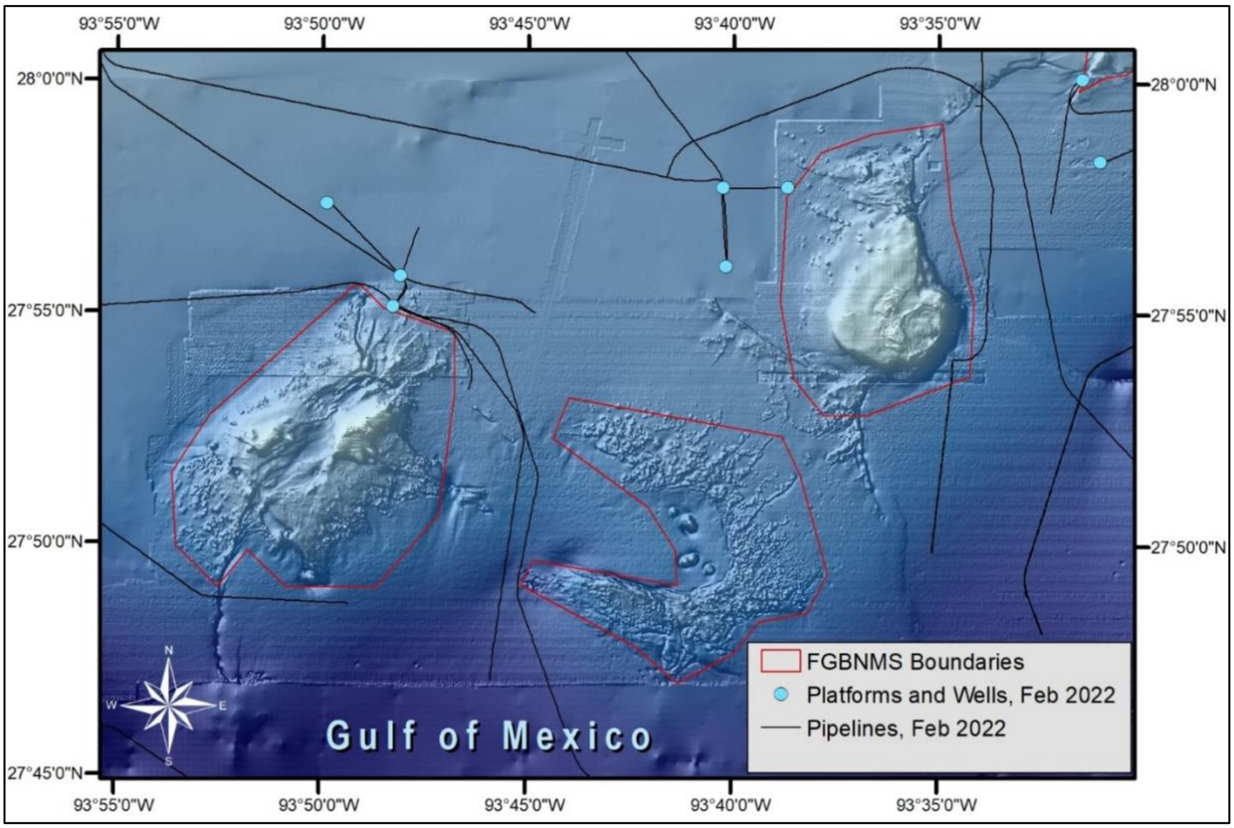


Figure 1.2. Map of oil and gas platforms, wells, and pipelines near EFGB and WFGB as of February 2022. Image: Marissa Nuttall/CPC

Initially under industry funding, then Minerals Management Service funding and a contract with Texas A&M University (TAMU), one-hectare long-term monitoring study sites were established on each bank in 1989, marking the start of the Flower Garden Banks long-term monitoring program (Continental Shelf Associates, 1989; Gittings et al., 1992; Figure 1.3). Monitoring was conducted by both TAMU and environmental consulting firms through competitive contracts until 2009, at which time BOEM and NOAA established an interagency agreement for FGBNMS to carry out the long-term monitoring program.

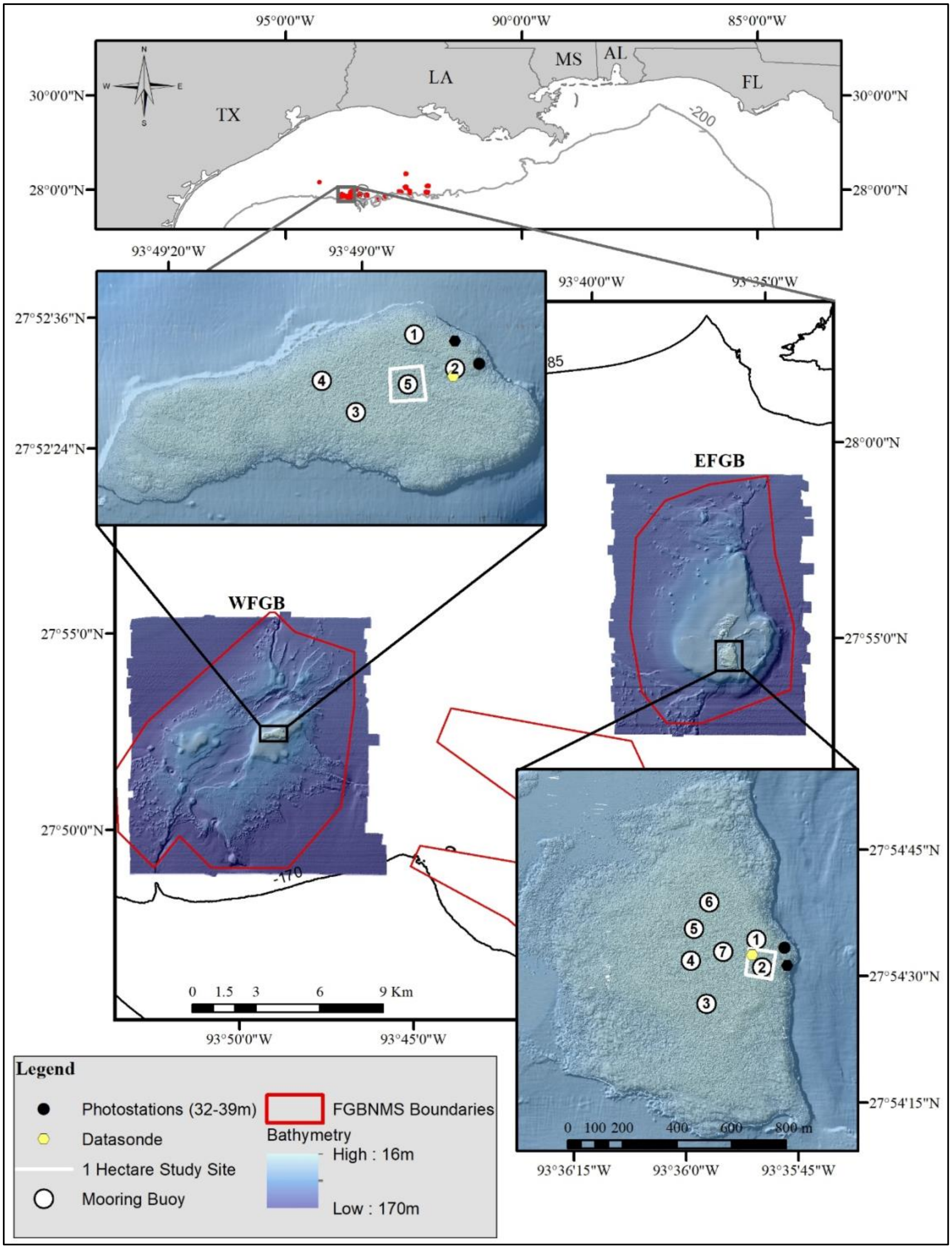


Figure 1.3. Shaded relief maps of EFGB and WFGB, with inset of the Gulf of Mexico coastline, long-term monitoring one-hectare study sites, datasonde, and repetitive photostation locations, which range in depth from 32–39 m. Image: Marissa Nuttall/CPC

Long-Term Monitoring Program Objectives

Priorities of FGBNMS include managing natural resources as stated in the National Marine Sanctuaries Act and identifying coral reef threats and potential sources of impacts, including: overfishing, pollution, runoff, visitor impacts, disease, bleaching, invasive species, hurricanes, and oil and gas exploration and extraction. Knowing the condition of natural resources within the national marine sanctuary and providing scientifically credible data is fundamental to NOAA's ability to protect and manage these areas and evaluate management actions.

Through the interagency agreement, the long-term monitoring program is of significant interest to both NOAA and BOEM, who share responsibility to protect and monitor these important marine resources. The five objectives (and corresponding indicators) of the FGBNMS long-term monitoring program are to:

- Monitor and evaluate environmental changes and variability in abundances of reef-associated organisms across multiple time scales
    - Indicators: Benthic percent cover, fish community dynamics, water quality, and coral demographics
- Identify changes in coral reef health resulting from both natural and human-induced stressors to facilitate management responses
    - Indicators: Bleaching, disease, and invasive species
- Facilitate adaptive management of activities impacting reef-related resources
    - Indicators: Baseline data and image archive of damage to resources
- Identify and monitor key species that may be indicative of reef and ecosystem health
    - Indicators: Sea urchin and lobster density
- Provide a consistent and timely source of data on environmental conditions and the status of living national marine sanctuary resources
    - Indicators: Published, peer-reviewed annual reports

Long-Term Monitoring Program Components

The long-term monitoring program was designed to assess the health of the coral reefs, detect change over time, and provide baseline data in the event that natural or human-induced activities alter the integrity of EFGB and WFGB coral communities. The high coral cover and robust fish populations compared to other reefs in the region, combined with historical data collection and the proximity to oil and gas infrastructure development, make EFGB and WFGB ideal sentinel sites for continued monitoring. The following techniques are used in this monitoring program to evaluate coral reef diversity, growth rates, and community health in designated monitoring areas at each bank:

- Random photographic transects document benthic cover;
- Repetitive photostations detect and evaluate long-term changes at the stations and in individual coral colonies;
- Biennial coral demographic surveys provide information on recruitment, coral density, and coral colony size;
- Stationary reef fish visual census surveys assess community structure of coral reef fishes;

- Long-spined sea urchin (*Diadema antillarum*) and lobster (*Panulirus argus* and *P. guttatus*) surveys establish current population levels and trends;
- Water quality datasondes record salinity, temperature, and turbidity at depth; and
- Quarterly sampling of chlorophyll *a*, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, and phosphorus documents water column productivity.

The long-term monitoring study area consists of several locations on the EFGB and WFGB coral reef caps where benthic, fish, and water quality data are collected. Long-term monitoring data have been collected annually during summer months since 1989 in permanent 10,000 m² study sites (100 m x 100 m or 1 hectare; hereafter referred to as "study sites") at EFGB and WFGB. The corners and centers of the study sites are marked by large eyebolts as reference markers. Depth ranges from 17–27 m within the EFGB study site and 18–25 m within the WFGB study site (Figure 1.4; Figure 1.5). Mooring buoy anchors (#2 at EFGB and #5 at WFGB) were installed near the study site centers to facilitate field operations (Figure 1.3; Table 1.1). Mooring buoys are attached at these sites only during field research activities, thus restricting access at other times. Additionally, permanent repetitive photostations were installed at each bank beyond the study site boundaries to capture benthic cover in depth ranges of 32–39 m: 23 repetitive photostations are located east of mooring buoy #2 at EFGB and 24 repetitive photostations are located north and east of mooring buoy #2 at WFGB (Figure 1.4; Figure 1.5). Water quality datasondes are located near mooring buoy #2 at EFGB and WFGB (Figures 1.3–1.5). Additional temperature loggers are paired with repetitive photostations at 30 m and 40 m at both banks (Figure 1.4; Figure 1.5).

Table 1.1. Coordinates and depths for permanent moorings within study sites at each bank.

Mooring	Lat (DDM)	Long (DDM)	Depth (m)
EFGB Mooring #2	27° 54.516 N	93° 35.831 W	19.2
WFGB Mooring #5	27° 52.509 N	93° 48.900 W	20.7
WFGB Mooring #2	27° 52.526 N	93° 48.836 W	24.4

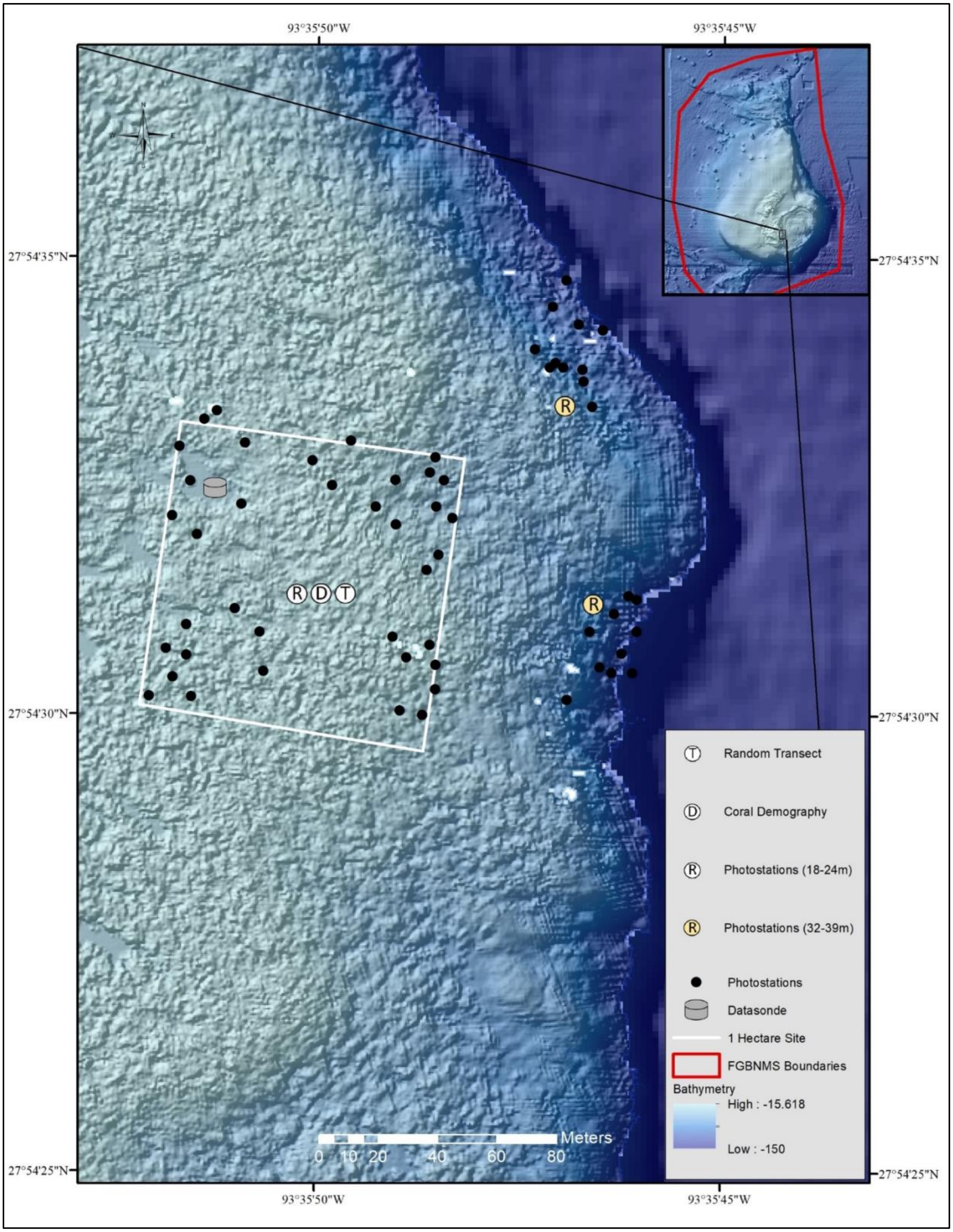


Figure 1.4. Shaded relief map of EFGB showing the location of the long-term monitoring study site, within which repetitive photostations (18–24 m), random transects, and coral demographic surveys are conducted. The locations of the water quality datasonde and repetitive photostations at 32–39 m are also shown. Image: Marissa Nuttall/CPC

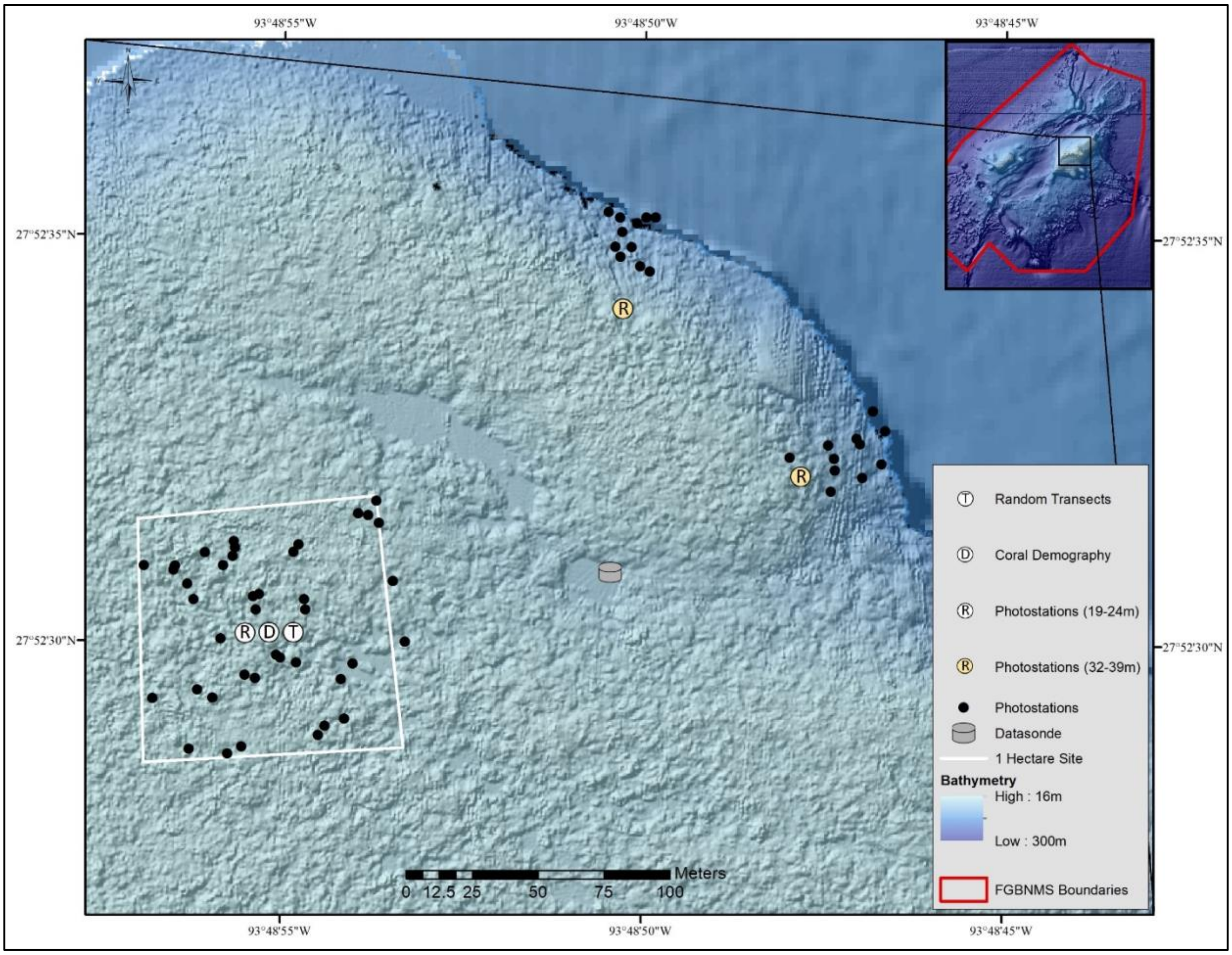


Figure 1.5. Shaded relief map of WFGB showing the location of the long-term monitoring study site, within which repetitive photostations (18–24 m), random transects, and coral demographic surveys are conducted. The locations of the water quality datasonde and repetitive photostations at 32–39 m are also shown. Image: Marissa Nuttall/CPC

Long-Term Monitoring Field Operations and Data Collection

To date, the monitoring program has spanned 33 years, with nearly continuous coral reef annual monitoring data collected. Long-term monitoring data were collected at both EFGB and WFGB in 2022 and scuba operations were conducted from the NOAA R/V *Manta* (Table 1.2). Water samples were collected, water quality instruments were exchanged, and data were downloaded by FGBNMS staff during water quality cruises in May 2022 and January 2023 (Table 1.2). See each respective chapter for detailed field operation methods.

Coral demographic surveys were conducted by FGBNMS and NOAA National Coral Reef Monitoring Program (NCRMP) divers on EFGB and WFGB during NCRMP cruises from August 25–27, 2022 and August 30–September 2, 2022. During the second cruise, coral tissue loss disease was observed by divers at both EFGB and WFGB (Johnston et al., 2023).

Annual field work at EFGB was conducted September 6–9, 2022 (Table 1.2), with mild surface and bottom currents (>0.25 kt), clear water column visibility (25 m), 29 °C water temperatures, and <1 m seas. Annual monitoring at WFGB was conducted September 20–21, 2022 (Table 1.2), with similar water column and sea conditions. The datasondes at EFGB and WFGB were not exchanged, as replacement instruments were being serviced by the manufacturer (SeaBird, Inc.) at the time of the cruises. In addition, the vessel's skiff crane was not operational, so water samples were not taken, as the skiff needed to be on the back deck for safety reasons and there was no operational room for the carousel. Due to coral disease response efforts, time did not allow for sea urchin and lobster surveys at night.

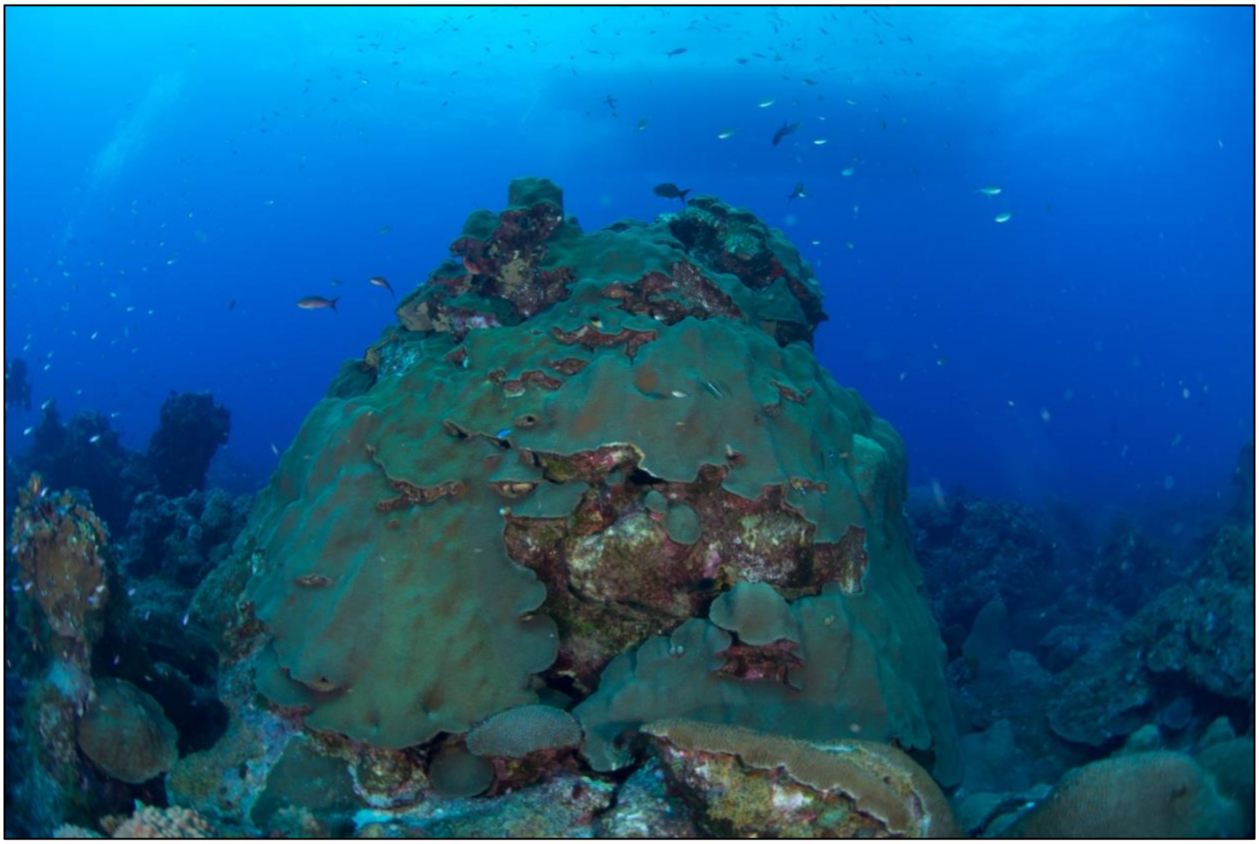
Water quality samples were collected and instruments were exchanged January 9–10, 2023, allowing for the download of the remaining 2022 data (September–December 2022).

Even though restrictions related to the COVID-19 pandemic were lifted 2022, all cruise participants took rapid COVID-19 antigen tests before embarking on the R/V *Manta*. Despite these efforts, several divers and crew contracted COVID-19 during the field season, which made filling all spots on the vessel, and cruise coordination in general, a continued challenge.

Table 1.2. Monitoring cruises completed at EFGB and WFGB in 2022.

Date	Cruise and Tasks Completed
05/13–14/2022	Water quality cruise: Instrument exchange and water samples collected
08/25–27/2022	NCRMP cruise I
08/30–9/02/2022	NCRMP cruise II
09/06–09/2022	Long-term monitoring cruise: EFGB annual monitoring and coral disease sampling and response
09/20–21/2022	Long-term monitoring cruise: WFGB annual monitoring and coral disease sampling and response
01/09–10/2023	Water quality cruise: Instrument exchange and water samples collected

Chapter 2: Benthic Community



Reef fish swim above massive bouldering star coral colonies at WFGB. The hull of the R/V *Manta* can be seen on the surface. Photo: G.P. Schmahl/NOAA

Benthic Community Introduction

Benthic cover, including components such as corals, sponges, crustose coralline algae (CCA), and macroalgae, was determined through analysis of a series of randomly located 8-m photo transects within EFGB and WFGB study sites. These surveys were used to compare habitat and document benthic reef community status and trends within and between the study sites. In addition, photo transect surveys were conducted in a random stratified design across the coral caps to assess benthic cover outside of the EFGB and WFGB study sites.

Permanent repetitive photostations were photographed to document changes in the composition of benthic assemblages at select locations ranging in depth from 18–39 m at EFGB and WFGB. The photographs were analyzed to measure percent benthic cover using random-dot analysis. All comparisons within this category are intended solely to assess differences among groups of repetitive photostations, as they were not randomly located; most were selectively installed in areas with high coral cover. While these stations can help identify directions and causes of change, they are not intended to estimate reef-wide populations or communities.

Benthic Community Methods

Random Transect Field Methods

In 2022, 16 non-overlapping random transects were completed within each one-hectare study site in depths ranging from 17–27 m. Divers were given a randomly generated start location and heading for each survey. A Canon Power Shot® G11 digital camera in an Ikelite® housing and 28 mm equivalent wet mount lens adapter, mounted on a 0.65-m T-frame with bubble level and two Inon® Z240 strobes, was used to capture images along the transects. The bubble level mounted to the T-frame center ensured images were taken perpendicular to the slope of the bottom substrate. The mounted camera was placed at pre-marked intervals 80 cm apart on a spooled 15-m measuring tape, producing 17 non-overlapping images along the transect (Figure 2.1). Each still frame image captured an approximate 0.8 x 0.6 m area (0.48 m^2). This produced a total photographed area of 8.16 m^2 per transect and a minimum of 130.56 m^2 photographed area per study site per year. For more detailed methods, reference Johnston et al. (2017a).

It should be noted that during the entirety of the monitoring program, a variety of underwater camera setups were used as technology advanced from 35-mm slides (1989 to 2001), digital videography using video still frame grabs (2002 to 2009), and digital still images (2010 to 2019; Gittings et al., 1992; Continental Shelf Associates, 1996; Dokken et al., 1999, 2003; Precht et al., 2006; Zimmer et al., 2010; Johnston et al., 2013, 2015, 2017a, 2017b, 2018a, 2020, 2021, 2022). Prior to the use of Coral Point Count with Microsoft® Excel® extensions (CPCe), percent cover was calculated with mylar traces and a calibrated planimeter from 1989 to 1995 (Gittings et al., 1992; Continental Shelf Associates, 1996). From 1996 to 2003, random-dot layers were generated manually in photo software programs (Dokken et al., 1999, 2003).

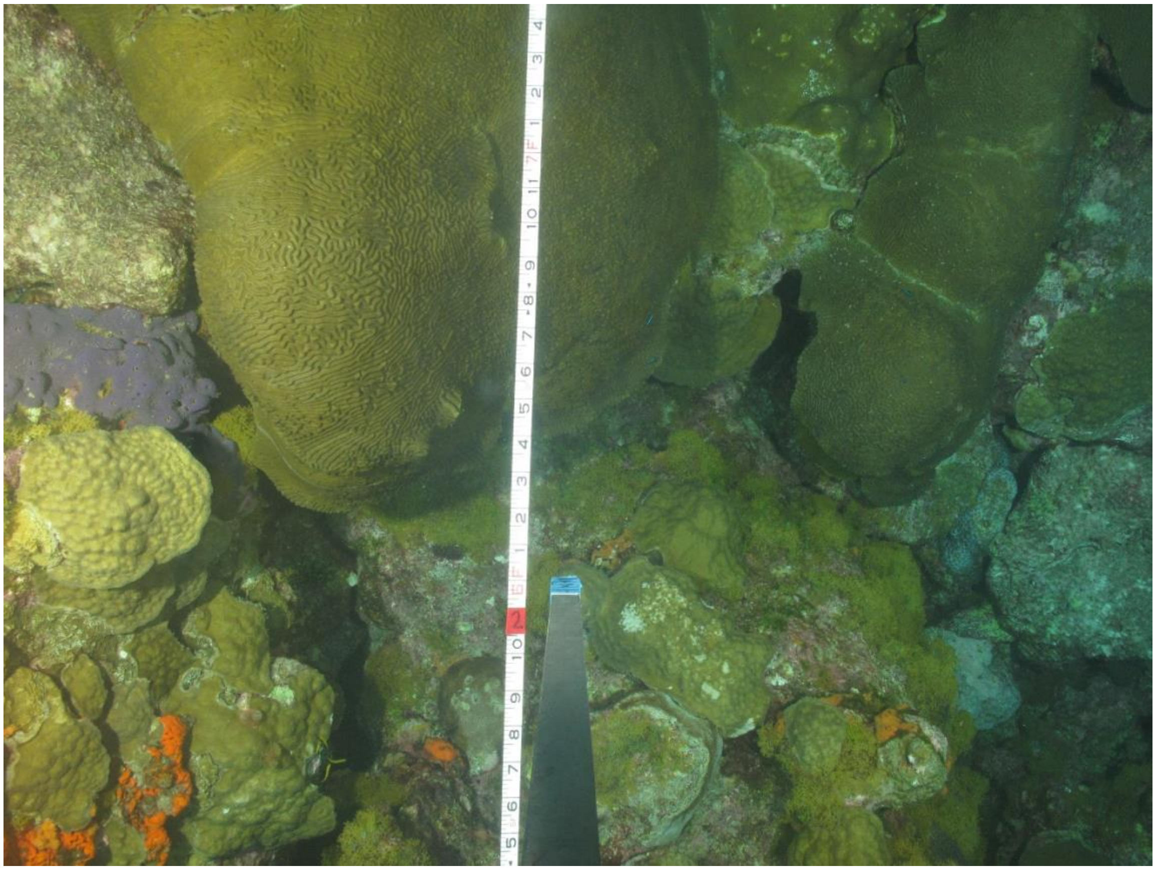


Figure 2.1. Photo taken at marked interval along random transect with camera mounted to aluminum T-frame at EFGB in 2022. Photo: Donavon French/CPC

In addition to random transect surveys inside the EFGB and WFGB study sites, transect surveys (n=28 at EFGB, n=14 at WFGB) were conducted in a random stratified designed across both coral caps to assess benthic cover outside of the study sites. These surveys were conducted in partnership with NCRMP cruises aboard the R/V *Manta* in August 2022. Fewer surveys were completed at WFGB due to time constraints in the field.

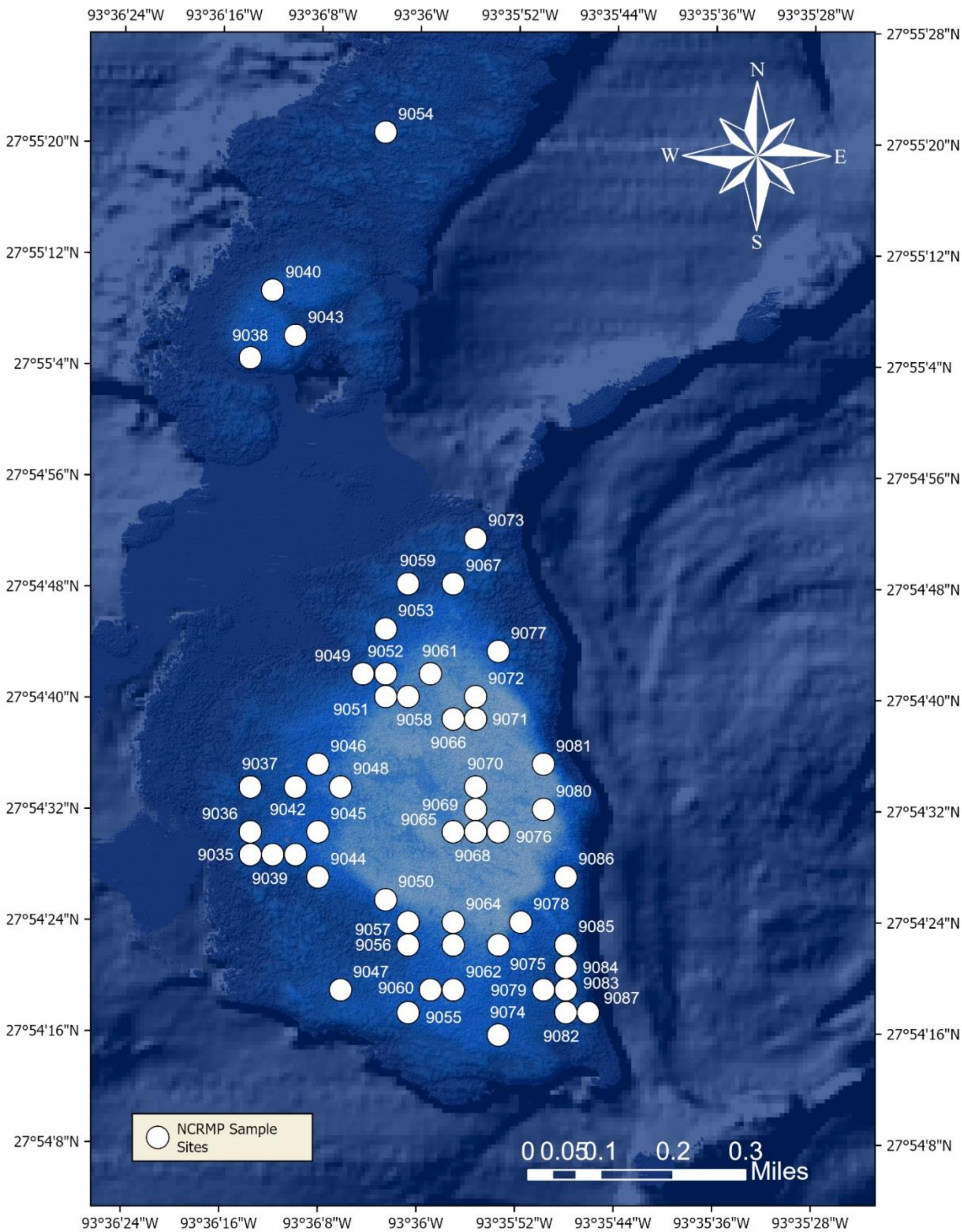


Figure 2.2. Reef-wide random photo transect survey sites at EFGB conducted in collaboration with NCRMP in August 2022. Primary sites were prioritized for surveys, while secondary sites were surveyed as time allowed. Image: Kelly O'Connell/CPC Inc

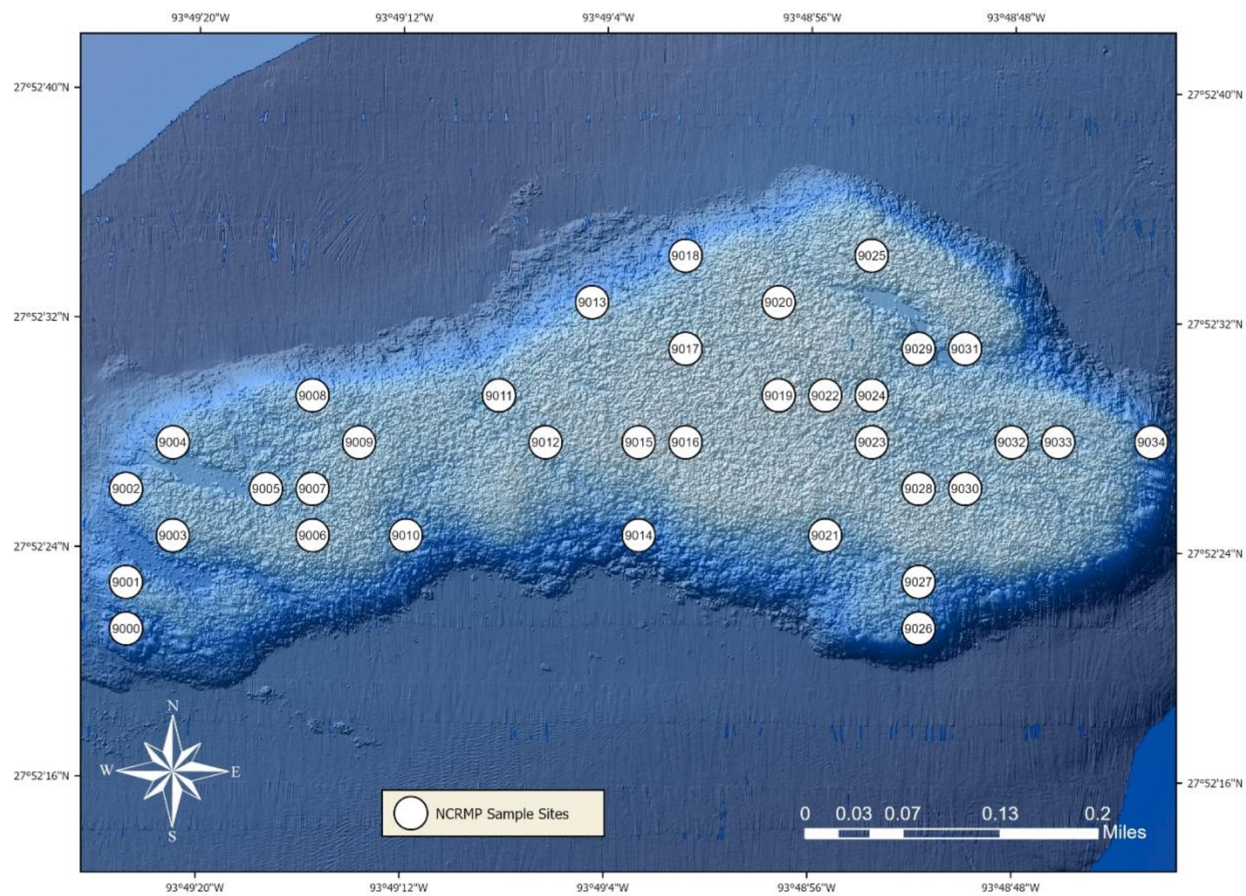


Figure 2.3. Reef-wide random photo transect survey sites at WFGB conducted in collaboration with NCRMP in August 2022. Image: Kelly O'Connell/CPC Inc

Random Transect Data Processing

Mean percent benthic cover from random transect images was analyzed using CPCe version 4.1 with a 510-point overlay randomly distributed among all images within a transect (30 spatially random points per image; Aronson et al., 1994; Kohler & Gill, 2006). Organisms or substrate type positioned beneath each random point were tallied, with organisms being identified to the lowest possible taxonomic level, and cover was categorized into seven groups: 1) coral, 2) sponges (including encrusting sponges), 3) CCA, 4) macroalgae (algae longer than approximately 3 mm and thick algal turfs covering underlying substrate), 5) colonizable substrate (including fine turf algae, rubble, and bare rock; Aronson & Precht, 2000; Aronson et al., 2005), 6) sand, and 7) an "other" category (biotic components such as sea urchins, ascidians, fish, serpulids, and unknown species). Additional features (photostation tags, tape measures, scientific equipment) and points with no data (shadows) were excluded from the analysis. Points on corals that could not be differentiated because of camera angle or camera distortion were labeled as "unidentified coral." *Orbicella* colonies that could not be identified to the species level were labeled as *Orbicella* spp. Point count analysis was applied on photos within a transect and mean percent cover for all groups was determined by averaging all transects per study site and all transects in reef-wide surveys. Results are presented as mean percent cover ± standard error (SE).

Incidences of coral bleaching, paling, concentrated and isolated fish biting, and mortality were also recorded as "notes" in CPCe, providing additional data for each random point. Any point that landed on a portion of coral that was white in color was characterized as "bleached." Any point that landed on coral that was pale relative to what is considered "normal" for the species was characterized as "paling" (Lang et al., 2012). If the colony displayed some bleaching or paling, but the point landed on a healthy area of the organism, the point was "healthy" and no bleaching or paling was noted in CPCe. To classify fish biting, any point that landed where fish biting occurred on a coral head more than once was classified as concentrated fish biting, and any point where there was only one occurrence of fish biting was classified as isolated fish biting. Mortality included any point on recently dead coral (exposed bare skeleton) with little to no algae growth that could still be identified to the species level. Any point that landed on a lesion (a stark border dividing healthy coral tissue from white, denuded skeleton along colony margins) due to the observed coral disease outbreak was classified as "disease" (Johnston et al., 2023).

Consistency for photographic random transect methods was ensured by training all scientific divers in the proper operation of the camera systems. Camera settings and equipment were standardized so that consistent transect images were taken annually, and equipment checklists were provided in the field to ensure divers had all equipment and were confident with tasks assigned. Random transect photographs were reviewed promptly after images were taken, in the field, to ensure the quality was sufficient for analysis. After all benthic components were identified in CPCe files, quality assurance/quality control (QA/QC) consisted of an independent review by a separate, trained researcher, different from the CPCe analyzer, to ensure all identified points from the random transect photographs were accurate. Any mistakes were corrected before percent cover analysis was completed.

Random Transect Statistical Analysis

Benthic community interactions in EFGB and WFGB random transects were evaluated with distance-based analyses using Primer® version 7.0 (Anderson et al., 2008; Clarke et al., 2014). Euclidean distance resemblance matrices were calculated using untransformed percent cover data from random transect benthic groups. Data were left untransformed so that the significance of non-dominant groups was not overinflated. Permutational multivariate analysis of variance (PERMANOVA) was based on Euclidean distance resemblance matrices and used to test for benthic community differences and estimate components of variation between study sites as well as reef-wide surveys (Anderson et al., 2008). If significant differences were found, groups or species contributing to observed differences were examined using similarity percentages (SIMPER) to assess the percent contribution of each variable to dissimilarity between groups (Clarke et al., 2014).

Coral species composition was compared between study sites and reef-wide surveys using PERMANOVA on square-root-transformed coral species percent cover data with Euclidean distance similarity matrices. Diversity indices for coral species, including Margalef's species richness (d), Pielou's evenness (J'), and Shannon diversity (H'), were calculated to make comparisons between banks from all survey combined. Similarity matrices from diversity indices, based on square-root-transformed data and Euclidean distance, were tested for significant dissimilarities using analysis of similarity (ANOSIM; Clarke et al., 2014).

To assess trends in historical random transect mean percent cover data (1992 to 2019), benthic groups by year and study site were visualized using principal coordinates ordination (PCO), based on Euclidean distance similarity matrices, with percent variability explained on each canonical axis. A time series trajectory with correlation vectors (correlation >0.2) was overlaid on PCO plots to represent the direction of the variable gradients for the plot (Anderson et al., 2008; Clarke et al., 2014). Cluster analyses for year groups were performed on Euclidean distance similarity matrices with SIMPROF tests to identify significant ($\alpha = 0.05$) clusters within the data (Clarke et al., 2008). Study site communities were compared using PERMANOVA. SIMPER identified groups contributing to observed dissimilarities (Clarke et al., 2014).

Mean percent benthic cover from random transect surveys was analyzed from 1989 to 2022. Monotonic trends in mean percent cover data were assessed using the Mann-Kendall trend test in R version 2.13.2 (Hipel & McLeod, 1994; Helsel & Hirsch, 2002). Tests for significant correlation among benthic cover groups were completed in R version 2.13.2 with Pearson's correlation (Helsel & Hirsch, 2002). It should be noted that the range of data collected has varied slightly over the years. From 1989 to 1991, only mean percent coral cover data were collected; other major benthic groups were added in 1992. No data were collected in 1993.

Repetitive Photostation Field Methods

Repetitive photostations, marked by permanent pins with numbered tags on the reef, were located by scuba divers using underwater maps displaying compass headings and distances to each station. Thirty-six out of 37 photostations were located and photographed within the EFGB study site and all 41 photostations were located and photographed within the WFGB study site, representing 97% and 100% of photostations, respectively. In addition, permanent repetitive photostations ranging in depth from 32–39 m and located beyond the study site boundaries were also documented. Nineteen out of 24 photostations were located and photographed at EFGB and all 24 were located and photographed at WFGB, representing 79% and 100% of the 32–39 m photostations, respectively.

After photostations were located, divers photographed each station using a Nikon® D7000® SLR camera with 16-mm lens in a Sea&Sea® housing with small dome port and two Inon® Z240 strobes (1.2 m apart). The camera was mounted in the center of a T-shaped camera frame, at a distance of 2 m from the substrate (Figure 2.4). To ensure that the stations were photographed in the same manner each year, the frame was oriented in a north-facing direction and kept vertical using an attached bullseye bubble level and compass (for more detailed methods, see Johnston et al. [2017a]). This set-up produced images covering 5 m^2.

It should be noted that during the entirety of the monitoring program, underwater camera setups used to capture benthic cover in the repetitive photostations changed as technology advanced from 35-mm slides and film (1989 to 2007) to digital still images (2008 to 2022; Gittings et al., 1992; Continental Shelf Associates, 1996; Dokken et al., 1999, 2003; Precht et al., 2006; Zimmer et al., 2010; Johnston et al., 2013, 2015, 2017a, 2017b, 2018a, 2020, 2021, 2022). From 1989 to 2009, photographs for each repetitive photostation encompassed an 8 m^2 area, but changed to a 5 m^2 area in 2009, a 9 m^2 area in 2010, and back to a 5 m^2 area from 2011 onward due to requirements for consistent image quality, changes in camera equipment, and updated technology. The total number of photostations changed over time as well, as new stations were established or old stations were lost or not located due to missing tags or overgrown station posts. Nevertheless, approximately 40 photostations have been maintained within each study site since 1989. Within the 32–39 m depth range, nine of the 23 EFGB deep photostations were established in 2003 and 12 of the 24 WFGB deep photostations were established in 2012. Two additional EFGB stations (30 m and 31 m) were added in 2013. The remaining 12 photostations in this depth range at each bank were added in 2017.

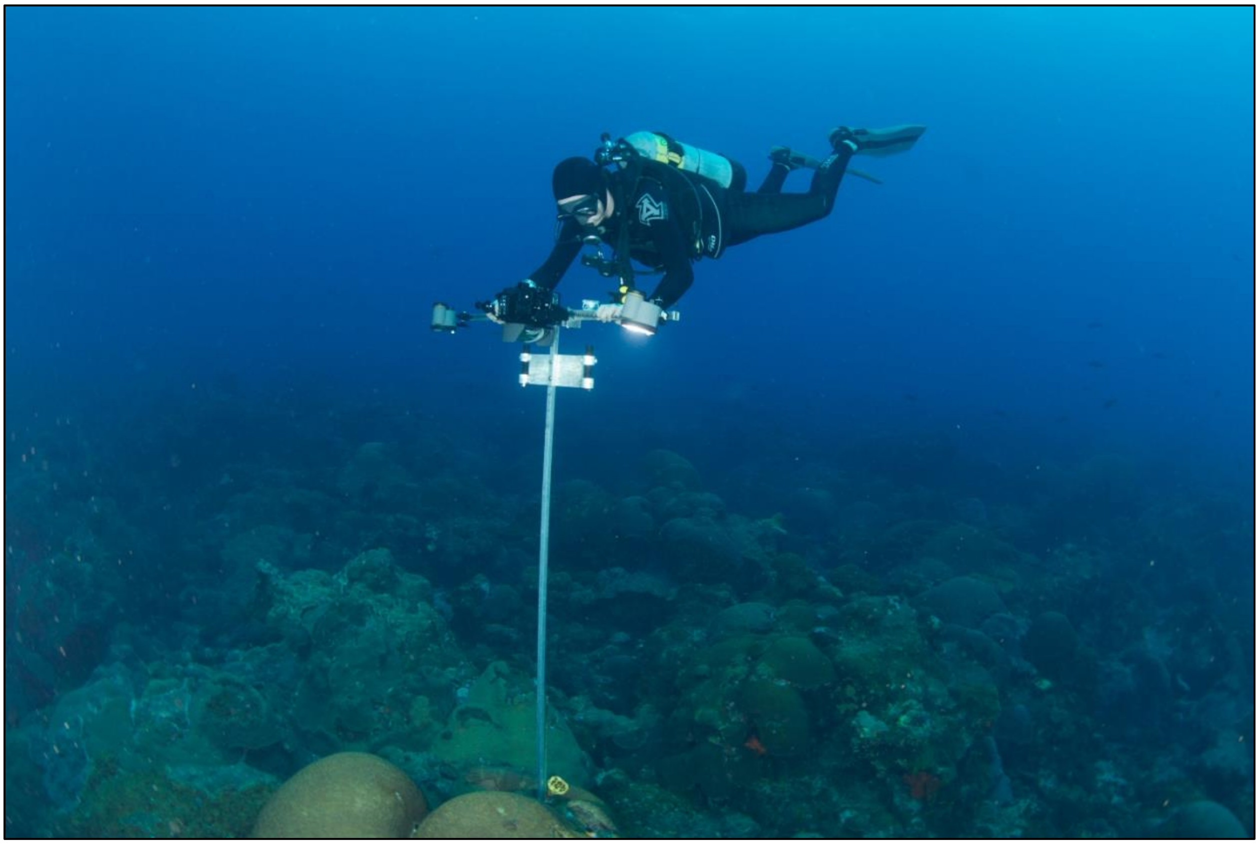


Figure 2.4. NOAA diver photographs a repetitive photostation with camera and strobes mounted to an aluminum T-frame. Photo: G.P. Schmahl/NOAA

Repetitive Photostation Data Processing

Mean percent benthic cover from repetitive photostation images was analyzed using CPCe version 4.1 (Aronson et al., 1994; Kohler & Gill, 2006). A total of 100 random dots were overlaid on each photograph and benthic species lying under these points were identified and verified by QA/QC (see Benthic Community Methods: Random Transect Data Processing for detailed methods). Point count analysis was conducted for all photos and mean percent cover for functional groups was determined by averaging across all photostations per bank. Results are presented as mean percent cover ± SE. Repetitive photostation comparisons were only made with other repetitive photostations, and not with data from random transects. Because photostations were not randomly selected, they are not intended to estimate study site or reef-wide benthic cover or populations.

Consistency for repetitive photographic methods was ensured by using trained divers and standardized camera settings, equipment, and operating procedures. Photographs were reviewed in the field promptly after images were taken to ensure the quality was sufficient for analysis. After all benthic components were identified in CPCe files, QA/QC consisted of an independent review by a separate, trained researcher, different from the CPCe analyzer. Any mistakes were corrected before percent cover analysis was completed.

Repetitive Photostation Statistical Analysis

Benthic community interactions were evaluated using distance-based analyses with Primer® version 7.0 (Anderson et al., 2008; Clarke et al., 2014) and PERMANOVA (see Benthic Community Methods: Random Transect Statistical Analysis). Percent coral cover was compared among repetitive photostations using PERMANOVA with photostation depth as a covariable on square-root-transformed coral species percent cover data with Euclidean distance similarity matrices. Mean percent coral cover from repetitive photostations was compared between 1989 and 2022 (n = 24 at EFGB and n = 27 at WFGB) using a paired t-test in R version 2.13.2.

Benthic Community Results

Random Transect Mean Percent Cover

Coral, followed by macroalgae, had the highest mean percent benthic cover at EFGB and WFGB in both study sites and reef-wide surveys in 2022 (Figure 2.5; Table 2.1).

PERMANOVA analysis revealed no significant differences in benthic community composition between EFGB and WFGB study sites in 2022; however, it revealed significant differences in benthic community composition between study site random transect surveys combined and reef-wide surveys combined (Table 2.2). Independent bank comparisons were not made due to low sample size at WFGB reef-wide surveys, so data for both banks were combined. SIMPER analysis indicated that the dissimilarity between study sites and reef-wide surveys was due to significantly higher macroalgae cover in reef-wide surveys and significantly higher coral cover within study sites (contributing 42% and 50%, respectively).

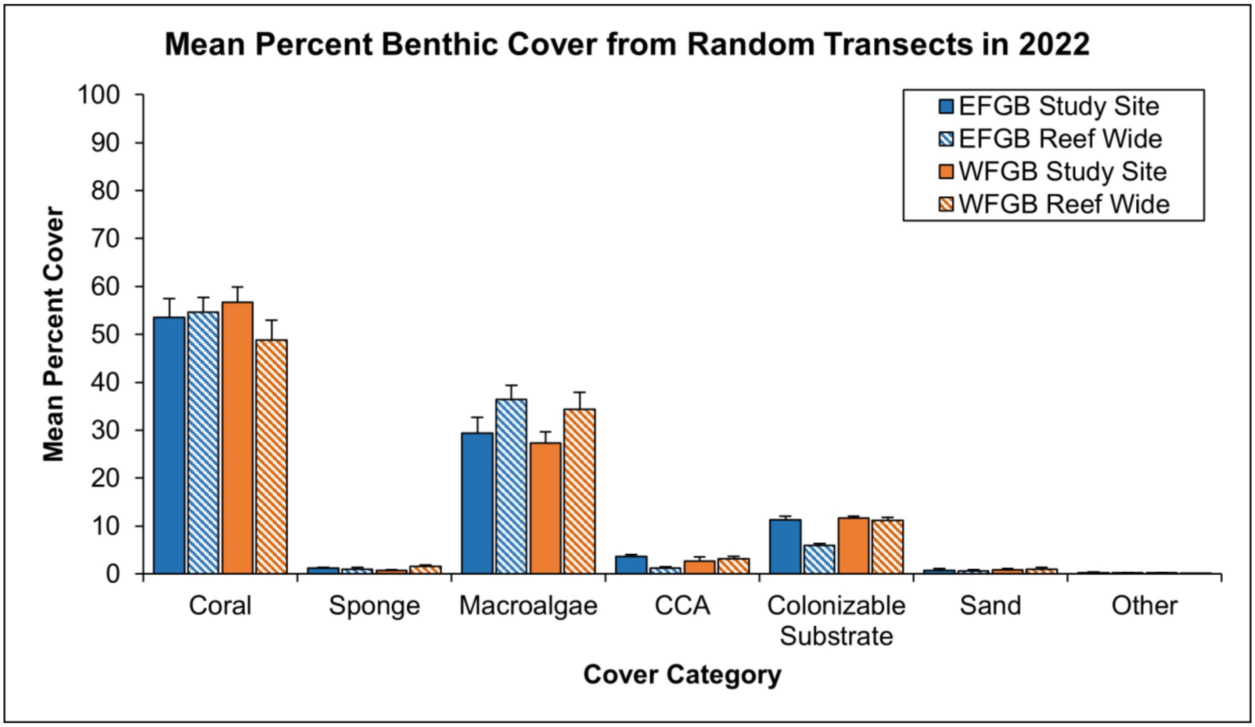


Figure 2.5. Mean percent benthic cover + SE from random transect surveys within EFGB and WFGB study sites and reef-wide surveys in 2022.

Table 2.2. PERMANOVA results comparing 2022 mean percent benthic cover in EFGB and WFGB random transect surveys as well as random transect surveys within study sites and reef wide survey locations. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank (EFGB vs. WFGB)	7.03	1	1.66	0.166
Location (Study Site vs. Reef wide)	21.06	1	4.96	**0.007**
Bank x Location	11.16	1	2.62	0.059
Res	297.03	70		
Total	336.28	73		

Eighteen species of coral were observed within the EFGB random transect study site surveys and 17 were observed in the EFGB reef-wide surveys. Thirteen species of coral were observed in the WFGB random transect study site surveys and 15 were observed in the WFGB reef-wide surveys (Figure 2.6). *Orbicella franksi* was the most abundant coral species observed within EFGB (27.52 ± 3.00%) and WFGB (35.40 ± 2.99%) surveys. *Pseudodiploria strigosa* ranked second (7.65 ± 1.12% at EFGB and 7.78 ± 1.08% at WFGB; Figure 2.4). The *Orbicella* spp. complex, consisting of *O. franksi, O. faveolata*, and *O. annularis,* are listed as threatened species under the Endangered Species Act.

PERMANOVA analysis revealed significant differences in coral species composition between study sites (Table 2.3). SIMPER analysis indicated that this was due to significantly higher *O. faveolata* cover in the EFGB study site and significantly higher *O. franksi* cover in the WFGB study site (contributing 14% and 15%, respectively); however, PERMANOVA analysis revealed no significant differences in coral species composition between EFGB and WFGB reef-wide surveys in 2022.

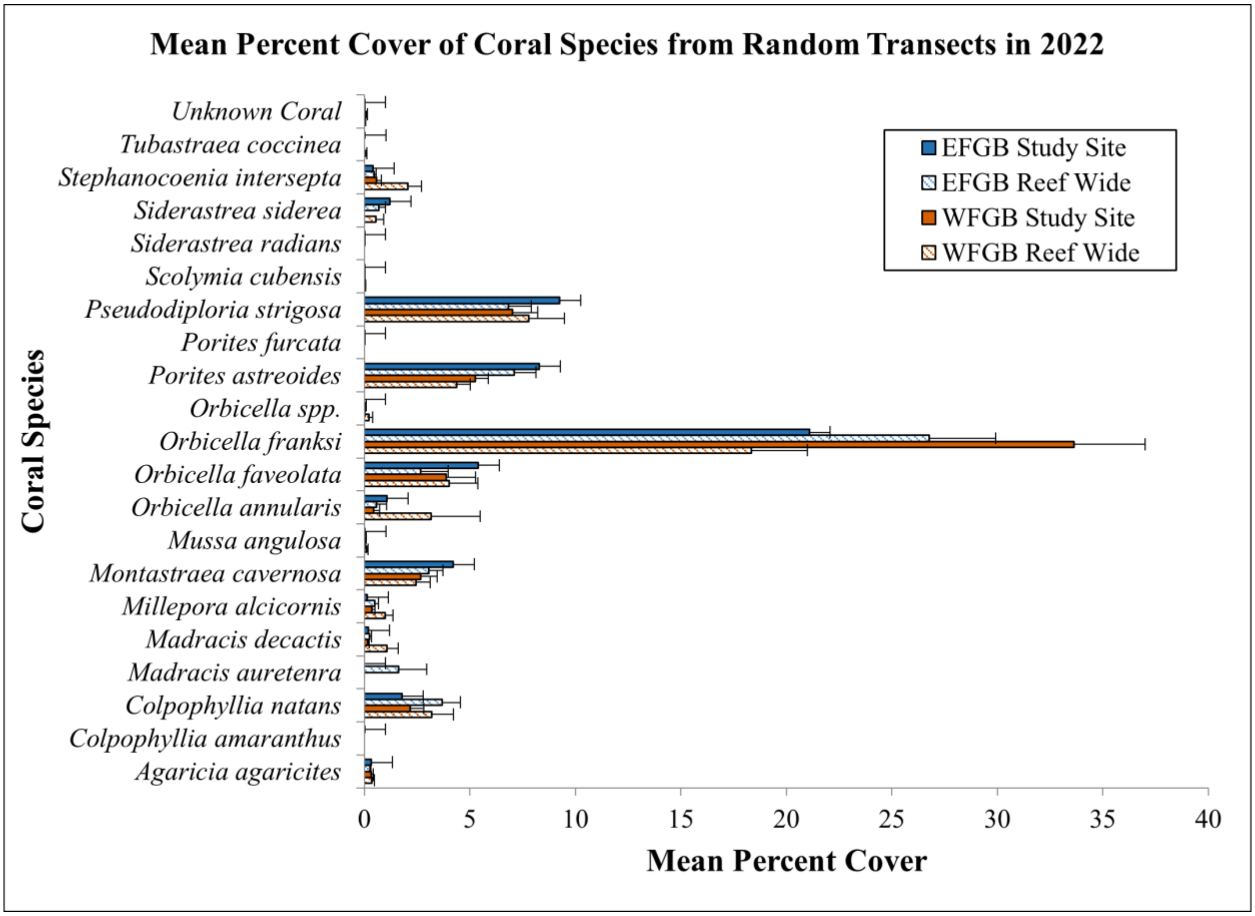


Figure 2.4. Mean percent cover + SE of observed coral species from random transect surveys within EFGB and WFGB study sites and reef-wide surveys in 2022.

Table 2.3. PERMANOVA results comparing coral species mean percent cover from EFGB and WFGB study site random transect surveys in 2022. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	20	1	2.27	**0.03**
Res	269	30		
Total	290	31		

Coral species diversity measures were averaged for all survey locations by bank in 2022 (Table 2.4). ANOSIM analysis revealed no significant differences between coral communities by bank for all surveys.

Table 2.4. Mean coral species diversity measures ± SE from all EFGB and WFGB random transect surveys in 2022.

Random Transect Coral Diversity Measures	EFGB	WFGB
Margalef's species richness (d)	2.57 ± 0.08	2.73 ± 0.11
Pielou's evenness (J')	0.87 ± 0.01	0.88 ± 0.01
Shannon diversity (H'(loge))	1.82 ± 0.04	1.88 ± 0.05

Approximately 2% of the coral cover within all random transect surveys was bleached or pale in late August and September of 2022. It is important to note that surveys occurred at the time of year when coral bleaching is not typically noted at FGBNMS, and water temperatures and exposure times were lower than threshold levels known to trigger bleaching (Ogden & Wicklund, 1988; Glynn & D'Croz, 1990; Hagman & Gittings, 1992; Johnston et al., 2019). In addition, less than 0.2% of coral cover was affected by fish biting. Fish biting that resulted in the removal of coral polyps from affected areas is most likely the result of damselfish gardening or grazing by stoplight parrotfish (*Sparisoma viride*; Bruckner & Bruckner, 1998; Bruckner et al., 2000). Signs of recent mortality and disease affected 0.6% of coral cover in all random transect surveys.

Random Transect Long-Term Trends

Mean percent coral cover in study sites (17–27 m) from 1989 to 2022 ranged from 40–64% at the EFGB and 37–66% at the WFGB. It increased significantly in the WFGB study site over that time period ($\tau = 0.57$, $p < 0.001$; Figure 2.5), and remained stable at EFGB. Data on sponge, CCA, macroalgae, colonizable substrate, and sand cover began to be collected in 1992. From then until 1999, macroalgae cover was consistently below 5% within the study sites; in 1999, however, macroalgae cover increased to over 20%, fluctuated dramatically during the following decade, and has averaged 30% over the past 12 years. In general, macroalgae and colonizable substrate varied inversely (algae typically grows preferentially on colonizable substrate) and were significantly negatively correlated at EFGB ($\tau = -8.97$, $p < 0.001$) and WFGB ($\tau = -9.07$, $p < 0.001$). While macroalgae colonized available substrate, it did not outcompete or displace coral. From 1992 to 2022, macroalgae increased significantly in EFGB ($\tau = 0.61$, $p < 0.001$) and WFGB ($\tau = 0.53$, $p < 0.001$) study sites. Colonizable substrate significantly decreased in EFGB ($\tau = -0.54$, $p < 0.001$) and WFGB ($\tau = -0.47$, $p < 0.001$) study sites (Figure 2.5).

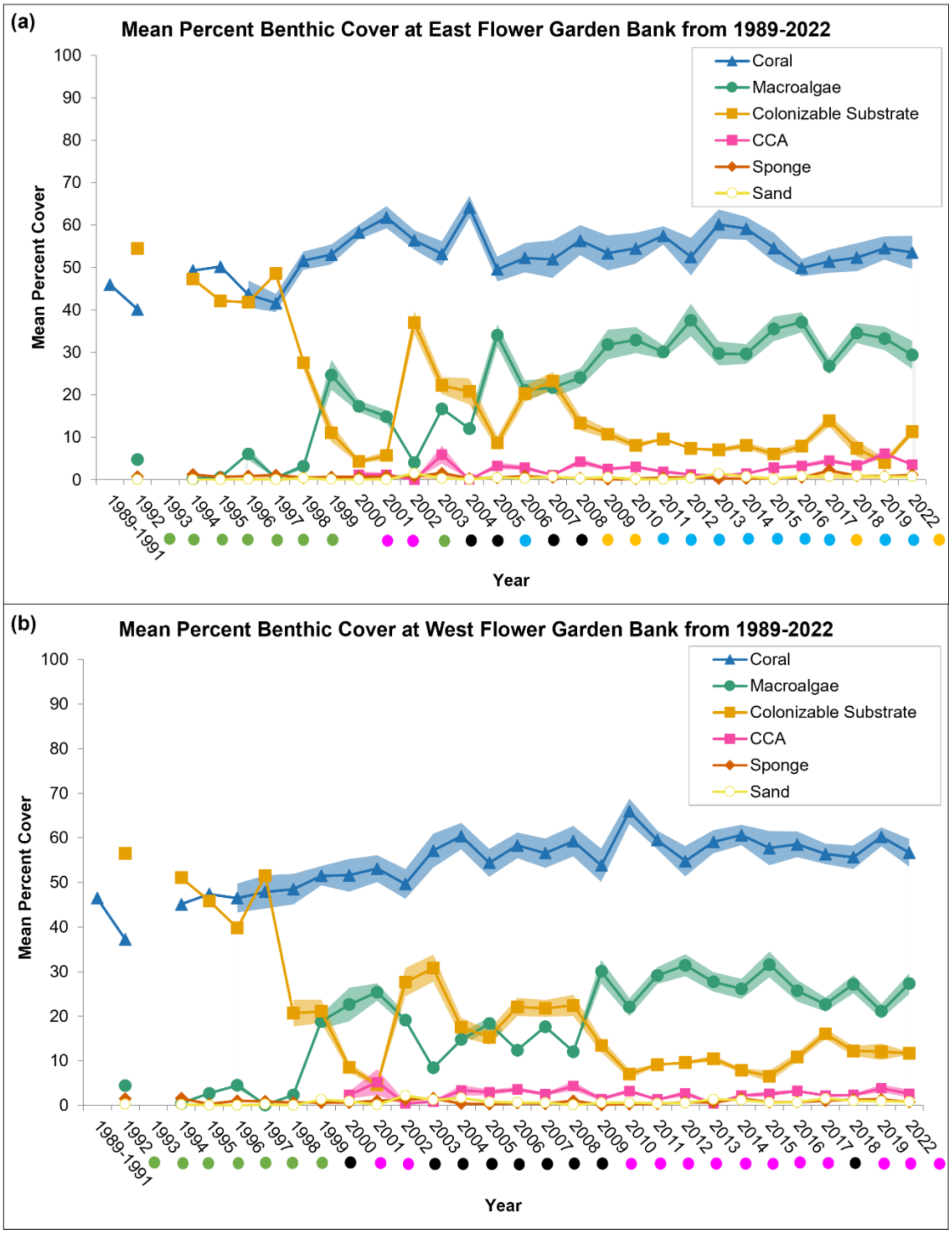


Figure 2.5. Mean percent benthic cover ± SE bands from random transect surveys within (a) EFGB and (b) WFGB study sites from 1989 to 2022. The colored dots below the years on the x-axis represent significant year clusters corresponding to SIMPROF groups in Figures 2.6 and 2.7. Only coral cover data were reported from 1989–1991 and no mean percent cover data were reported in 1993, 2020, or 2021. Sources: Gittings et al., 1992 (1989 to 1991); Continental Shelf Associates, 1996 (1992 to 1995); Dokken et al., 2003 (1996 to 2001); Precht et al., 2006 and Zimmer et al., 2010 (2002 to 2008); Johnston et al., 2013, 2015, 2017a, 2017b, 2018a, 2020, 2021, 2022 (2009 to 2018).

For available complete yearly mean benthic percent cover data (1992 to 2022), SIMPROF analysis detected five significant year clusters in the EFGB study site (1992 to 1998 and 2002; 2003 to 2004 and 2006 to 2007; 2000 to 2001; 2008 to 2009, 2017, and 2022; and 2005, 2010 to 2016, and 2018 to 2019), while the year 1999 was not grouped with any other years (Figures 2.5 and 2.6). Colonizable substrate and macroalgae mean percent cover contributed to the majority of the dissimilarity among all year group clusters.

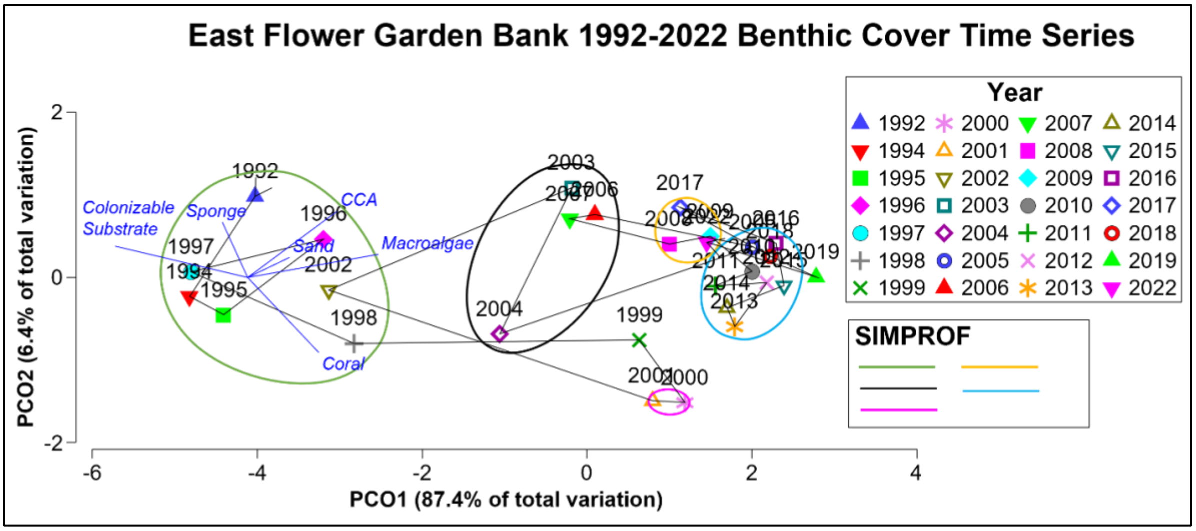


Figure 2.6. PCO plot for random transect benthic cover analysis within the EFGB study site from 1992 to 2022. The ovals are SIMPROF groups representing significant year clusters grouped by color. The blue vector lines represent the directions of the variable gradients for the plot.

Yearly mean benthic percent cover from 1992 to 2022 at the WFGB study site displayed a similar pattern to EFGB, resulting in three significant year clusters (1992 to 1998; 1999, 2002 to 2008, and 2017; and 2000 to 2001 and 2009 to 2022; Figure 2.7). Macroalgae and colonizable substrate contributed to the majority of the dissimilarity among year group clusters.

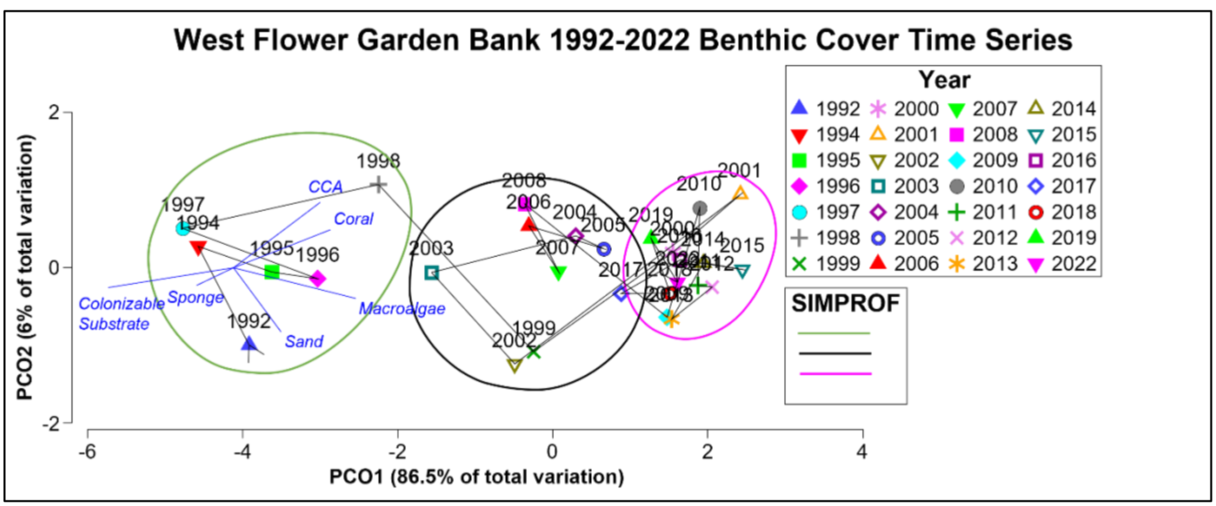


Figure 2.7. PCO plot for random transect benthic cover analysis within the WFGB study site from 1992 to 2022. The ovals are SIMPROF groups representing significant year clusters grouped by color. The blue vector lines represent the directions of the variable gradients for the plot.

PERMANOVA results revealed no significant differences between study sites, suggesting that EFGB and WFGB study sites were similar to each other from 1992 to 2022 in overall benthic community composition, experiencing similar shifts though time.

Repetitive Photostation Mean Percent Cover

Coral and macroalgae were the dominant benthic cover categories in EFGB and WFGB repetitive photostations in 2022 (Figure 2.8; Table 2.5). At EFGB, 2.6% of the coral cover was pale or bleached in the photostations. At WFGB, 0.6% was pale or bleached. In addition, EFGB photostations had 0.6% fish biting, 0.8% recent and transitional mortality, and 0.5% coral disease. The WFGB photostations had 0.1% fish biting, 0.04% recent and transitional mortality, and 0.35% coral disease.

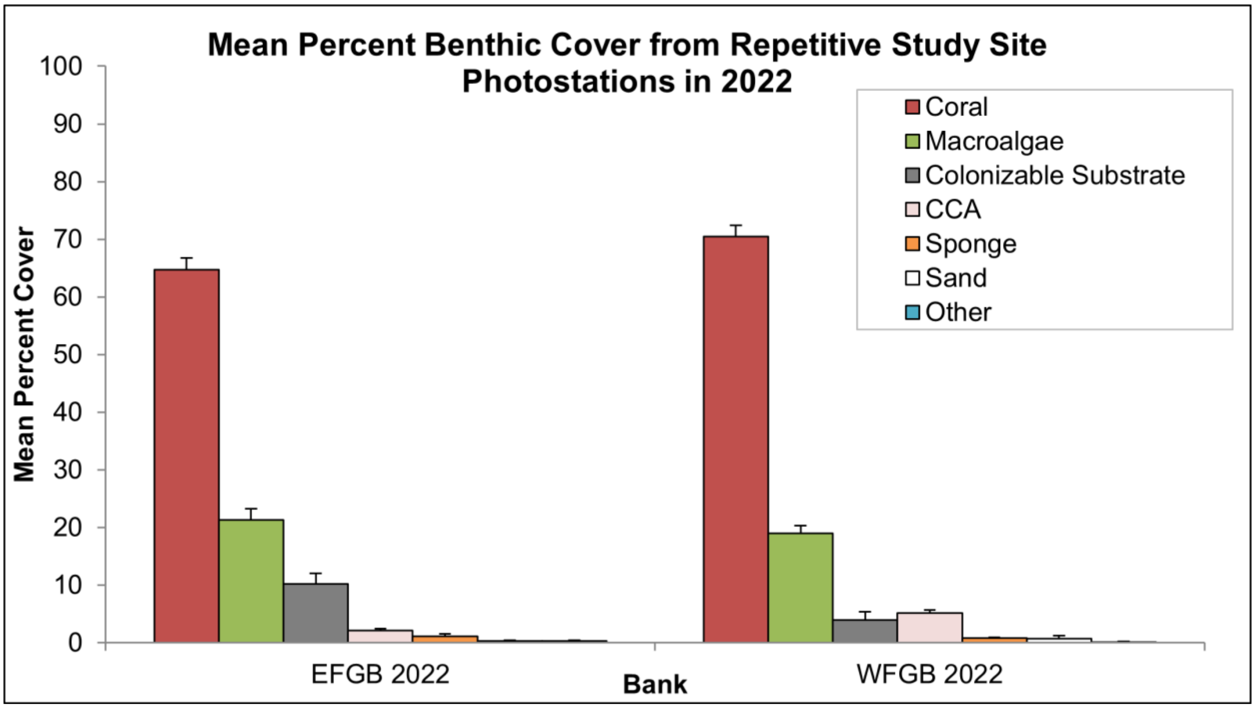


Figure 2.8. Mean percent benthic cover + SE within EFGB and WFGB repetitive photostations in 2022.

Table 2.5. Range of mean percent cover by category from EFGB and WFGB repetitive photostations, and all photostations combined, in 2022.

Percent Cover Range	EFGB	WFGB	EFGB and WFGB Combined
Coral	25.26–95.00%	28.13–97.75%	25.26–97.75%
Macroalgae	0.00–63.16%	1.12–56.25%	0.00–63.16%
CCA	0.00–10.42%	0.00–20.62%	0.00–20.62%
Colonizable substrate	0.00–44.79%	0.00–44.21%	0.00–44.79%
Sponge	0.00–20.41%	0.00–07.29%	0.00–20.41%
Sand	0.00–05.05%	0.00–35.71%	0.00–35.71%
Other	0.00–04.12%	0.00–01.14%	0.00–1.14%

PERMANOVA analysis comparing benthic groups revealed significant differences, suggesting that the EFGB and WFGB repetitive photostations were dissimilar in benthic community composition in 2022 (Table 2.6). SIMPER analysis identified the observed dissimilarity among photostations was due to significantly higher colonizable substrate cover in the EFGB photostations (contributing 26%).

Table 2.6. PERMANOVA results comparing 2022 mean percent benthic cover in EFGB and WFGB repetitive photostations. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
EFGB and WFGB photostations	74	1	10.31	**0.001**
Res	875	118		
Total	949	119		

The repetitive photostations ranged in depth from 18–39 m at EFGB (averaging 25 m depth) and 20–38 m at WFGB (averaging 26 m depth). Mean percent benthic coral cover categories ranged widely among the photostations (by about 70% at each bank; Table 2.5). Less than 3% of coral cover was pale or bleached. In addition, there was approximately 1% of old mortality less than 2% recent mortality.

Fifteen coral species were recorded in EFGB repetitive photostations and 14 at WFGB. *Orbicella franksi* was the dominant species at EFGB (36.05% ± 2.70), followed by *P. strigosa* (8.55% ± 1.33) and *Montastraea cavernosa* (5.58% ± 1.12; Figure 2.4). *Orbicella franksi* was the dominant coral at WFGB (40.21% ± 2.46), followed by *P. strigosa* (7.09% ± 1.11) and *M. cavernosa* (6.53% ± 1.19; Figure 2.9).

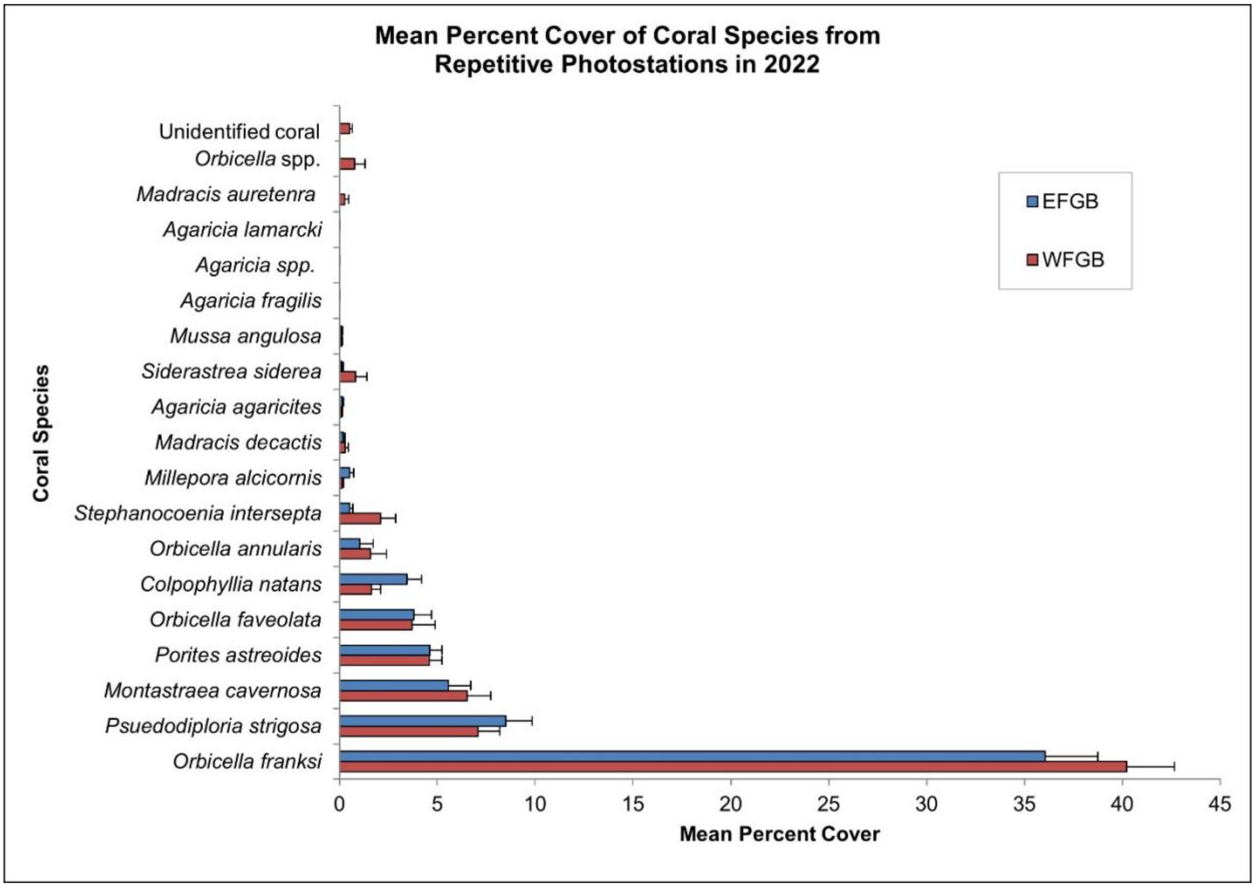


Figure 2.9. Mean percent cover + SE of coral species from repetitive photostations at EFGB and WFGB in 2022.

Qualitative Analysis of Repetitive Photostations and Coral Disease

The most prominent difference between 2021 and 2022 images was coral disease-like lesions (2.1–2.6% prevalence) observed on seven coral species during EFGB and WFGB surveys in August and September 2022 (Johnston et al., 2023; Table 2.7; Table 2.8). The repetitive photostations were invaluable for documenting the disease outbreak on impacted colonies (Figure 2.10). As described in Johnston et al. (2023), the proportion of colonies with lesions was calculated in each photostations. Marginal and/or multi-focal lesions and tissue loss were observed, affecting three dominant coral species: *Colpophyllia natans* (11–18% of colonies), *Pseudodiploria strigosa* (7–8% of colonies), and *Orbicella* spp. (1% of colonies; Johnston et al., 2023).

Table 2.7. Qualitative comparison of EFGB 2021 to 2022 repetitive photostations. Images taken in 2021 with a GoPro camera instead of the Nikon® D7000® camera are in bold. Stations 305, 401, 404, and 409 were not located and photographed in 2021. Station 107 was not located and photographed in 2022.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 101	Station dominated by *O. franksi* colonies; some with transitional damage present. *Dictyota* sp. and turf present but infrequent. CCA in patches.	Transitional damage still present on *O. franksi*. Transitional mortality on two *P. astreoides* colony margins from disease. Increased coverage of *Dictyota* sp. with a decrease in turf.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 102	Station dominated by large *P. strigosa* colonies and *Orbicella* spp. Small *A. clathrodes* sponge present in the left center and bottom center. *Dictyota* sp. present and in patches. Singular *Tubastraea* sp. colony present in top right.	Mortality on colony margin between two bordering *P. strigosa* colonies. *P. astreoides* colony covered in patchy disease lesions. *A. clathrodes* sponges still present. *Dictyota* sp. still present and in patches. *Tubastraea* sp. still present.
EFGB 103	Station dominated by *P. strigosa* colonies and *Orbicella franksi* colonies. *A. clathrodes* sponge present. *Arolochroia crassa* sponge present. *Dictyota* sp. and turf algae mostly absent.	Small *P. astreoides* colonies growing in the center have disease lesions in both patches and on colony margins. *A. clathrodes* and *A. crassa* sponges are still present. *Dictyota* sp. and turf algae have increased and are in patches.
EFGB 104	Station dominated by *Orbicella* species. Unhealthy central *P. strigosa* colony with patchy tissue loss. Turf algae and CCA present. *Dictyota* sp. are minimal and small when present.	*P. strigosa* colony has recovered. Two central *P. astreoides* now have heavy damselfish gardening. *Dictyota* sp. have remained mostly absent from the site.
EFGB 105	Station dominated by *P. astreoides* colonies. Multiple *A. clathrodes* sponges and singular *A. crassa* sponge present. Two *M. alcicornis* colonies are bleached. Sand patches line the left side. *Dictyota* sp. in infrequent patches. Central CCA patches.	Central *P. strigosa* has mortality on colony margin with fine algae overgrowth. The two *M. alcicornis* colonies are still bleaching. General sponge health has improved between the *A. crassa* and *A. clathrodes* with some smaller sponges showing growth. *Dictyota* sp. are more frequent but still in patches.
EFGB 106	Station dominated by *Orbicella* species. Single *Tubastraea* sp. present. Multiple small, algae overgrown, *A. clathrodes* sponges. Large *E. ferox* sponge patch. *M. decactis, Dictyota* sp. and CCA patches present.	Health of *A. clathrodes* sponges improving with less algae overgrowth. *E. ferox* sponges are less numerous. *Tubastraea* sp. still present.
EFGB 107	Station dominated by *O. franksi* and *P. strigosa* colonies. *Dictyota* sp. present. *E. ferox* and *A. clathrodes* sponges present.	Not found in 2022.
EFGB 108	Station dominated by relatively small *P. strigosa* and *P. astreoides* colonies. Some *P. astreoides* with partial tissue loss. Paling *M. cavernosa* colony present with some tissue loss. *Orbicella* spp. present. CCA, turf algae, and *Dictyota* sp. present. *A. clathrodes* and *A. crassa* sponges present, both with damage and algae overgrowth.	*P. astreoides* colonies have recovered lost tissue from 2021, many have since formed disease lesions in both patches and on colonies margins. *M. cavernosa* colony has recovered. *A. clathrodes* sponge still has some algae overgrowth but has increased in size. *A. crassa* sponges are no longer overgrown but have reduced in size. *Dictyota* sp. have increased in coverage.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 109	Photo smaller as taken with GoPro. Station dominated by *P. strigosa* and *O. franksi*. Large mats of turf algae. *Dictyota* sp. present but infrequent. Small *A. crassa* and *E. ferox* sponges present.	*M. decactis* colony has tissue loss with algae overgrowth. *Dictyota* sp. coverage has increased slightly. Large mats of turf algae are no longer present, only small patches. *E. ferox* sponges have decreased in size.
EFGB 201	Station dominated by large *O. faveolata* colony and surrounded by *O. franksi* colonies. Turf algae and CCA present. Partial tissue loss on *O. faveolata* in lower right. Bleaching *M. cavernosa* in top right.	*M. cavernosa* is still light in color and has areas of algae overgrowth. *O. faveolata* has recovered from tissue loss but has tissue loss in new regions. The colony has lost cover in center right regions. Singular *P. astreoides* now has signs of damselfish gardening. Multiple *P. astreoides* in the lower left have mortality on colony margins from disease. Turf cover has decreased while *Dictyota* sp. cover has slightly increased.
EFGB 202	Station dominated by *O. franksi* colonies and large *M. cavernosa* colony. Small *C. natans* colony. CCA and turf algae found between colonies.	Site is still healthy. *O. franksi* colony on the bottom left show's signs of damselfish gardening. Central small *P. strigosa* colony has mortality on colony margin. Turf algae has decreased coverage.
EFGB 203	Station dominated by *O. franksi*, *Dictyota* sp., and *L. variegata*. CCA and turf algae present. The singular *M. alcicornis* colony is bleached.	*M. alcicornis* colony has recovered from bleaching. *L. variegata* has increased in size and is growing in turf algae mats. *Dictyota* sp. and turf algae cover have slightly increased.
EFGB 204	Station dominated by *O. franksi* and *Dictyota* sp. Turf algae and *L. variegata* present. Some transitional mortality on edges of *O. franksi* colonies with no algae. Paling of some *Orbicella* spp. colonies.	*O. franksi* has recovered with lost cover replaced by CCA. Site is absent of paling colonies. Center and left *P. astreoides* colonies have patches of disease lesions. *Dictyota* sp. have lost coverage to turf algae. *L. variegata* has increased in size is growing in turf mats.
EFGB 205	Station dominated by *O. franksi* and *Dictyota* sp. Small *Ircinia felix* sponge and *C. natans* colony present. Some paling on *O. franksi* colonies.	Site shows no signs of paling. Small *I. felix* sponge is still present. *Dictyota* sp. cover increased.
EFGB 206	Station dominated by *O. faveolata*, *Dictyota* sp., and *P. strigosa.* Turf and *L. variegata* present. Large patch of tissue mortality on a *P. strigosa* in the bottom right.	*P. strigosa* mortality area noted in 2021 remains present with no signs of recovery. Left *P. strigosa* has tissue loss on colony margin from disease, with fine algae overgrowth.
EFGB 207	Station dominated by large *O. faveolata* colony. *P. strigosa* and *O. franksi* colonies present. *Dictyota* sp. and turf present.	Large *O. faveolata* colony has patches of tissue mortality with fine algae overgrowth from disease. Left *O. franksi* has lost cover but does not look damaged. *Dictyota* sp. cover has increased.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 208	Station dominated by *O. franksi*. CCA and turf algae present. Loss of tissue on multiple *O. franksi* and *O. faveolata* colonies.	*O. franksi* and *O. faveolata* colonies have recovered from tissue loss in some areas while losing tissue in new regions. Increased tissue loss on margins of bordering colonies. Turf algae cover decreased slightly.
EFGB 209	Station dominated by *O. franksi* and *O. annularis* colonies. Turf and CCA present. Paling on *M. cavernosa* colony and paling on *O. franksi* colony.	Site shows no signs of paling. Many *P. astreoides* colonies have tissue loss on colony margins from disease.
EFGB 210	Station dominated by *O. franksi* colonies. *L. variegata,* turf algae, and CCA present. Single *Xestospongia muta* sponge. Bleaching *M. alcicornis* colony.	*Dictyota* sp. are now present. *X. muta* sponge is still present and healthy. Bleaching *M. alcicornis* colony has recovered. Left *O. faveolata* has tissue loss in patches from disease.
EFGB 211	Station dominated by large *P. strigosa* colony and various *O. franksi* colonies. CCA, turf algae, and *Dictyota* sp. present.	Bottom left *O. faveolata* colony has tissue loss on colony margin from disease with fine algae overgrowth. No other distinct changes.
EFGB 212	Station dominated by large *O. franksi* colonies and large *P. strigosa* colonies. CCA, turf algae, and *Dictyota* sp. present. *P. strigosa* colony has bleaching in certain valleys. Left *O. franksi* colony shows signs of damselfish gardening.	*Dictyota* sp. cover increased. *P. strigosa* colony still shows signs of bleaching in certain valleys. Left *O. franksi* colony still shows signs of damselfish gardening.
EFGB 301	Station dominated by large *O. franksi* colonies and *P. strigosa* colonies. CCA and turf present.	*P. strigosa* colony has a large band of concentrated fish biting. Central *C. natans* has patches of paling and mortality from disease. Many other *C. natans* colonies show tissue loss with fine algae overgrowth from disease. *O. faveolata* has formed old mortality in patches. Small patch of *L. variegata* has grown.
EFGB 302	Station dominated by *O. franksi* colonies. CCA and turf present. Tissue loss of fragmented *O. franksi* colonies, tissue loss of *P. astreoides* colonies.	Past areas of tissue loss on both colonies have recovered. Fragmented *O. franksi* is continuing to grow into one large colony. Many *P. astreoides* colonies have tissue loss on margins and in patches from disease. *X. muta* sponge has spots of paling tissue. Turf algae still present but has decreased in coverage near the fragmented *O. franksi*.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 303	Station dominated by *O. franksi* and *P. strigosa* colonies. CCA and turf algae present. Many *P. astreoides* have fish biting.	Left *O. franksi* has almost completely died with a small unhealthy patch at the bottom. The *P. astreoides* colonies have recovered from fish biting. *P. astreoides* colonies throughout the site have tissue loss on colony margins from disease with fine algae overgrowth. Turf algae cover decreased.
EFGB 304	Station dominated by *O. franksi* and *P. strigosa*. Patches of CCA.	Central *P. strigosa* has paling and mortality on colony margin from disease with fine algae. Many *Orbicella* species have patches of mortality with fine algae overgrowth. *Dictyota* sp. have increased in cover.
EFGB 306	Station dominated by large *P. strigosa* and *O. franksi* colonies. Right *P. strigosa* is paling. Turf and CCA present.	Multiple coral colonies have mortality on colony margins from disease, with fine algae overgrowth. The *P. strigosa* colony has recovered. *Dictyota* sp. and *L. variegata* have increased in cover.
EFGB 307	Station dominated by *M. cavernosa* and *O. franksi*. Central *A. clathrodes* and *A. crassa* sponges. Turf and CCA present. Bleaching *M. cavernosa* colonies.	Bleaching on *M. cavernosa* has recovered. *A. clathrodes* sponge is larger but has algae overgrowth.
EFGB 402	Station dominated by *P. strigosa* and *O. franksi. Dictyota* sp., turf, and CCA present. *A. clathrodes* sponges are present around the dominant *P. strigosa*. Right *M. alcicornis* colony is bleached.	*M. alcicornis* colony has recovered. Turf algae is less dominant. No other distinct changes.
EFGB 403	Station dominated by *O. franksi* colonies. *Dictyota* sp. patches, turf, and CCA present.	Cover of *Dictyota* sp. decreased slightly. Left *P. strigosa* colony has mortality on colony margin from disease and another colony, top left, has patches of paling.
EFGB 405	Station dominated by *P. strigosa* and *O. franksi. Dictyota* sp., turf, and CCA present. Algae overgrown mortality focused in the valleys of central *P. strigosa* and *C. natans*.	Mortality area has spread in both colonies and is heavily overgrown with algae. Similar mortality on *P. strigosa* colonies in the bottom left and on a central *P. astreoides* colony. Paling on a left *P. strigosa* colony.
EFGB 406	Large *C. natans* colony, *Dictyota* sp. patches, turf algae, *P. astreoides* colonies, and *M. cavernosa* colonies present. Concentrated fish biting and edge mortality on some *P. astreoides*.	Many *P. astreoides* colonies are still being targeted by fish biting. *P. astreoides* edge mortality on colonies has recovered. Top left *P. strigosa* colony has paling and patchy mortality from disease. Turf algae density has decreased.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
EFGB 407	Large *O. faveolata* colony, *A. clathrodes* sponges, *A. crassa* sponge, few *P. astreoides* colonies, and few *P. strigosa* colonies present. *Dictyota* sp. and turf present.	Top *O. faveolata* has lost a patch of tissue and is now old mortality. Same *O. faveolata* has small patches of tissue mortality. No other distinct changes.
EFGB 408	Station dominated by *O. franksi* and large *M. cavernosa* colony. Turf algae present. *M. cavernosa* colony has a patch tissue mortality with fine algae overgrowth.	*M. cavernosa* has reclaimed most of lost tissue. Bottom left *P. strigosa* colonies have tissue mortality concentrated in valleys with algae overgrowth.

Table 2.8. Qualitative comparison of WFGB 2021 to 2022 repetitive photostations taken with a Nikon® D7000® camera. Stations 703, 704, 706, 707, and 810 were not photographed in 2021.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
WFGB 501	Station dominated by *P. strigosa* and *O. franksi*. Large patches of turf algae. Small *P. astreoides* colony with mortality. *A. clathrodes* sponges present.	Small *P. astreoides* colony has recovered from mortality with some tissue loss. Top left large *P. astreoides* colony has lost cover in a large area and is now old mortality. *A. clathrodes* sponges are still present.
WFGB 502	Station dominated by *P. strigosa* and *O. franksi. P. astreoides* colonies and *A. clathrodes* sponge present. *P. strigosa* colony has edge mortality.	*A. clathrodes* sponges still present. *P. strigosa* colony has recovered from edge mortality and has reclaimed tissue.
WFGB 503	Station dominated by healthy *O. franksi* and *P. strigosa* colonies and one large *M. cavernosa* colony. One *A. clathrodes* sponge and turf algae.	Turf algae is denser. *A. clathrodes* sponge is still present. Bottom *O. franksi* colony has mortality on colony margin from disease with fine algae overgrowth.
WFGB 504	Station dominated by *O. franksi*, small *P. strigosa* colonies, and one large *O. faveolata* colony. Small patches of turf algae and CCA. Bleaching in one *M. cavernosa*.	*M. cavernosa* colony has recovered from bleaching. *O. faveolata* has three small patches near its margin of mortality.
WFGB 505	Large *P. strigosa* colony and *O. franksi* colonies. Two *A. clathrodes* sponges. Partial mortality (25%) of large *P. strigosa* colony. Mortality not recent and potentially from damselfish farming.	*A. clathrodes* sponges are still present. Large *P. strigosa* has begun to regrow into the old mortality area.
WFGB 506	Station dominated by *O. franksi* colonies and small *P. astreoides* and *M. cavernosa* colonies. Patches of turf algae and *A. clathrodes* sponges. Colony of *M. alcicornis* bleached and one *M. cavernosa* partially bleached.	*M. alcicornis* colony has completely recovered from bleaching. Bleached area on *M. cavernosa* has regained color but is still pale.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
WFGB 507	Station dominated by large *O. faveolata* colony with large bleached patch and patchy *M. cavernosa* colony with paling. *A. clathrodes* and *Xestospongia muta* sponges present. *M. alcicornis* colony bleached.	*O. faveolata* and *M. cavernosa* colonies have recovered from their respective bleaching. *M. alcicornis* colony has also recovered from bleaching. *A. clathrodes* and *X. muta* sponges are still present.
WFGB 508	Station dominated by a large *P. strigosa* colony and *O. faveolata* colony. Minor bleaching observed in large *P. strigosa* colony.	Bleaching on large *P. strigosa* has recovered with some tissue loss. The colony now has signs of damselfish gardening in areas adjacent to old bleaching areas. Turf cover appears less dense.
WFGB 509	Station dominated by *Orbicella* sp., *O. faveolata*, and *O. franksi* colonies. Turf algae present. Small sections of overgrown mortality on *Orbicella* sp.	Multiple *O. faveolata* colonies have patchy mortality concentrated on the lumps of the colony. Some patches have taken the majority of their colony and most are overgrown with fine algae. Two *P. astreoides* colonies have mortality on the colony's margin with fine algae overgrowth. All of the forementioned lesions are from disease.
WFGB 510	Station dominated by healthy large *O. franksi* colony and small colonies of *M. cavernosa* and *M. alcicornis*. CCA and turf algae present. *M. cavernosa* colonies paling and two *M. alcicornis* colonies bleached.	*M. cavernosa* colony has recovered from paling with no tissue loss. Two *M. alcicornis* colonies have recovered from bleaching with no tissue loss. Bottom left *P. astreoides* has mortality on colony margin from disease, with fine algae overgrowth.
WFGB 511	Small *P. strigosa*, *O. franksi*, and *P. astreoides* colonies present. Patches of CCA and *L. variegata*. *M. alcicornis* colonies bleached.	*M. alcicornis* colony has recovered from bleaching with no tissue loss. No other distinct changes.
WFGB 512	Station dominated by *O. faveolata*, and *O. franksi* colonies. Patches of transitional mortality on *O. faveolata* colony. Paling in small *O. franksi* colony. Rectangular debris object with attached line covered in CCA.	*O. faveolata* has begun to regrow onto old mortality sites. *O. franksi* has recovered from paling with no tissue loss. *O. faveolata* has patches of tissue mortality from disease, with fine algae overgrowth.
WFGB 513	Station dominated by *O. faveolata*, *O. franksi*, and *P. astreoides* colonies.	Site overall is healthy. Slight increase in *Dictyota* sp. cover. No other distinct changes.
WFGB 601	Station dominated by *O. franksi* and *C. natans* colonies. *C. natans* colony has recovering tissue likely from past damselfish gardening.	*O. franksi* and left large *C. natans* colonies are paling. *C. natans* paling is far more extreme and is close to bleaching in some areas. Right *C. natans* colony is healthy and has regrown recovering tissues. Increase in *Dictyota* sp. cover.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
WFGB 602	Station dominated by *O. franksi*, *O. faveolata*, *P. strigosa*, and *P. astreoides*. *O. faveolata* colony with and *P. strigosa* colony with old mortality covered with fine turf.	*P. strigosa* continues to grow into old mortality area. Top left *O. faveolata* has area of paling and mortality possibly from disease. Bottom *P. strigosa* colony has mortality from concentrated fish biting.
WFGB 603	Station dominated by *O. franksi*, *P. strigosa*, and *C. natans* colonies. All living coral tissue appears healthy.	Site appears to still be healthy. *Dictyota* sp. cover has greatly decreased and is only found in small patches. Site has small substrate exposure on right side of photostation.
WFGB 604	Station comprised of *O. franksi*, *P. strigosa*, *M. cavernosa*, and *P. astreoides* colonies. Two *O. franksi* colony paling and bleaching. Many *P. astreoides* colonies have mortality from fish biting. Patches of CCA, *Dictyota* sp., and turf algae.	Both *O. franksi* colonies have recovered from their ailments and did not lose tissue. *P. astreoides* colonies have recovered from fish biting and are regrowing or have regrown mortality areas. *Dictyota sp.* cover has increased. Turf algae appears slightly denser.
WFGB 605	Station dominated by large *O. franksi* and *M. cavernosa* colonies. Paling observed in two large *M. cavernosa* colony and bleaching in one *O. franksi* colony. Patches of CCA and *L. variegata*.	Paling *M. cavernosa* colonies have recovered with no tissue loss. Bleaching *O. franksi* has also recovered with no tissue loss. Bottom right *P. astreoides* colonies have mortality on colony margin from disease, with some fine algae overgrowth.
WFGB 606	Station dominated by *O. franksi* and *P. strigosa* colonies. Concentrated fish biting on small *O. annularis* colony. Patches of turf algae.	Small *O. annularis* colony has recovered from concentrated fish biting with tissue loss in patches. No other distinct changes.
WFGB 607	Station dominated by *O. franksi* with small *O. annularis* colony and *Stephanocoenia intersepta* colony. One colony of *Mussa angulosa* includes CCA patches. Bleaching on small portion of *O. annularis* colony. Central *P. astreoides* colonies show signs of damselfish gardening.	*O. annularis* colony is still bleaching in different regions. Old regions are now old mortality. Central *P. astreoides* colonies no longer show signs of damselfish gardening but are heavy with patchy mortality from disease. Bottom right *C. natans* is paling.
WFGB 608	Station dominated by large *P. strigosa* colony with large patch of mortality. *M. cavernosa* colony is paling. Large areas of substrate covered with CCA. One *A. clathrodes* sponge.	Large *P. strigosa* colony has continued to lose tissue with signs of damselfish gardening. *M. cavernosa* colony has recovered from paling with no tissue loss. *O. faveolata* colony has patches of tissue mortality from disease, with fine algae overgrowth.
WFGB 609	Station dominated by *O. franksi* and *M. cavernosa* colonies. Large *M. cavernosa* colony with bleached area and one smaller colony paling. Two *O. franksi* colonies paling. Turf algae covering mortality area on C*. natans* colony.	Both *M. cavernosa* colonies recovered from bleaching and paling with no tissue loss. The right *O. franksi* recovered from paling with no tissue loss while the left *O. franksi* lost much of the tissue that was paling. The *C. natans* mortality area increased slightly and now has turf algae coverage.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
WFGB 701	Station dominated by large *P. strigosa* colonies and small *P. astreoides* colonies. Three small *P. strigosa* colonies with small bleaching areas near margins and *M. alcicornis* colony bleached.	*P. strigosa* colonies and *M. alcicornis* colony recovered from bleaching with no tissue loss. Turf has slightly less cover and appears less dense.
WFGB 702	Healthy *P. strigosa* and *O. franksi* colonies near sand patch. Patches of CCA and one *A. clathrodes* sponge.	Algae now covers much of the sand patch. No other distinct changes.
WFGB 705	Station is dominated by *Siderastrea siderea* colonies with *P. strigosa, M. cavernosa,* and *P. astreoides* colonies. CCA and turf algae are present. *M. cavernosa* and large *P. strigosa* colonies are paling.	Both colonies recovered from paling with no tissue loss. No other distinct changes.
WFGB 708	Station dominated by large *O. franksi* and small *M. cavernosa* colonies. Three *M. cavernosa* colonies paling.	All *M. cavernosa* colonies recovered from paling with no tissue loss. No other distinct changes.
WFGB 709	Station comprised of small *P. astreoides* and *O. annularis* colonies with large patches of CCA and substrate covered with fine turf algae.	*M. decactis* colony has lost tissue and is now covered with CCA. No other distinct changes.
WFGB 801	Station comprised of *P. astreoides* and *M. cavernosa* colonies and one large *S. siderea* colony. *M. cavernosa* colonies paling and bleaching and *S. siderea* colony with mortality and bleaching.	Both *M. cavernosa* colonies recovered with no tissue loss. *S. siderea* colony has begun to grow onto old mortality but has new bleaching areas.
WFGB 802	Station dominated by *O. franksi* colonies surrounded by *O. faveolata*, *P. strigosa*, *C. natans*, and *P. astreoides* colonies. *M. alcicornis* colony bleached in middle of station with patches of CCA. One *P. strigosa* colony with mortality.	*M. alcicornis* colony recovered from bleaching with no tissue loss. *P. strigosa* no longer has mortality but did not recover in the mortality area.
WFGB 803	Station comprised of large *O. franksi* and *O. faveolata* colonies surrounded by *M. cavernosa* and *P. astreoides* colonies. All *M. cavernosa* colonies paling and one with large bleached patch. One *O. franksi* colony paling.	*M. cavernosa* colonies are no longer paling or bleaching with no loss in tissue. Paling *O. franksi* recovered with no tissue loss.
WFGB 804	Station dominated by *O. franksi* colonies surrounded by *O. annularis* colonies. One small *M. cavernosa* colony is paling.	*M. cavernosa* colony is no longer paling with no tissue loss. No other distinct changes.

Photostation	Site Description in 2021	Comparison from 2021 to 2022
WFGB 805	Station dominated by *O. faveolata* colony surrounded by *O. annularis* colonies. Two small *M. cavernosa* colonies are bleached. Left *O. annularis* shows signs of damselfish gardening.	*M. cavernosa* colonies have recovered from bleaching with no tissue loss. Left *O. annularis* still shows signs of damselfish gardening.
WFGB 806	Station comprised of large *O. franksi* colonies surrounded by *M. cavernosa* and *P. strigosa* colonies. Three small *M. cavernosa* colonies are bleached.	*M. cavernosa* colonies are no longer bleaching but have some tissue loss. No other distinct changes.
WFGB 807	Station dominated by large *O. franksi* colony. All living coral tissue appears healthy.	Top left *P. astreoides* colony with mortality on colony margin from disease. *O. faveolata* has patch of mortality from disease, with fine algae overgrowth.
WFGB 808	Station comprised of small *O. franksi*, *O. annularis*, and *P. astreoides* colonies. Two *A. clathrodes* sponges. Transitional mortality on two small *P. astreoides* colonies and one *M. cavernosa* colony is bleached.	*P. astreoides* colonies with transitional mortality are now areas of old mortality. *M. cavernosa* colony is no longer bleaching, with no tissue loss. Both sponges are still present.
WFGB 809	Two *P. strigosa* colonies and one large *O. franksi* colony surrounded by sand patch. Full mortality on two *P. astreoides* colonies and three small *P. astreoides* colonies growing on colonizable substrate. One small *M. cavernosa* colony is paling.	*P. astreoides* with full mortality are now old mortality areas while the three small colonies are completely removed. *M. cavernosa* colony is no longer bleaching with no tissue loss. Sand patch has an increased algae cover.

Figure 2.10. Examples of active disease lesions on the margins of *P. strigosa* colonies. Photo: Michelle Johnston/NOAA

Repetitive Photostation Long-Term Trends

Twenty-four EFGB photostations and 27 WFGB photostations (ranging in depth from 20–24 m) have been in place since the beginning of the monitoring program, spanning 1989 to 2022. Mean percent coral cover increased from 58.72 ± 3.80% in 1989 to 66.59 ± 3.22% in 2022 among the 24 EFGB photostations and 50.30 ± 3.06% in 1989 to 72.71 ± 2.66% in 2022 among the 27 WFGB photostations (Figure 2.11). Coral cover significantly increased from 1989 to 2019 in EFGB photostations (t-test, df = 45, t = 2.01, p = 0.04) and WFGB photostations (t-test, df = 51, t = 2.01, p <0.001).

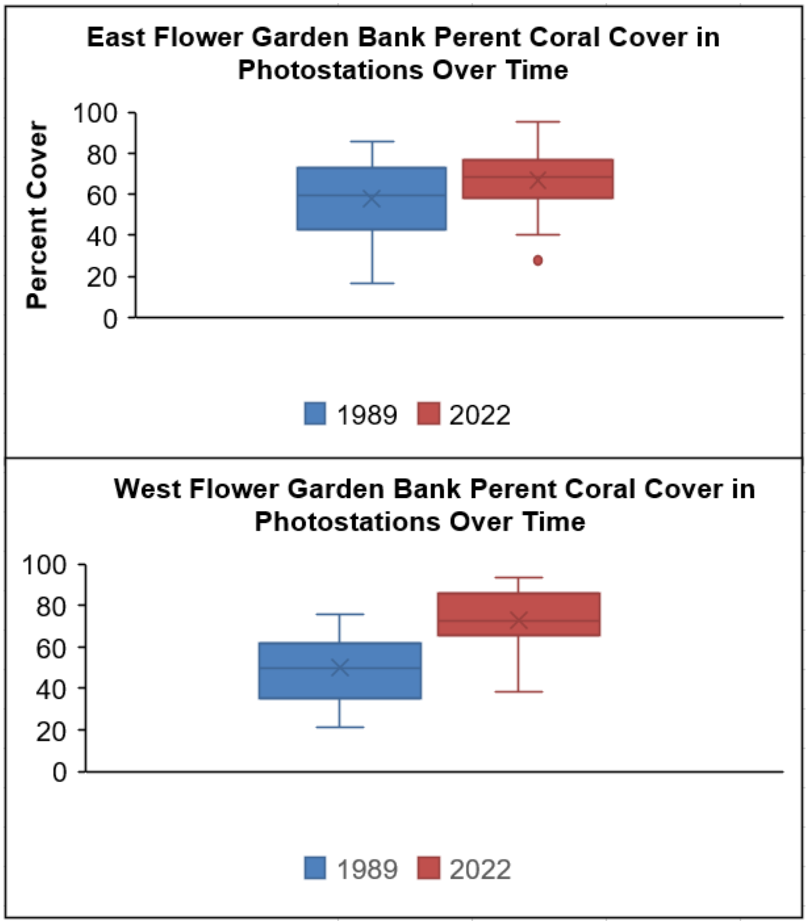


Figure 2.11. Box plot depicting percent coral cover in (top) EFGB (n = 24) and (bottom) WFGB (n = 27) repetitive photostations in 1989 and 2022.

As an example of the value of long-term repetitive photographs, Figure 2.12 documents changes in two photostations over time. It should be noted that some colonies appeared paler in certain years due to variations in photographic equipment (e.g., 35 mm slides, 35 mm film, and digital images), ambient conditions, and as colony health or condition changed. Furthermore, photo quality is affected by time of day, camera settings, and lighting. In EFGB photostation #102, changes from 1989 to 2022 include recruitment and growth of *P. strigosa* and *P. astreoides* on bare substrate in the center of the station and algal colonization on a *P. strigosa* colony in the lower left corner that affected approximately 30% of the colony in 2022 (Figure 2.12a; Figure 2.12b). This photostation represents an extreme example of increased coral cover, but shows how processes like recruitment and growth can be captured in long-term records when they may be difficult to track in the short term. In WFGB photostation #501, *O. franksi* cover increased from 1989 to 2019 and a black *Ircinia strobilina* sponge that was present in 1989 was absent in 2022 (Figure 2.12c; Figure 2.12d).

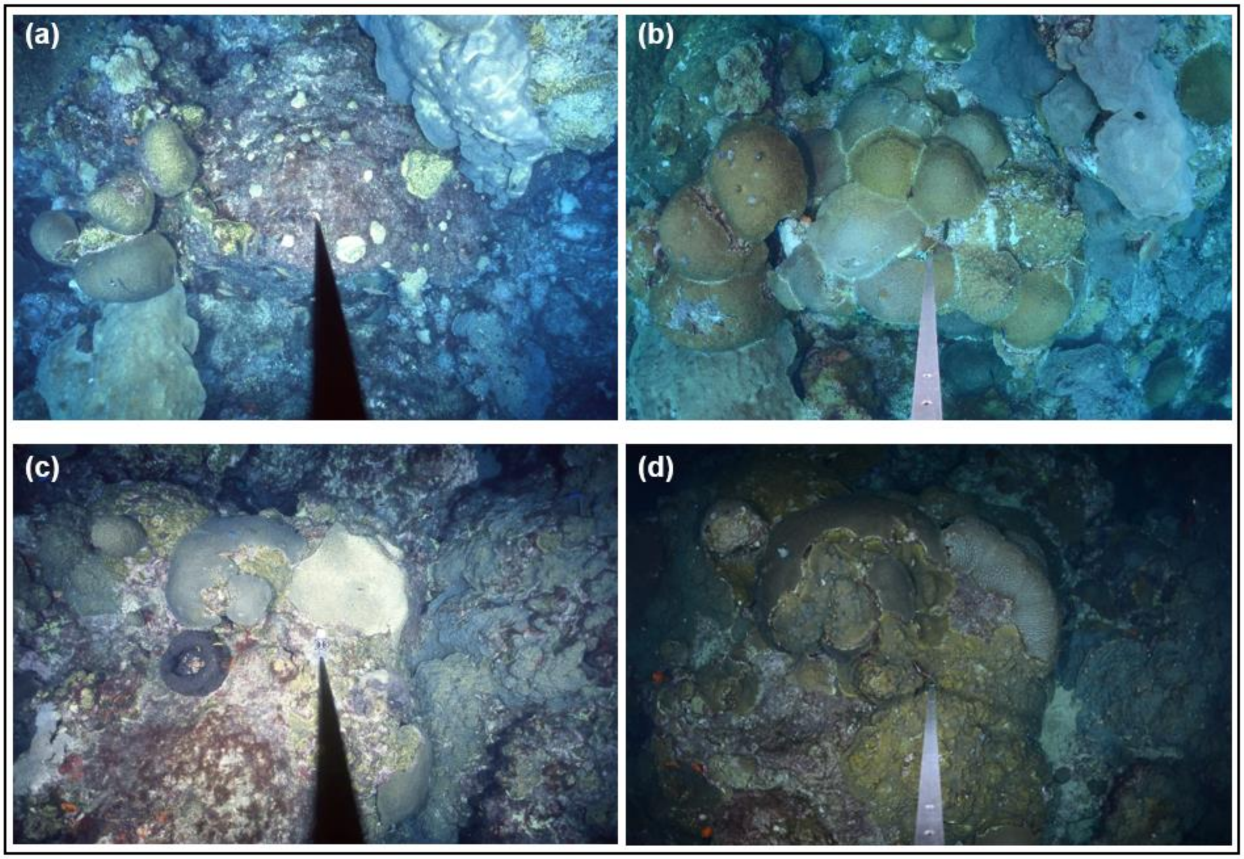


Figure 2.12. Time series of two repetitive photostations: EFGB photostation #102 (20 m) from (a) 1989 to (b) 2022 and WFGB photostation #501 (20 m) from (c) 1989 to (d) 2022. Photos: NOAA

Benthic Community Discussion

Despite global coral reef declines in recent decades, coral cover within EFGB and WFGB study sites has remained near or above 50% for the combined 33 years of monitoring. While macroalgae cover increased to approximately 30% over the past 10 years, random transect data suggest that, while macroalgae has grown over exposed hard bottom, it may not have substantially impeded coral or sponge growth.

Reef-wide transect surveys were conducted in 2022 in partnership with NCRMP. Conducting these surveys had been planned for over six years, but hurricanes, boat malfunctions, and COVID-19 restrictions prevented the surveys until this year. Reef-wide surveys will be a part of the long-term monitoring project from this point forward so that benthic cover is calculated using a random stratified design across the reef caps, not just within the study sites.

Beginning on August 30, 2022, disease lesions were observed on colonies of seven coral species. Lesions generally consisted of a stark boundary dividing healthy tissue from white, denuded coral skeleton, usually along coral colony margins. As a result of these observations, rapid response cruises were conducted in September and October 2022 according to action items in the *Strategy for Stony Coral Tissue Loss Disease Prevention and Response at FGBNMS* (Johnston, 2021). They focused on 1) characterizing signs and epizootiological aspects of the disease across EFGB and WFGB and within long-term monitoring sites, 2) treating affected coral colonies with Base 2B plus amoxicillin, and 3) collecting baseline images through photostations and photomosaics. The repetitive photostations proved to be invaluable for calculating disease prevalence and revisiting infected colonies to track lesion progression. Characterizing this disease event during its early epizootic phase allowed for researchers to observe how coral disease functions in a healthy coral ecosystem versus on reefs chronically affected by various stressors (e.g., Caribbean reefs adjacent to urban centers; Papke et al., 2024). Regardless of the etiology of the disease event (stony coral tissue loss disease, a type of white plague, or another disease), the response framework outlined in the *Strategy for Stony Coral Tissue Loss Disease Prevention and Response at FGBNMS* completed the year prior (Johnston, 2021) allowed resource managers and research partners to respond efficiently, conduct monitoring to document the event, and collect samples for diagnostic analyses (Johnston et al., 2023).

Despite bleaching events, hurricanes, and disease outbreaks, the EFGB and WFGB study sites have not shown any overall decline in coral cover since 1989. In fact, the opposite has been documented, with gradually increasing cover in the study sites. Furthermore, the FGBNMS reefs have six to 11 times higher coral cover values than selected other locations in the Caribbean region (Caldow et al., 2009; Clark et al., 2014; Jackson et al., 2014; Johnston et al., 2017a, 2017b). This may be due to a combination of remoteness, the banks' offshore locations, and deep water surrounding the banks, all of which provide a cleaner, more stable environment than typically experienced by shallower, coastal reefs (Aronson et al., 2005; Johnston et al., 2015). Long-term protection from potential human stressors, which include oil and gas development activities, vessel discharges, and anchoring, has also contributed to the favorable environmental quality of the banks.

Despite their remote location and deeper depth compared to other Caribbean reefs, EFGB and WFGB are not impervious to impacts typically associated with human activity. Localized mortality in 2016, the apparent increasing frequency of bleaching events, and the recent disease outbreak could reflect reductions in resistance, impacts directly caused by climate change, or both (Johnston et al., 2018b, 2019; Johnston et al., 2023). Climate change, invasive species, and water quality degradation are continued threats to the resources of the FGBNMS (Office of National Marine Sanctuaries, 2008; Nuttall et al., 2014; Johnston et al., 2016b). As the environment in the Gulf of Mexico changes over time (Karnauskas et al., 2015), continued monitoring will be important to document ecosystem variation.

Chapter 3:
Coral Demographics

A scuba diver conducts a coral demographic survey at WFGB in 2022. Photo: Kelly O’Connell/CPC

Coral Demographic Introduction

Coral demographic surveys were carried out in collaboration with NCRMP to record data on coral density, relative size composition for individual species, and condition. These surveys offer valuable species-specific information beyond simply measuring percent cover, with metrics like coral size and abundance helping to describe trends in coral reef population dynamics.

Coral Demographic Methods

Coral Demographic Field Methods

The surveys took place during two cruises aboard the R/V *Manta* from August 25th to 27th, 2022 and August 30th to September 2nd, 2022. The locations selected for surveys were stratified random sites on the EFGB and WFGB coral caps. The survey design ensures proportional allocation of survey sites based on hard-bottom habitat types (low relief and high relief) and geography (EFGB and WFGB) up to a maximum depth of 30 m. A total of 29 surveys were completed at EFGB and 20 were completed at WFGB (Figure 3.1).

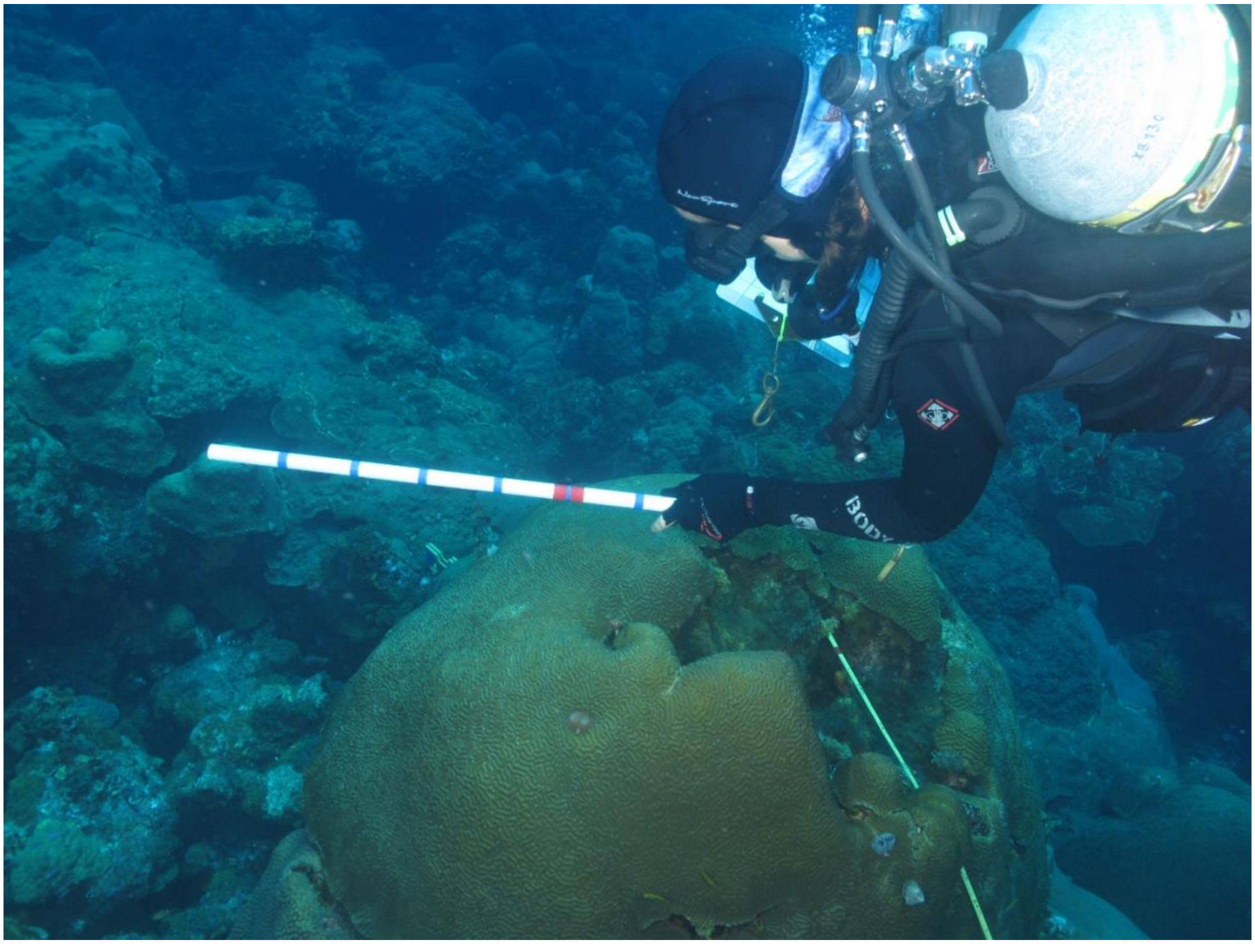


Figure 3.1. A scuba diver holds a PVC measuring pole to measure length, width, and height of a brain coral colony at EFGB. Photo: G.P. Schmahl/NOAA

Surveys were conducted within a 10 m x 1 m belt-transect area (Viehman et al., 2023). Each coral colony (diameter > 4 cm) was identified and measured (length x width x height (cm); Figure 3.1). The entire coral colony (skeleton and live tissue) was measured on a planar dimension, where length was the maximum diameter, width was the perpendicular diameter, and height was measured from the base of the skeletal unit to the top of the colony (Lang et al., 2012; Roberson et al., 2014). Partial mortality was assessed as the percentage of the colony's surface area exhibiting old, recent, or both types of mortality. Additionally, relative condition factors like disease (categorized as present, slow, or fast) and bleaching (classified as total, partial, or paling) were documented for each colony when observed (Viehman et al., 2023). Datasheets included additional information to be collected by surveyors, such as survey depth and seawater temperature. After the data passed quality checks, they were archived at NOAA's National Centers for Environmental Information and released publicly.

Coral Demographic Data Analysis

Length frequency distributions were generated from total colony size (maximum diameter) of colonies ≥4 cm, which included areas of partial mortality (Bak & Meesters, 1999, Meesters et al., 2001; Viehman et al., 2023). For temporal comparisons, a pairwise two-tailed t-test was performed to evaluate differences between years. Site-level coral bleaching and disease prevalence were calculated as the percentage of colonies with any bleaching or disease divided by the total number of corals by species at each site. Results are presented as mean ± SE.

Coral Demographic Results

In 2022, NCRMP surveyed 53 sites at EFGB and WFGB, with an average survey depth of 24 m. Species richness included 19 coral species across both banks. Coral species listed as threatened under the U.S. Endangered Species Act (79 Fed. Reg, 53852 [Setpember 10, 2014]) were highly prevalent at EFGB and WFGB, found at 96% of the benthic survey sites (Viehman et al., 2023). The dominant coral species contributing to overall density were *Porites astreoides*, *Madracis auretenra*, *Orbicella franksi*, *Agaricia agaricites*, and *Pseudodiploria strigosa*. Although *P. astreoides* was the most abundant, these smaller corals covered less area compared to larger species. Coral density depends on species composition, size distribution, and colony mortality; thus, high density does not necessarily indicate large, healthy, reef-building corals (Viehman et al., 2023).

NCRMP surveys showed a decline in overall coral density over time, with a statistically significant change observed between 2015 (5.7 ± 0.33 corals per m^2) and 2022 (4.9 ± 0.36 corals per m^2; Viehman et al., 2023). Relative length frequencies (using maximum diameter) for select coral species at EFGB and WFGB indicated stable size distributions of *Colpophyllia natans*, *Orbicella faveolata*, *O. franksi*, and *P. strigosa* from 2013 to 2022. These species were chosen based on metrics to measure reef building capability such as Endangered Species Act status, disease susceptibility, and ecological importance (Viehman et al., 2023).

Coral disease was documented on *O. franksi* and *P. astreoides* at EFGB and on *C. natans*, *O. faveolata*, *O. franksi*, and *P. strigosa* at WFGB, although the percentage of recent mortality on colonies was low (Viehman et al., 2023). Detailed demographic results are available in Viehman et al. (2023).

Coral Demographic Discussion

Relative size and abundance are important metrics for describing trends in coral reef population dynamics. Although the corals of the *Orbiella* species complex are the dominant reef building corals at EFGB and WFGB in terms of percent cover, *P. astreoides* was the most abundant species, despite the smaller area covered by these colonies.

Though the coral community in the study sites has remained relatively stable throughout the monitoring program from 1989 to 2022, coral communities are rapidly changing worldwide (Jackson et al., 2014; Johnston et al., 2016a, 2020, 2021). Over the past few decades, both natural and human-induced factors, including hurricane damage, pollution, overfishing, disease, and the warming of the ocean, have led to the deterioration of coral reefs in the Tropical Western Atlantic (Eakin et al., 2010; Jackson et al., 2014; Gil-Agudelo et al., 2020; Cróquer et al., 2021; Johnston et al., 2023). In the Caribbean region, numerous reefs have experienced a decline in dominant reef-building corals, many of which include those found at EFGB and WFGB. This decline has allowed opportunistic and "weedy" coral species to proliferate (Alvarez-Filip et al., 2013), though in most places, even those have declined significantly. Declines and shifts in coral composition have led to reduced reef function and complexity, posing a threat to the overall stability and biodiversity of coral ecosystems (Alvarez-Filip et al., 2013; Graham & Nash, 2013). Although FGBNMS historically has exhibited low incidence of coral disease and bleaching, disease-like lesions on seven coral species were reported during routine monitoring surveys on EFGB and WFGB (Johnston et al., 2023).

To better understand these changes, continuous monitoring of the coral community in long-term monitoring study sites is essential, particularly given the availability of robust historical baselines. NCRMP demographic data, in addition to data collected annually by the FGBNMS long-term monitoring program, enables resource managers to make informed decisions and detect problems in their early stages, and focus not only on maintaining high coral cover, but also on ensuring the survival of critical reef-building species, thus promoting the long-term health of the ecosystem.

Chapter 4: Fish Surveys

A Spanish hogfish (*Bodianus rufus*) swims over the reef at FGBNMS. Photo: G.P. Schmahl/NOAA

Fish Surveys Introduction

Divers conducted stationary reef fish visual census surveys in EFGB and WFGB study sites to examine and compare fish community composition and changes over time.

Fish Surveys Methods

Field Methods

Fishes were assessed by divers using modified stationary reef fish visual census surveys as originally described by Bohnsack and Bannerot (1986). Ten randomly located surveys were conducted within the study site at EFGB and nine were conducted within the study site at WFGB. The number of fish surveys at each bank in 2022 was reduced by approximately half due to time needed for the coral disease response. Each survey represented one sample. Observations of fishes were restricted to an imaginary cylinder with a 7.5-m radius, extending from the substrate to the surface (for more detailed methods, refer to Johnston et al. [2017a]; Figure 4.1).

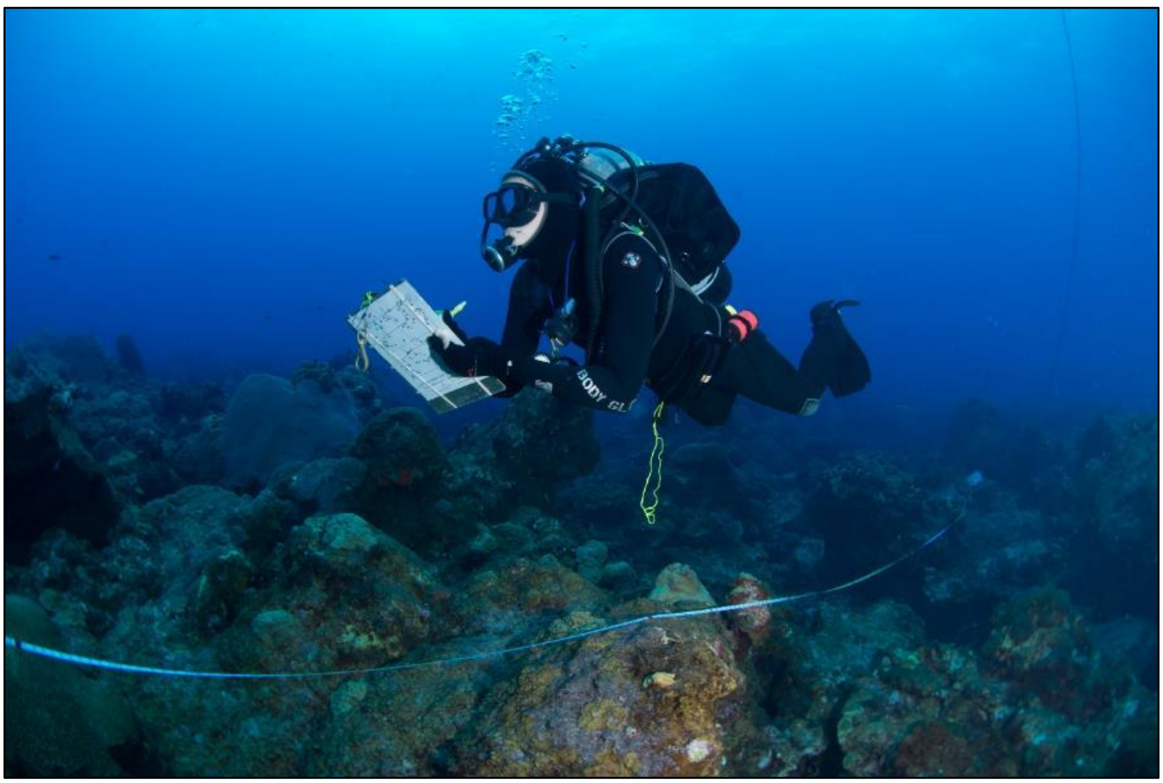


Figure 4.1. NOAA diver conducting a fish survey at EFGB. Photo: G.P. Schmahl/NOAA

All fish species observed within the first five minutes of the survey were recorded while the diver slowly rotated in place in the imaginary cylinder. Immediately following this period, one rotation was conducted for each species noted in the original five-minute period to record abundance (number of individuals per species) and fork length. Size for each individual was estimated and binned into one of eight groups: <5 cm, ≥5 to <10 cm, ≥10 to <15 cm, ≥15 to <20 cm, ≥20 to <25 cm, ≥25 to <30 cm, ≥30 to <35 cm, and ≥35 cm. If fishes were greater than 35 cm in length, divers estimated the size to the nearest cm. Each survey required approximately 15 to 20 minutes to complete. Transitory or schooling species were counted and measured at the time the individuals moved through the cylinder during the initial five-minute period. After the initial five-minute period, additional species were recorded but marked as observed after the official survey period. These observations were excluded from the analysis, unless otherwise stated, except for reporting the total number of species observed in all 2022 surveys. Fish surveys began in the early morning (after 0700 CDT), and were conducted throughout the day until dusk (1900 CDT).

Consistency in the survey method was ensured by using scientific divers trained to identify FGBNMS fish species and experienced in the survey technique used. Equipment checklists were used to ensure divers had equipment for assigned tasks, which included a pre-marked PVC measuring stick for size reference.

Data Processing

Surveyors reviewed and entered data in a Microsoft® Excel® database the day the survey took place. Datasheets were retained, reviewed, and compared to data entered in the database to check for entry errors, and any mistakes were corrected prior to data processing. For each entry, fish family, trophic guild, and biomass were automatically recorded in the database (Bohnsack & Harper 1988; Froese & Pauly 2019). Species were classified into four major categories: herbivores (H), piscivores (P), invertivores (I), and planktivores (PL) as defined by NOAA's Center for Coastal Monitoring and Assessment BioGeography Branch fish-trophic level database (Caldow et al., 2009).

Statistical Analysis

Summary statistics of fish census data included abundance, density, sighting frequency, species richness, and biomass. Total abundance was calculated as the number of individuals per sample, and percent relative abundance was the total number of individuals of a given species divided by the total of all species, multiplied by 100. Density was expressed as the number of individual fish per 100 m^2 ± SE, and calculated as the total number of individuals per sample divided by the area of the survey cylinder (176.7 m^2) and multiplied by 100. Sighting frequency for each species was the percentage of samples in which the species was recorded. Mean species richness was the average number of species represented per sample ± SE. Fish biomass was expressed as kilograms per 100 m^2 ± SE and computed by converting length data to weight using the allometric length-weight conversion formula (Bohnsack & Harper, 1988) based on information provided by FishBase (Froese & Pauly, 2019). Previous long-term monitoring reports expressed biomass as grams per 100 m^2, however, moving forward, biomass estimates will be reported in kilograms. As sizes less than 35 cm were binned, the median size in each size bin was used to calculate biomass (for example, fish in the ≥5 to <10 cm size bin were assigned the total length of 7.5 cm). Observations of manta rays and stingrays were removed from biomass analyses only, due to their rare nature and large size.

For family analysis, percent coefficient of variation was calculated to determine the power of the analyses. Percent coefficient of variation was calculated using the following formula:

$$CV\% = SE/\bar{X}$$

where $\bar{X}$ = population mean. A percent coefficient of variation of 20% or lower is optimal, as it would be able to statistically detect a minimum change of 40% in the population within the survey period (Roberson et al., 2014).

Statistical analyses were conducted on dispersion-weighted transformed density and biomass data (reducing the influence of large schooling species on analyses) using distance-based Bray-Curtis similarity matrices with Primer® version 7.0 (Anderson et al., 2008; Clarke et al., 2014). Differences in the fish community based on species-level resemblance matrices were investigated using PERMANOVA (Anderson et al., 2008). If significant differences were found, species contributing to observed differences were examined using SIMPER to assess the percent contribution of species to dissimilarity between study sites (Clarke et al., 2014). No analysis was done at the family level for key species due to limited data and poor statistical power. For long-term density and biomass trends for which data were available (2011 to 2019 and 2022), the distance between centroids was calculated from Bray-Curtis similarity matrices and visualized using metric multi-dimensional scaling plots with a time series trajectory overlay split between locations (Anderson et al., 2008).

Dominance plots were generated based on species abundance and biomass with Primer® version 7.0 (Anderson et al., 2008; Clarke et al., 2014). W-values (difference between the biomass and abundance curves) were calculated for each survey (Clarke, 1990). W-values range between $-1 < w > 1$, where $w = 1$ indicates that the population is dominated by a few large species, $w = -1$ indicates that the population is dominated by numerous small species, and $w = 0$ indicates that accumulated biomass is evenly distributed between large and small species. Dissimilarities in w-values between study sites were assessed using ANOSIM on untransformed data with Euclidean distance similarity matrices (Clarke et al., 2014).

Fish Surveys Results

A combined total of 18 families and 47 species (40 at EFGB and 34 at WFGB, respectively) were observed in 2022 at EFGB and WFGB study sites. Mean species richness was 15.10 ± 1.42 per survey at EFGB, 11.11 ± 0.81 per survey at WFGB, and 13.21 ± 0.94 per survey for both study sites combined. Brown chromis (*Azurina multilineata*) had the highest relative abundance of all species in EFGB surveys (29.97%), followed by bluehead (*Thalassoma bifasciatum*; 24.34%), creole wrasse (*Clepticus parrae*; 5.80%), and bicolor damselfish (*Stegastes partitus*; 5.12%). In WFGB surveys, brown chromis had the highest relative abundance (17.73%), followed by blue chromis (*Azurina cyanea*; 17.60%), bluehead (13.48%), Atlantic creolefish (*Paranthias furcifer*; 10.99%), and bicolor damselfish (6.62%).

Sighting Frequency

The most frequently sighted species was brown chromis, observed in 100% of surveys at EFGB and WFGB. Other frequently sighted species included blue chromis, bluehead, and bicolor damselfish (Table 4.1). No manta or devil rays (*Mobula* spp.) or sharks were observed in 2022 surveys and are considered “rare,” typically occurring in <20% of all surveys (Reef Environmental Education Foundation, 2014).

Table 4.1. Sighting frequencies for the 10 most frequently sighted species at EFGB and WFGB study sites in 2022.

Fish Species	EFGB	WFGB	Combined
Brown chromis (*Azurina multilineata*)	100.0%	100.0%	100.0%
Blue chromis (*Azurina cyanea*)	90.0%	100.0%	94.7%
Bluehead (*Thalassoma bifasciatum*)	100.0%	77.8%	89.5%
Bicolor damselfish (*Stegastes partitus*)	80.0%	88.9%	84.2%
Black durgon (*Melichthys niger*)	80.0%	66.7%	73.7%
Great barracuda (*Sphyraena barracuda*)	50.0%	77.8%	63.2%
Queen parrotfish (*Scarus vetula*)	80.0%	33.3%	57.9%
Threespot damselfish (*Stegastes planifrons*)	70.0%	33.3%	52.6%
Blue tang (*Acanthurus coeruleus*)	40.0%	66.7%	52.6%
Sharpnose puffer (*Canthigaster rostrata*)	60.0%	44.4%	52.6%

Density

Mean fish density (individuals/100 m^2) was 66.27 ± 9.20 in EFGB surveys, 50.37 ± 5.67 in WFGB surveys, and 58.74 ± 5.71 for all surveys combined. Density was significantly greater in EFGB surveys (Table 4.2). SIMPER analysis identified greater abundance of brown chromis (10.36%) and bluehead (*Thalassoma bifasciatum*; 6.72%) at EFGB and greater abundance of black durgon (*Melichthys niger*; 6.16%) and blue chromis (5.83%) at WFGB as the main contributors to the differences (Table 4.3).

Table 4.2. PERMANOVA results comparing mean fish density between EFGB and WFGB study sites from 2022. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	3776	1	1.71	**0.0349**
Res	37612	17		
Total	41388	18		

Table 4.3. Mean density (individuals/100 m^2) ± SE of the 10 most abundant species from EFGB and WFGB study site surveys, and all surveys combined, in 2022. Densities in **bold** indicate statistically significant differences.

Fish Species	EFGB	WFGB	Combined
Brown chromis (*Azurina multilineata*)	**19.9 ± 3.7**	8.9 ± 1.8	14.7 ± 2.4
Bluehead (*Thalassoma bifasciatum*)	**16.1 ± 3.7**	6.8 ± 2.2	11.7 ± 2.4
Blue chromis (*Azurina cyanea*)	2.8 ± 0.6	**8.9 ± 3.3**	5.7 ± 1.7
Bicolor damselfish (*Stegastes partitus*)	3.4 ± 1.3	3.3 ± 0.9	3.4 ± 0.8
Atlantic creolefish (*Paranthias furcifer*)	1.0 ± 0.4	5.5 ± 2.9	3.1 ± 1.4
Creole wrasse (*Clepticus parrae*)	3.8 ± 2.8	2.2 ± 2.2	3.1 ± 1.8
Queen parrotfish (*Scarus vetula*)	1.8 ± 0.3	2.1 ± 1.5	1.9 ± 0.7
Great barracuda (*Sphyraena barracuda*)	1.9 ± 0.6	1.8 ± 1.0	1.8 ± 0.5
Bermuda/yellow chub (*Kyphosus*	0.7 ± 0.3	2.8 ± 1.4	1.7 ± 0.7

Fish Species	EFGB	WFGB	Combined
Horse-eye Jack (*Caranx latus*)	2.4 ± 1.6	0.1 ± 0.1	1.3 ± 0.9
Black durgon (*Melichthys niger*)	0.9 ± 0.2	**1.3 ± 0.6**	1.1 ± 0.3
Total density	66.27 ± 9.20	50.37 ± 5.67	58.74 ± 5.71

Trophic Guild Analysis

Size-frequency distributions using relative abundance were graphed for each of the four assigned trophic guilds (herbivores, piscivores, invertivores, and planktivores; Figure 4.2). Invertivores dominated the small size classes at both study sites. Planktivores and herbivores dominated the mid-range size classes. Piscivores dominated the largest size class. No fish sized ≥30 to <35 cm were sighted in WFGB surveys in 2022 (Figure 4.2).

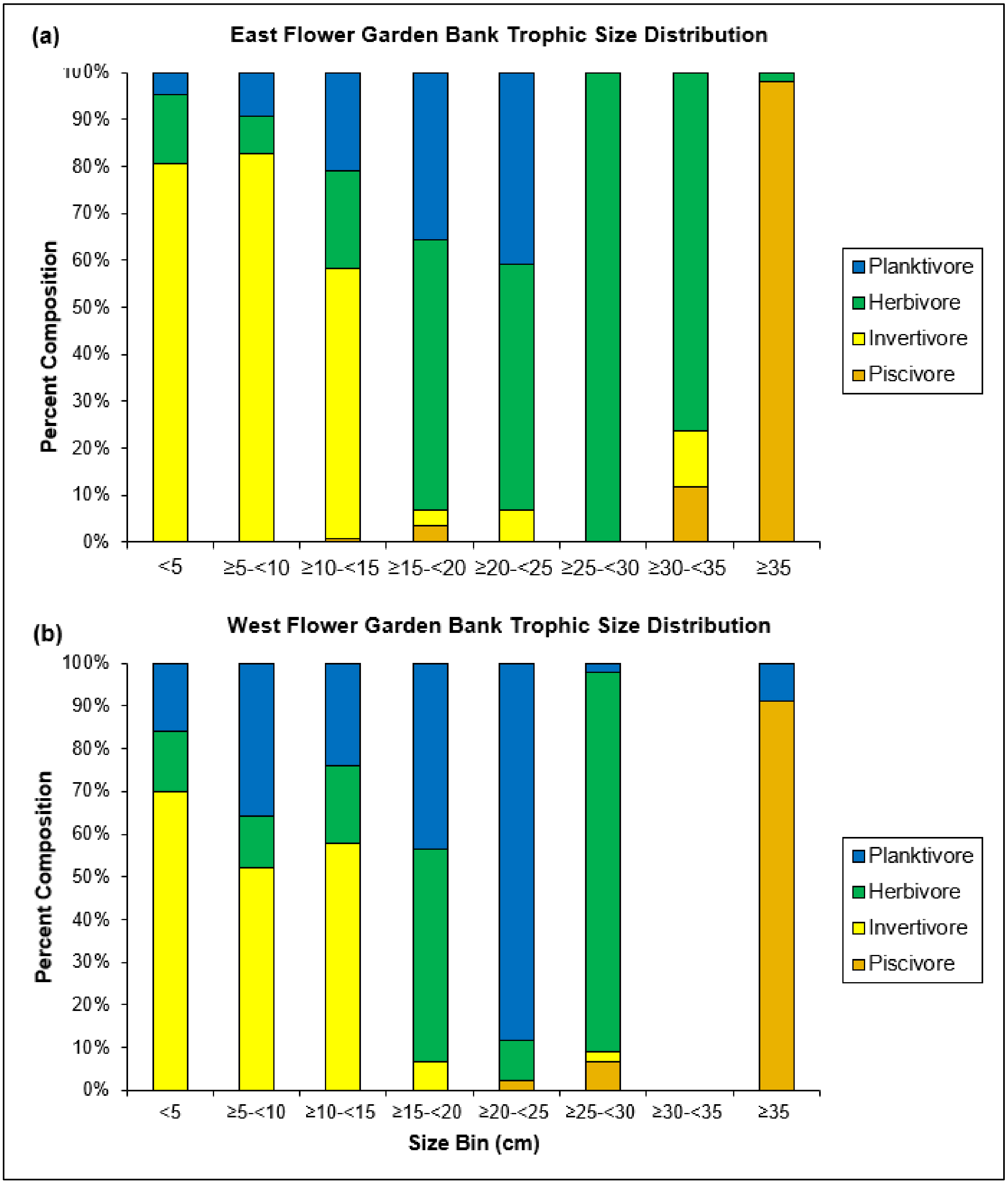


Figure 4.2. Fish size distribution by trophic guild at (a) EFGB and (b) WFGB study sites in 2022.

Biomass

Mean biomass (kg/100 m^2) ± SE was 9.06 ± 4.29 in EFGB surveys, 5.04 ± 1.88 in WFGB surveys, and 7.16 ± 2.41 for study site surveys combined in 2022. PERMANOVA analysis revealed that there was no significant difference between EFGB and WFGB surveys (Table 4.4). SIMPER analysis identified stoplight parrotfish (*Sparisoma viride*) as the main contributor to fish biomass at the EFGB study site (7.43%) and great barracuda (*Sphyraena barracuda*) as the main contributor to biomass at the WFGB study site (6.22%).

Table 4.4. PERMANOVA results comparing mean fish biomass between EFGB and WFGB study sites from 2022.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	4309	1	1.37	0.1157
Res	53350	17		
Total	57659	18		

When classified by trophic guild, piscivores possessed the highest mean biomass for all surveys and invertivores had the lowest mean biomass (Table 4.5). There were no significant differences among trophic guilds between study sites. Overall, piscivores represented approximately 60% of biomass, followed by herbivores (25%), planktivores (10%), and invertivores (5%) for study sites combined.

Table 4.5. Mean biomass (kg/100 m^2) ± SE for each trophic guild from EFGB and WFGB study site surveys, and surveys from both banks combined, in 2022.

Trophic Group	EFGB	WFGB	Combined
Herbivore	2.18 ± 0.69	1.39 ± 0.46	1.81 ± 0.32
Invertivore	0.49 ± 0.16	0.22 ± 0.07	0.36 ± 0.05
Planktivore	0.40 ± 0.13	1.03 ± 0.34	0.70 ± 0.24
Piscivore	5.99 ± 1.89	2.41 ± 0.80	4.30 ± 0.55

Mean biomass for each species, grouped by trophic guild, is presented in Table 4.6. At the EFGB study site, 37% of herbivore biomass was contributed by Bermuda/yellow chub (*Kyphosus sectatrix/incisor*). For invertivores, the greatest contribution was from brown chromis (27%). Horse-eye jack (*Caranx latus*) contributed the greatest biomass among piscivores (88%). The greatest contribution among planktivores was from creole wrasse (74%; Table 4.6).

At the WFGB study site, 45% of herbivore biomass was contributed by queen parrotfish (*Scarus vetula*). For invertivores, the greatest contribution was from brown chromis (25%). Great barracuda contributed the greatest biomass among piscivores (94%). The greatest contribution among planktivores was from Atlantic creolefish (69%; Table 4.6)

Table 4.6. Biomass (kg/100 m^2) ± SE of each species, grouped by trophic guild, from EFGB and WFGB study site surveys, and surveys from both banks combined, in 2022.

Trophic Guild	Fish Species	EFGB	WFGB	Combined
Herbivore	Bermuda/yellow chub (*Kyphosus saltatrix/incisor*)	0.81 ± 0.43	0.06 ± 0.0659.3	0.45 ± 0.24
Herbivore	Queen parrotfish (*Scarus vetula*)	0.288 ± 0.07	0.63 ± 0.55	0.44 ± 0.26
Herbivore	Black durgon (*Melichthys niger*)	0.51 ± 0.24	0.21 ± 0.09	0.36 ± 0.13
Herbivore	Stoplight parrotfish (*Sparisoma viride*)	0.39 ± 0.13	0.04± 0.03.1	0.23 ± 0.08
Herbivore	Princess parrotfish (*Scarus taeniopterus*)	0.01 ± 0.01	0.29 ± 0.27	0.14 ± 0.13
Herbivore	Blue tang (*Acanthurus coeruleus*)	0.08 ± 0.04	0.06 ± 0.03	0.07 ± 0.02
Herbivore	Bicolor damselfish (*Stegastes partitus*)	0.02 ± 0.01	0.07 ± 0.04	0.04 ± 0.02
Herbivore	Doctorfish (*Acanthurus chirurgus*)	0.02 ± 0.01	0.03 ± 0.02	0.03 ± 0.01
Herbivore	Redband parrotfish (*Sparisoma aurofrenatum*)	0.04 ± 0.03	0.0 ± 0.0	0.02 ± 0.02
Herbivore	Ocean surgeonfish (*Acanthurus tractus*)	0.008 ± 0.006	0.01 ± 0.009	0.01 ± 0.005
Herbivore	Yellowtail damselfish (*Microspathodon chrysurus*)	0.004 ± 0.002	0.0 ± 0.0	0.002 ± 0.001
Herbivore	Dusky damselfish (*Stegastes adustus*)	0.002 ± 0.001	0.0 ± 0.0	0.001 ± 0.0008
Herbivore	Cocoa damselfish (*Stegastes variabilis*)	0.002 ± 0.002	0.0002 ± 0.0002	0.001 ± 0.0009
Herbivore	Striped parrotfish (*Scarus iseri*)	0.0001 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Invertivore	Brown chromis (*Azurina multilineata*)	0.13 ± 0.04	0.06 ± 0.02	0.10 ± 0.03
Invertivore	Queen triggerfish (*Balistes vetula*)	0.09 ± 0.09	0.0 ± 0.0	0.04 ± 0.04
Invertivore	Porcupinefish (*Diodon hystrix*)	0.08 ± 0.08	0.0 ± 0.0	0.04 ± 0.04
Invertivore	Ocean triggerfish (*Canthidermis sufflamen*)	0.04 ± 0.04	0.03 ± 0.03	0.04 ± 0.03
Invertivore	Threespot damselfish (*Stegastes planifrons*)	0.02 ± 0.007	0.03 ± 0.02	0.03 ± 0.009
Invertivore	Rock beauty (*Holacanthus tricolor*)	0.03 ± 0.019	0.02 ± 0.01	0.02 ± 0.01
Invertivore	Bluehead	0.02 ± 0.005	0.02 ± 0.01	0.02 ± 0.005

Trophic Guild	Fish Species	EFGB	WFGB	Combined
	(*Thalassoma bifasciatum*)			
Invertivore	Reef butterflyfish (*Chaetodon sedentarius)*	0.02 ± 0.01	0.01 ± 0.008	0.02 ± 0.07
Invertivore	Queen angelfish (*Holacanthus ciliaris*)	0.0 ± 0.0	0.02 ± 0.02	0.01 ± 0.009
Invertivore	Yellowhead wrasse (*Halichoeres garnoti*)	0.007 ± 0.005	0.008 ± 0.006	0.007 ± 0.004
Invertivore	Spotfin butterflyfish (*Chaetodon ocellatus*)	0.01 ± 0.01	0.003 ± 0.003	0.006 ± 0.005
Invertivore	Sergeant major (*Abudefduf saxatilis*)	0.005 ± 0.003	0.006 ± 0.006	0.005 ± 0.003
Invertivore	Yellow goatfish (*Mulloidichthys martinicus*)	0005 ± 0.005	0.005 ± 0.003	0.005 ± 0.003
Invertivore	Spanish hogfish (*Bodianus rufus*)	0.006 ± 0.003	0.003 ± 0.002	0.005 ± 0.002
Invertivore	Smooth trunkfish (*Lactophrys triqueter*)	0.006 ± 0.004	0.004 ± 0.004	0.005 ± 0.003
Invertivore	Sharpnose puffer (*Canthigaster rostrata*)	0.005 ± 0.003	0.001 ± 0.001	0.004 ± 0.002
Invertivore	Gray snapper (*Lutjanus griseus*)	0.0 ± 0.0	0.004 ± 0.004	0.002 ± 0.002
Invertivore	Orangespotted filefish (*Cantherhines pullus*)	0.003 ± 0.003	0.0 ± 0.0	0.002 ± 0.001
Invertivore	Clown wrasse (*Halichoeres maculipinna*)	0.0003 ± 0.0003	0.002 ± 0.002	0.001 ± 0.0009
Invertivore	Longsnout butterflyfish (*Prognathodes aculeatus*)	0.002 ± 0.002	0.0 ± 0.0	0.0008 ± 0.0008
Invertivore	Puddingwife (*Halichoeres radiatus*)	0.0003 ± 0.0003	0.0 ± 0.0	0.0002 ± 0.0002
Piscivore	Horse-eye jack (*Caranx latus*)	5.26 ± 3.52	0.05 ± 0.05	2.79 ± 1.91
Piscivore	Great barracuda (*Sphyraena barracuda*)	0.66 ±0.24	2.17 ± 0.86	1.38 ± 0.45
Piscivore	Dog snapper (*Lutjanus jocu*)	0.0 ± 0.0	0.09 ± 0.07	0.04 ± 0.03
Piscivore	Graysby (*Cephalopholis cruentata*)	0.07 ± 0.06	0.0 ± 0.0	0.03 ± 0.03
Piscivore	Tiger grouper (*Mycteroperca tigris*)	0.004 ± 0.004	0.0 ± 0.0	0.002 ± 0.002
Planktivore	Atlantic creolefish (*Paranthias furcifer*)	0.09 ± 0.04	0.71 ± 0.43	0.38 ± 0.21

Trophic Guild	Fish Species	EFGB	WFGB	Combined
Planktivore	Creole wrasse (*Clepticus parrae*)	0.29 ± 0.28	0.28 ± 0.28	0.29 ± 0.19
Planktivore	Blue chromis (*Azurina cyanea*)	0.016 ± 0.005	0.03 ± 0.02	0.02 ± 0.008
Planktivore	Sunshinefish (*Chromis insolata*)	0.0007 ± 0.0007	0.0004 ± 0.0004	0.0005 ± 0.0004

Abundance-Biomass Curves

Mean w-values for both the EFGB and WFGB study sites were 0.09 ± 0.02. For all samples at each study site, mean w-values remained close to 0, indicating a balanced community where biomass was spread uniformly between large and small individuals (Figure 4.3). ANOSIM comparisons of w-values between study sites revealed no significant dissimilarities between the dominance plot w-values.

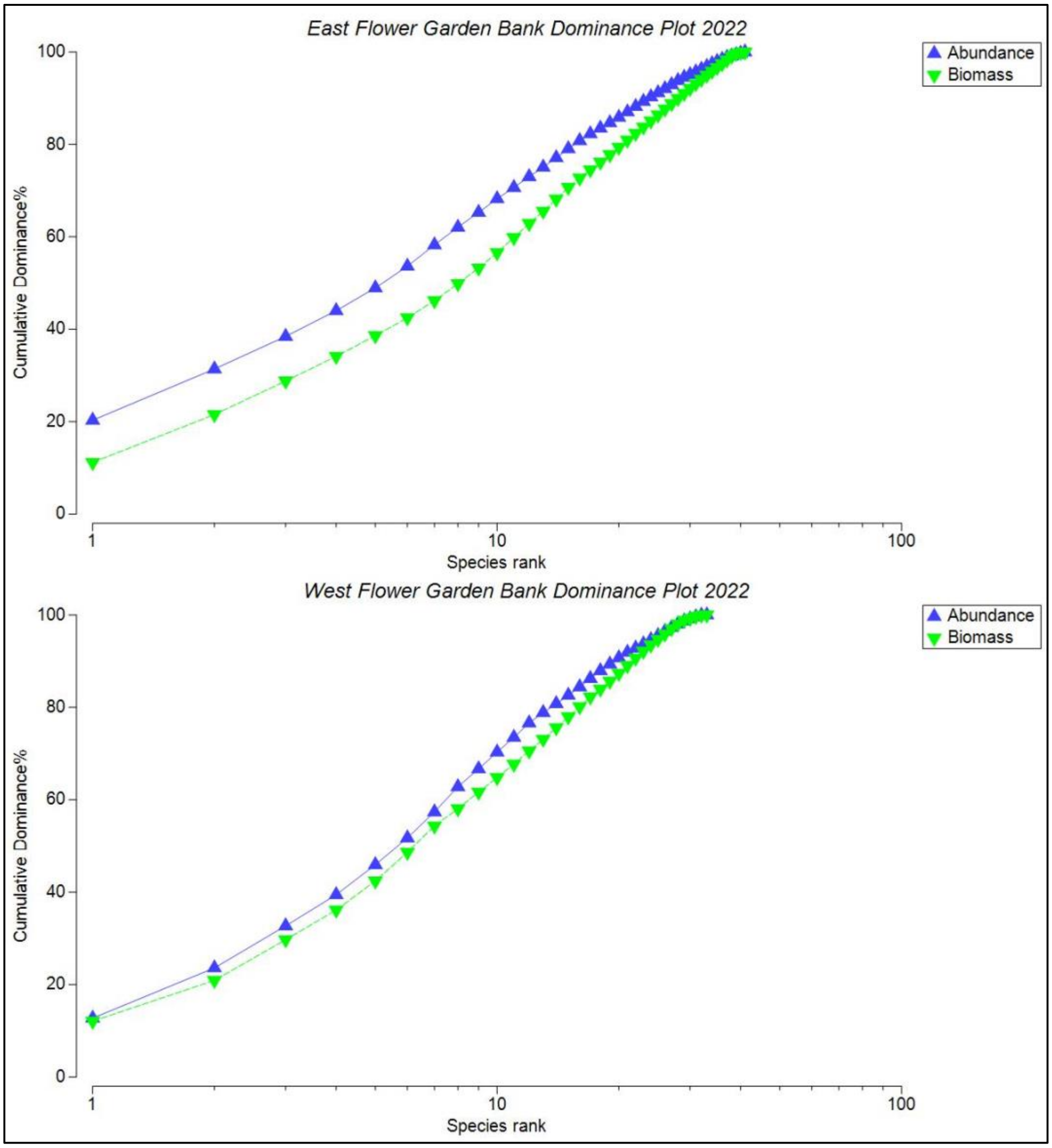


Figure 4.3. Abundance-biomass curves for (top) EFGB and (bottom) WFGB study sites in 2022.

Family Level Analysis

Additional analyses were conducted for grouper and snapper families due to their importance in fishing, and parrotfish due to their role as important herbivores.

In 2022, two species of grouper were observed in EFGB surveys: graysby (*Cephalopholis cruentata*) and tiger grouper (*Mycteroperca tigris*). No groupers were observed in WFGB surveys (Figure 4.4). Coefficient of variation percentages (55.28% for density, 65.59% for biomass) indicated that the data had poor power to detect differences due to the low number observed; therefore, no statistical tests were performed on grouper community data.

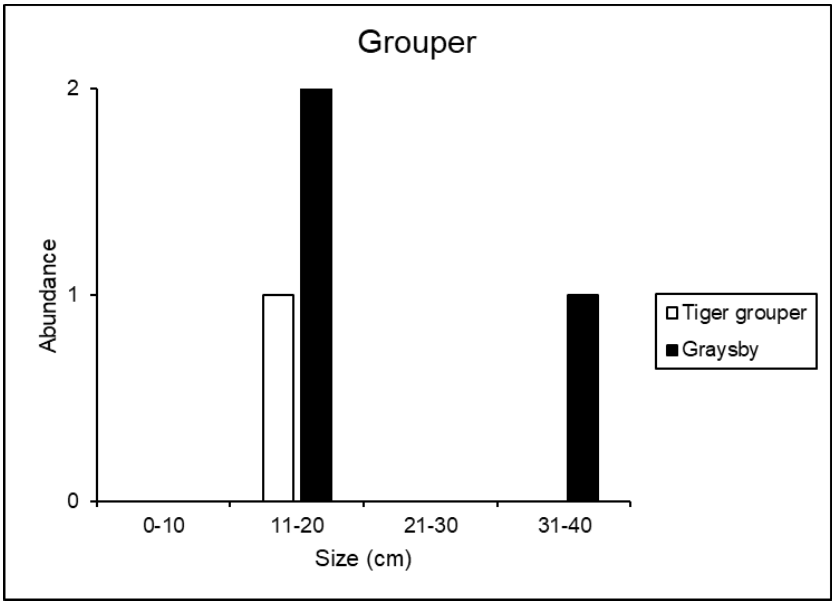


Figure 4.4. Size frequency of tiger grouper and graysby in the EFGB study site in 2022.

Two snapper species were observed in 2022 surveys at WFGB: dog snapper (*Lutjanus jocu*) and gray snapper (*Lutjanus griseus*; Figure 4.5). No snappers were observed in surveys at EFGB in 2022. The snapper observed at WFGB were all reproductively immature (Froese & Pauly, 2019). Coefficient of variation percentages (51.51% for density, 71.58% for biomass) indicated that the data had poor power to detect population differences due to the low number of snapper observed. Mean snapper biomass was 0.091 ± 0.065 kg/100 m^2 in WFGB surveys. No statistical tests were run on the snapper community due to poor statistical power.

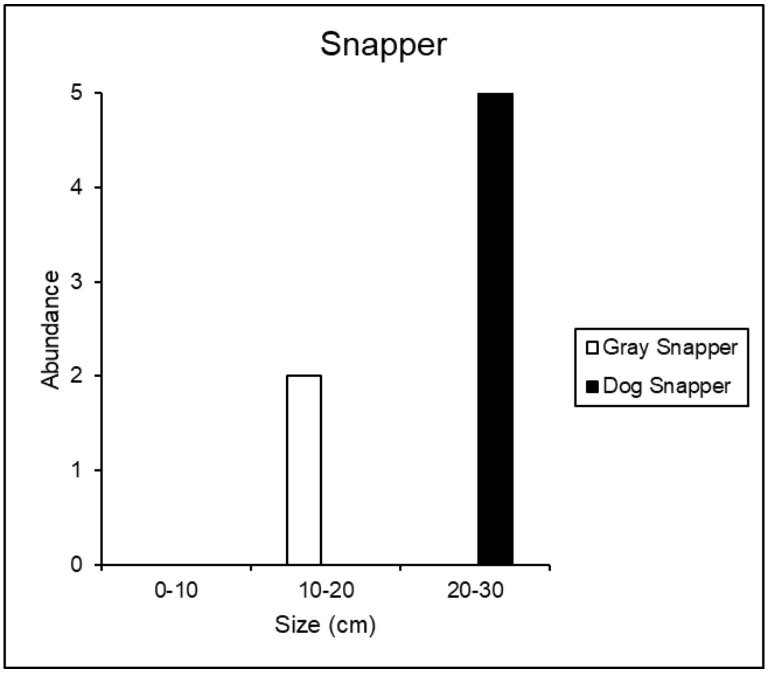


Figure 4.5. Size frequency of gray snapper and dog snapper at the WFGB study site in 2022.

Parrotfishes are important grazers on coral reefs (Jackson et al., 2014). Parrotfish observed in EFGB and WFGB 2022 surveys included five species: striped parrotfish (*Scarus iseri*), princess parrotfish (*Scarus taeniopterus*), queen parrotfish (*Scarus vetula*), redband parrotfish (*Sparisoma aurofrenatum*), and stoplight parrotfish. Coefficient of variation percentages (33.72% for density and 45.64% for biomass) indicated that the data had poor power to detect population differences. Mean biomass of parrotfishes was 0.73 ± 0.18 kg/100 m^2 in EFGB surveys and 0.96 ± 0.81 kg/100 m^2 in WFGB surveys. No statistical tests were run on the parrotfish community due to poor statistical power (Figure 4.6).

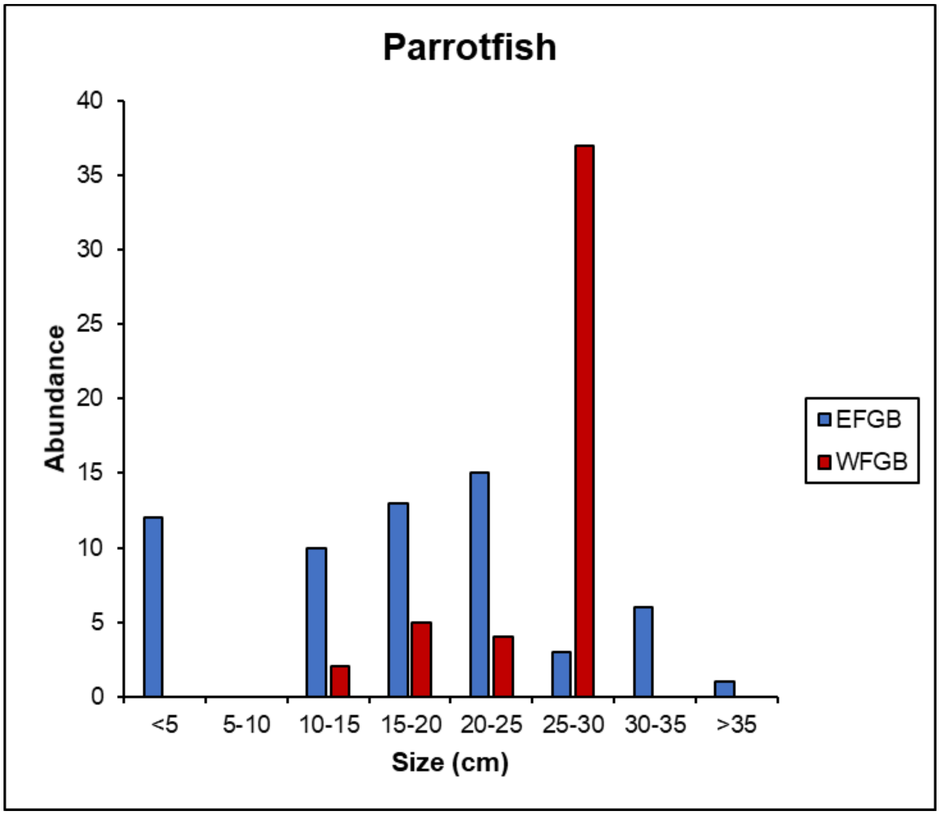


Figure 4.6. Size frequency of parrotfishes at EFGB and WFGB study sites in 2022.

Lionfish

Lionfish, an invasive species native to the Indo-Pacific, were first observed by scuba divers in FGBNMS in 2011 and in study site surveys in 2013. No lionfish were observed in surveys in 2022; however, they were observed by divers during a permitted lionfish removal cruise held in June 2022.

Fish Survey Long-Term Trends

Since 2002, mean fish density ranged from 52.70–564.68 individuals/100 m^2 at the EFGB study site and 50.37–471.87 individuals/100 m^2 at the WFGB study site (Figure 4.7). Fish community density was compared among years and study sites when complete survey data were available (2011 to 2022). Due to the COVID-19 pandemic, no fish surveys were completed in 2020 and 2021. PERMANOVA analysis revealed significant differences between study sites and among years (Table 4.7), demonstrating fish community, based on density, was highly variable among years and locations from 2011 to 2022 (Figure 4.7). The observed dissimilarity in study site communities based on density from 2011 to 2022 was mainly attributable to variations in bonnetmouth (*Emmelichthyops atlanticus*; 9.69%) and brown chromis (8.30%).

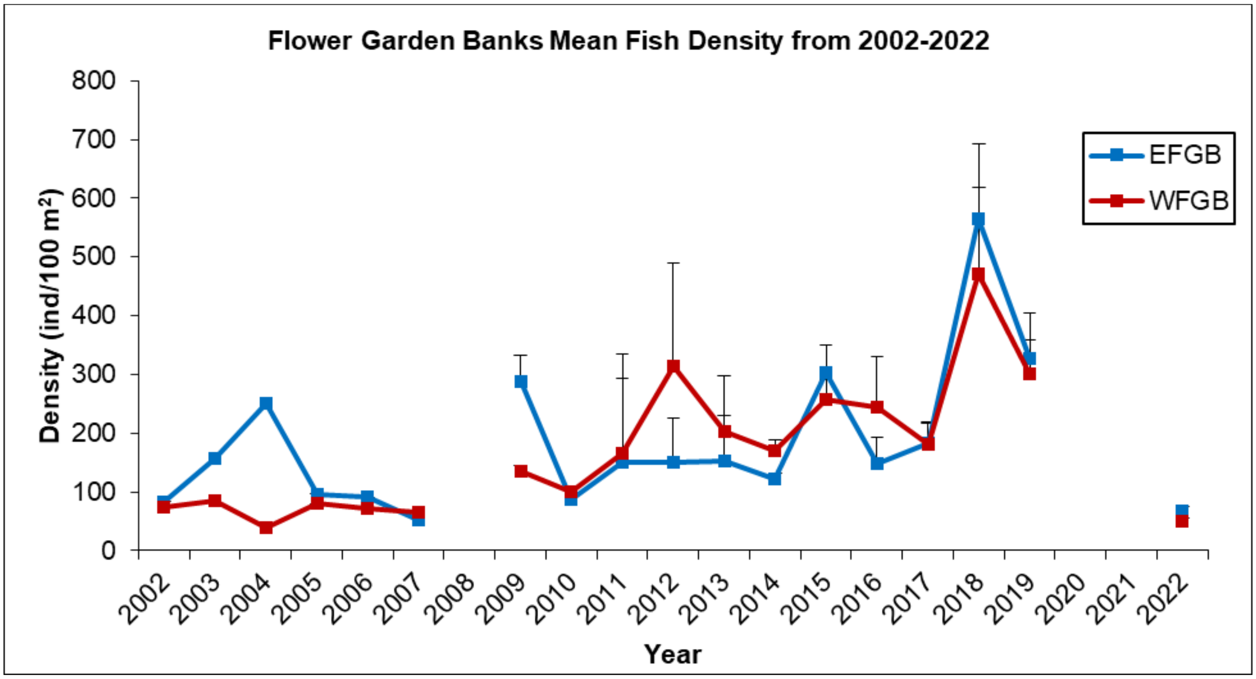


Figure 4.7. Mean fish density (individuals/100 m^2) + SE in EFGB and WFGB study sites from 2002 to 2022. No data were collected in 2008 and 2020–2021 and SE was not available before 2009. Source: Precht et al., 2006; Zimmer et al., 2010 (2002 to 2008); Johnston et al., 2013, 2015, 2017a, 2017b, 2018a, 2020, 2021 (2009 to 2019)

Table 4.7. PERMANOVA results comparing mean fish density in EFGB and WFGB study sites and among years from 2011 to 2022. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	7744	1	6.058	**0.0001**
Year	1.11E+05	9	9.6534	**0.0001**
Bank*Year	35107	9	3.0515	**0.0001**
Res	5.62E+05	440		
Total	7.18E+05	459		

Community biomass data, first collected in 2006, was highly variable in the study sites and ranged from 4.55–60.16 kg/100 m^2 in EFGB surveys and 2.46–27.23 kg/100 m^2 in WFGB surveys from 2006 to 2022 (Figure 4.8). PERMANOVA analysis revealed significant differences between study sites and among years (Table 4.8). The observed dissimilarity in community based on biomass between study sites from 2011 to 2022 was mainly attributable to great barracuda (10.45%) and Bermuda/yellow chub (8.10%). The spike in biomass at EFGB in 2018 was attributable to greater local abundance of great barracuda and horse-eye jack (Johnston et al., 2020).

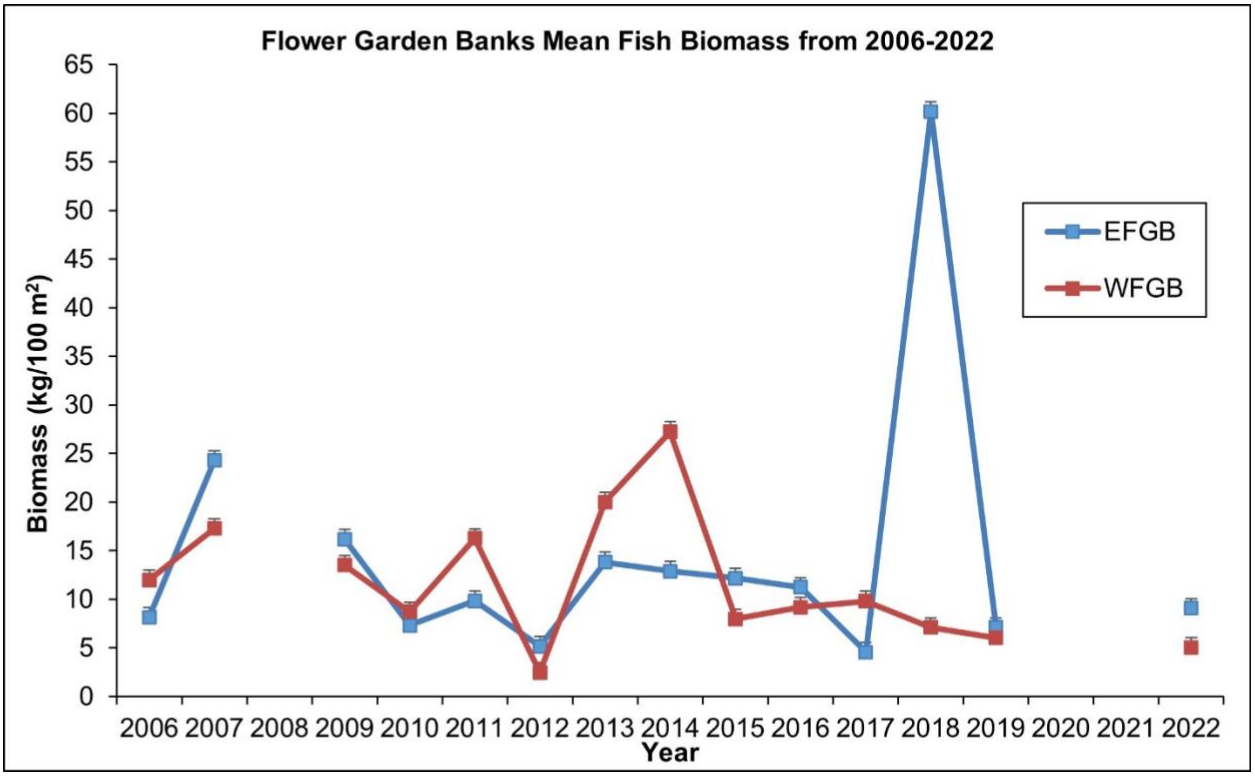


Figure 4.8. Mean fish biomass (kg/100 m^2) + SE in EFGB and WFGB study sites from 2006 to 2022. No data were collected in 2008 and 2020–2021 and SE was not available before 2009. Source: Precht et al., 2006; Zimmer et al., 2010 (2002 to 2008); Johnston et al., 2013, 2015, 2017a, 2017b, 2018a, 2020, 2021 (2009 to 2022)

Table 4.8. PERMANOVA results comparing mean fish biomass in EFGB and WFGB study sites and among years from 2011 to 2022. **Bold** text denotes significant values.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	7113.8	1	3.3654	**0.0001**
Year	4.32E+05	9	22.75	**0.0001**
Bank*Year	48325	9	2.5402	**0.0001**
Res	9.3007E+05	440		
Total	1.4199E+06	459		

Additional analyses were conducted to investigate trends in grouper and snapper density at EFGB and WFGB study sites over time (when complete survey data were available, 2011 to 2022). The most common grouper species at both EFGB and WFGB study sites were graysby and yellowmouth grouper (Figure 4.9; Figure 4.10). Tiger grouper, scamp, coney, red hind, and rock hind were denser in EFGB surveys, and black grouper were denser in WFGB surveys (Figure 4.9; Figure 4.10).

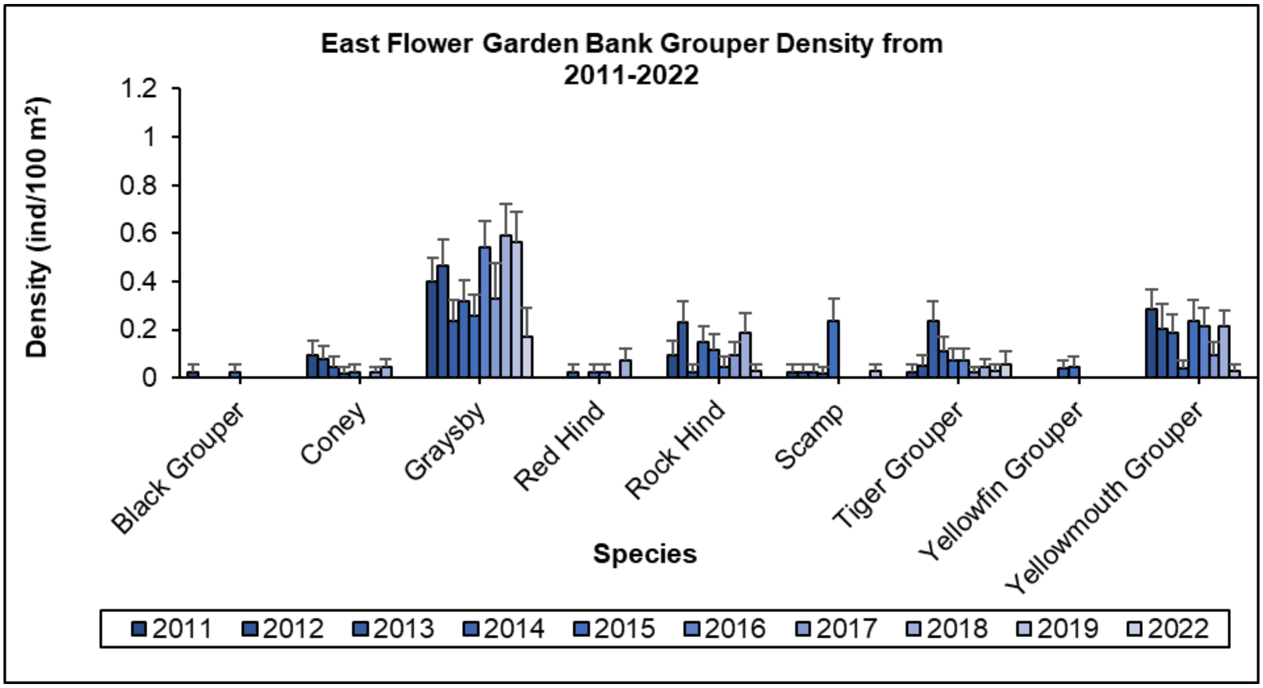


Figure 4.9. Mean density (individuals/100 m^2) + SE of grouper species within EFGB study site surveys from 2011 to 2022. Source: Johnston et al., 2015, 2017a, 2017b, 2018a, 2020, 2021

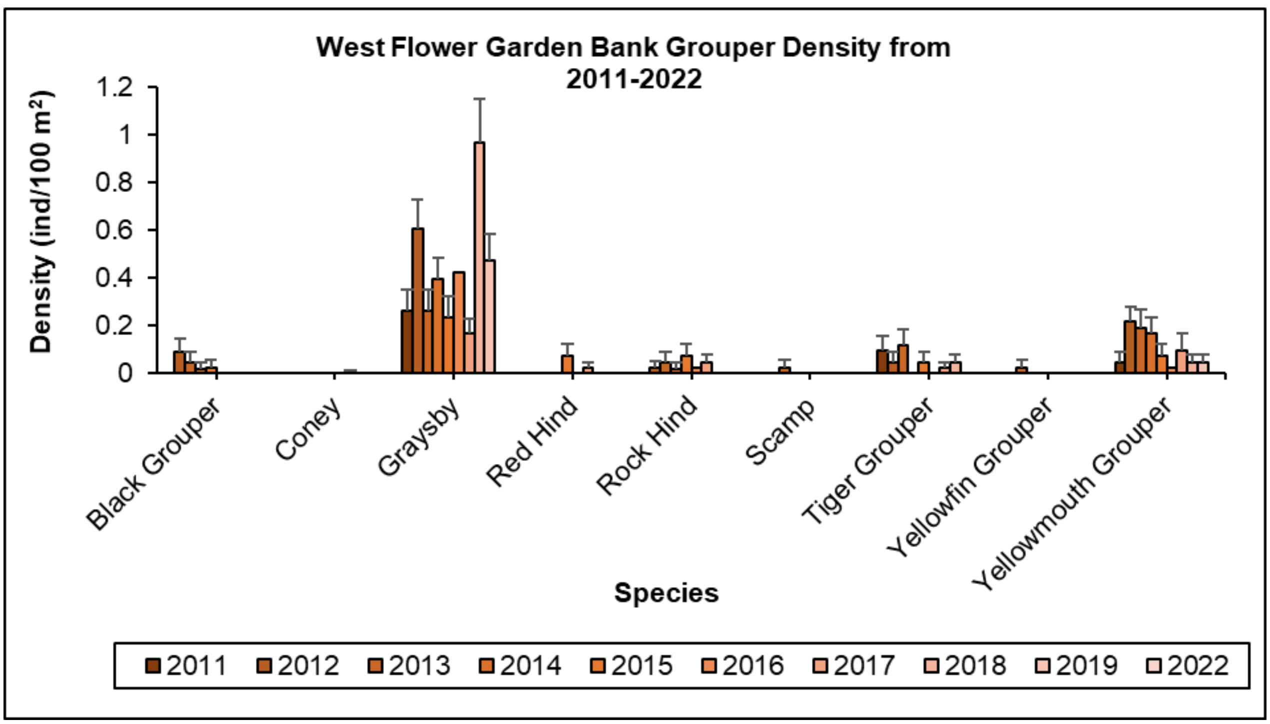


Figure 4.10. Mean density (individuals/100 m^2) + SE of grouper species within WFGB study site surveys from 2011 to 2022. Source: Johnston et al., 2015, 2017a, 2017b, 2018a, 2020, 2021

Grouper community density was compared among years and study sites from 2011 to 2022. PERMANOVA analysis revealed that grouper density was significantly higher in EFGB surveys than in WFGB surveys, and also varied among years (Table 4.9). The observed dissimilarity between study sites from 2011 to 2022 was mainly attributable to graysby (47.65%) and yellowmouth grouper (20.40%).

Table 4.9. PERMANOVA results comparing mean grouper density within EFGB and WFGB study sites from 2011 to 2022. **Bold** text denotes significant value.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	1.9549	1	3.7591	**0.0131**
Year	11.414	9	2.4388	**0.0003**
Bank*Year	4.5731	8	1.0992	0.3224
Res	216.86	417		
Total	235.53	435		

From 2011 to 2022, dog snapper were consistently denser in WFGB surveys and gray snapper were denser in most years (Figure 4.11). PERMANOVA analysis revealed that snapper density was significantly higher at study sites at WFGB compared to those at EFGB (Table 4.10). The observed dissimilarity was mainly attributable to the greater abundance of dog snapper at WFGB (61.85%).

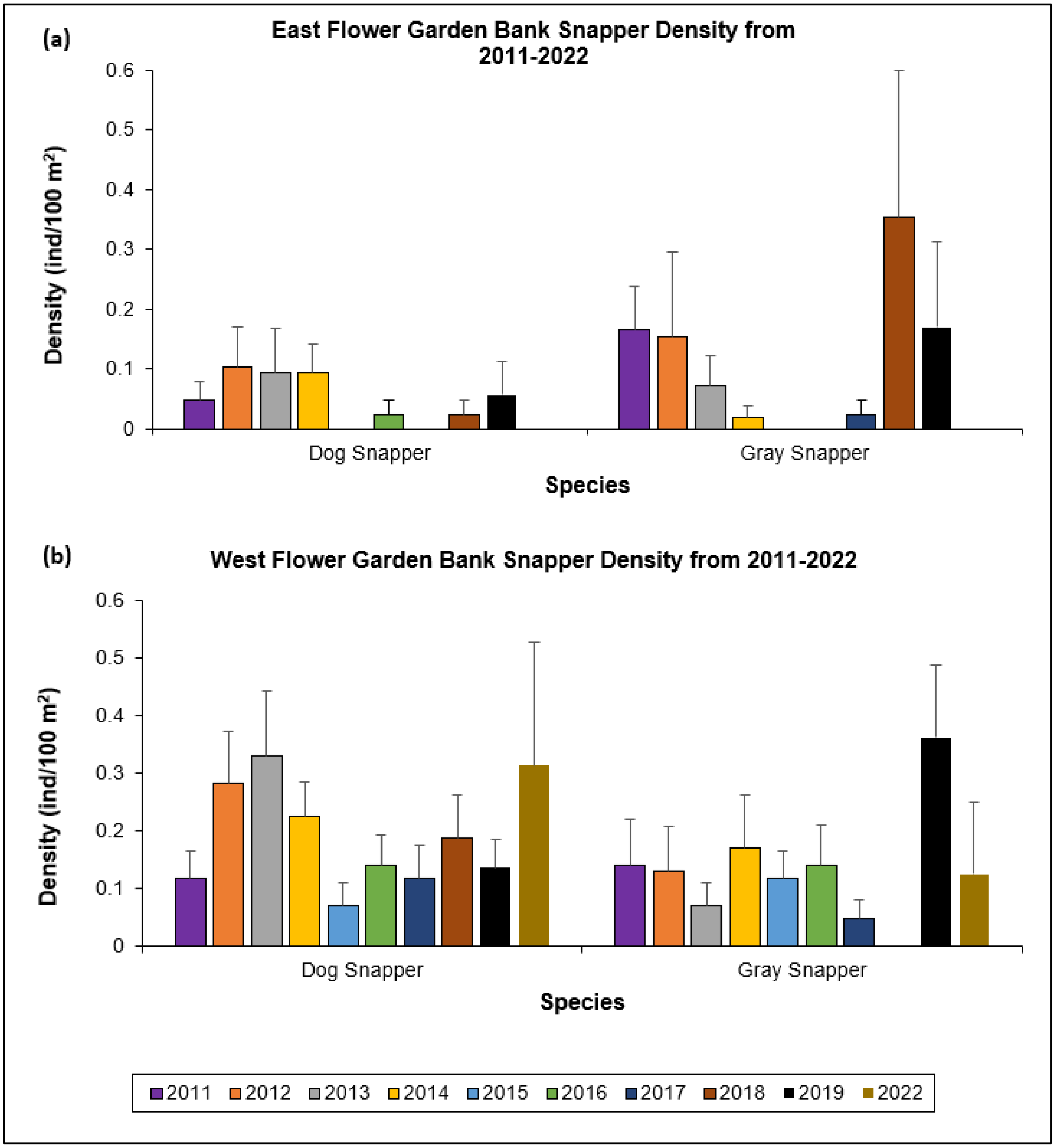


Figure 4.11. Mean density (individuals/100 m^2) + SE of snapper species within (a) EFGB and (b) WFGB study sites from 2011 to 2022. Source: Johnston et al., 2015, 2017a, 2017b, 2018a, 2020, 2021

Table 4.10. PERMANOVA results comparing mean snapper density within EFGB and WFGB study sites from 2011 to 2022. **Bold** text denotes significant values.

Source	Sum of Squares	df	Pseudo-F	P (perm)
Bank	2.3423	1	12.687	**0.0001**
Year	2.5415	9	1.5295	0.0726
Bank*Year	1.7441	9	1.0496	0.4084
Res	81.234	440		
Total	87.789	459		

Fish Surveys Discussion

Fish communities are indicators of ecosystem health (Sale, 1991; Knowlton & Jackson, 2008; Jackson et al., 2014) and are therefore an important component of long-term monitoring programs. Long-term monitoring is necessary to distinguish natural and abnormal levels of variation. Historically, the fish communities at EFGB and WFGB have been considered low in species diversity but high in biomass (Zimmer et al., 2010). The fish assemblages of EFGB and WFGB differ somewhat from Caribbean and other lower-latitude reefs because they occur near the northern latitudinal limit of coral reefs in the Gulf of Mexico, are remote from other tropical reef communities, and exist in slightly different habitat types. Approximately 150 reef fish species have been documented on the EFGB and WFGB reef caps (Pattengill, 1998; Pattengill-Semmens & Semmens, 1998); these include only a few lutjanids (snappers) and haemulids (grunts; Rooker et al., 1997; Precht et al., 2006; Johnston et al., 2017a).

EFGB and WFGB also have lower abundance of herbivorous fishes than other Caribbean reefs (Dennis & Bright, 1988; Bauer et al., 2015a, 2015b, 2015c; Caldow et al., 2015; Clark et al., 2015a, 2015b). Historically, low macroalgae cover was reported in annual monitoring surveys (Gittings et al., 1992), while recent data suggest a significant increase in mean macroalgae cover over time (Johnston et al., 2018a). During the 2022 study period, the herbivore guild possessed the second highest mean biomass, contributing to 25% of the total biomass within study site surveys. Herbivore biomass was also greater at EFGB, where macroalgae percent cover was higher in 2022 in both repetitive stations and reef-wide transects. Within the herbivore guild, 37% of the total biomass was accounted for by Bermuda/yellow chub.

Still, piscivores had the highest mean biomass, with approximately 60% of the total biomass within study sites. In the piscivore guild, horse-eye jack accounted for 65% of the total biomass, followed by great barracuda (33%). It is unknown how the presence of the research vessel might affect estimates of abundance and biomass for species like great barracuda, which often congregate below the R/V *Manta*. On one hand, the vessel concentrates the fish in an area directly over the study sites in which the divers work, potentially inflating estimates if they are seen in the water column by fish surveyors; more likely however, because the fish tend to remain near the surface, and not directly over most fish survey sites (where some might otherwise be if not for the presence of the vessel), the phenomenon probably decreases biomass estimates.

Abundance-biomass curves have historically been used to ascertain community health on shallow-water coral reefs; a community dominated by few large species is considered “healthy” and a community dominated by many small species is considered “impacted” (DeMartini et al., 2008; Southern Ocean Knowledge and Information Wiki, 2014). At EFGB and WFGB study sites, results indicated that fish communities were evenly distributed (w-values close to 0), and the dominance plots for surveys were representative of a healthy population.

Commercially and recreationally important grouper and snapper density was low (<1 individual/100 m^2) at EFGB and WFGB study sites in 2022. The grouper species observed consisted of only juvenile tiger groupers and mature graysbys. The snapper species consisted of only juveniles. It should be noted that typical recruitment/nursery habitat for snappers (mangroves and seagrasses) are not present at EFGB and WFGB, and the mechanism for recruitment of this family to the area is not well understood (Mumby et al., 2004; Clark et al., 2014). Due to the biogeographic isolation of EFGB and WFGB, the fish assemblage is thought to rely on self-recruitment, as planktonic larval duration can limit larval supply and dispersal from other reefs in the southern Gulf of Mexico to EFGB and WFGB; complicating the process is the dynamic nature of oceanographic conditions (i.e., variability in the Loop Current and associated eddies; Wetmore et al., 2020).

Parrotfish are recognized as key algae grazers on coral reefs, and their abundance and biomass have been positively correlated with coral cover (Jackson et al., 2014). The mean biomass of parrotfish at FGBNMS is considered low, though not significantly different than many other Caribbean reefs (Jackson et al., 2014; Table 4.11). And while low parrotfish biomass can be associated with high fishing pressure and low coral cover, neither have been documented at EFGB or WFGB. Given the abundance of food for parrotfish at EFGB and WFGB, their low abundance is perplexing.

Table 4.11. Mean biomass (kg/100 m^2) for parrotfish at EFGB and WFGB study sites and other Caribbean reefs. All data, with the exception of EFGB and WFGB data, are from Lang et al. (2012).

Location	Biomass (kg/100 m^2)
Mexico	1.710
Belize	1.200
East and West Flower Garden Banks study site surveys	0.740
Guatemala	0.670
Honduras	0.440

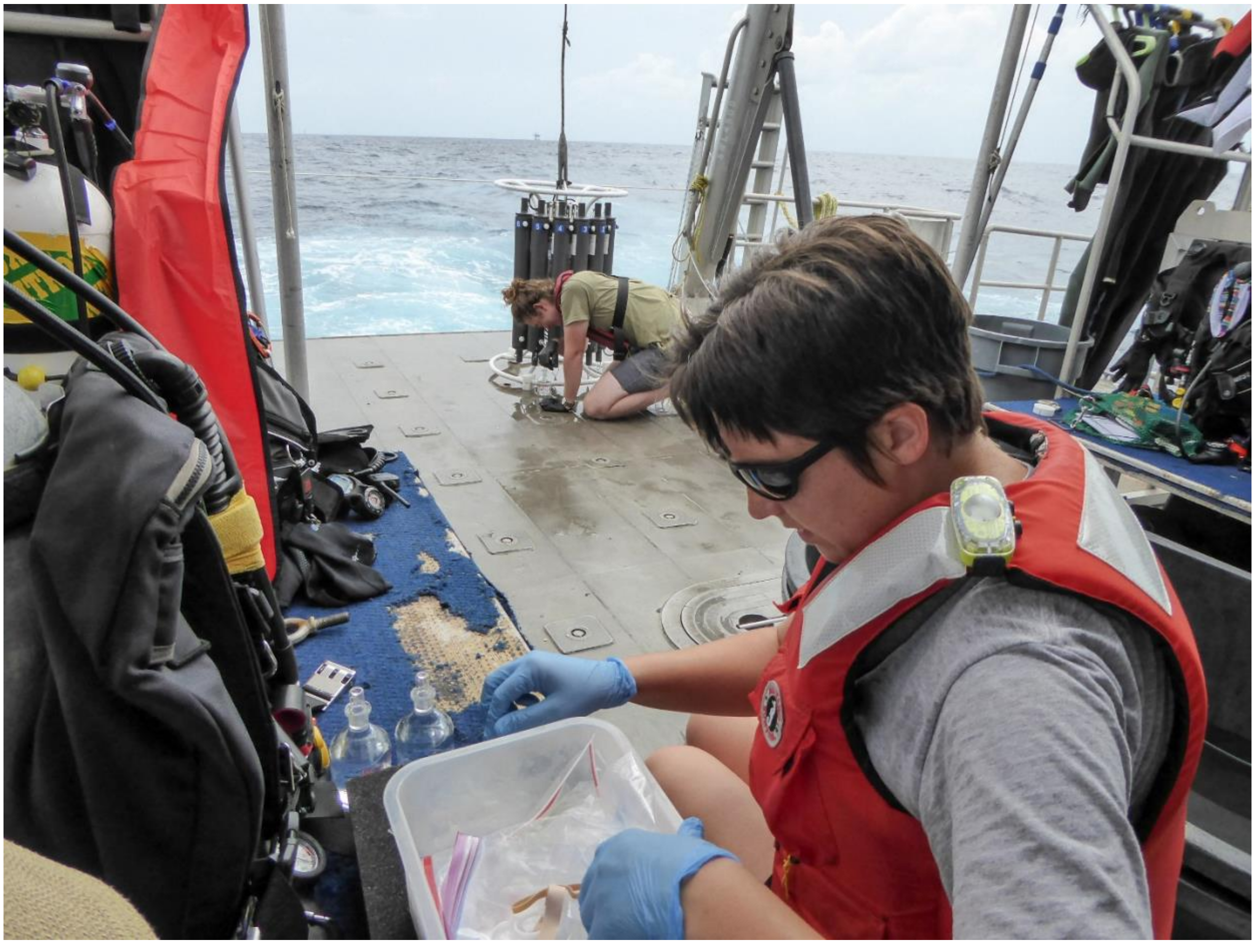
Lionfish have been observed consistently by divers at FGBNMS since 2011, but they were not recorded in surveys in 2022. Since their first observation, numbers rapidly increased through 2014, declined after 2015, rose again in 2018, and declined sharply in 2019 (Johnston et al., 2021). It has been suggested that the recent lionfish density declines in the northern Gulf of Mexico may be related to the emergence of an ulcerative skin disease in late 2017 and 2018, which may have reduced recruitment in the region (Harris et al., 2020). Another possibility is that low density in 2022 may be the result of high numbers of lionfish (n = 228) removed from FGBNMS in June 2022 during the Lionfish Invitational cruise on the M/V *Fling*. Other possibilities include predation on adult or juvenile lionfish by native fish, but this has not yet been documented.

Lionfish are most commonly seen during crepuscular feeding periods at dawn and dusk. Though fish surveys are conducted throughout the day, the fact that most surveys are not conducted when lionfish are most active may reduce the accuracy of estimates of their densities. However, mean lionfish densities at EFGB and WFGB (approximately 4–40 lionfish ha^{-1}) remain below levels recorded elsewhere in the southeast U.S. and Caribbean region, such as North Carolina (150 lionfish ha^{-1}; Morris & Whitfield, 2009) and the Bahamas (100–390 lionfish ha^{-1}; Green & Côté, 2009; Darling et al., 2011), as well as on artificial reefs in the northern Gulf of Mexico (10–100 lionfish ha^{-1}; Dahl & Patterson, 2014). Since 2015, permitted lionfish removal cruises during summer months on the recreational dive vessel M/V *Fling* have been conducted to help suppress lionfish predation on native fish; however, dives are limited to the upper portion of the reef crest (<40 m) and focus around the mooring buoys typically used for recreational diving

(Green et al., 2014). Thus, removals do not take place over large portions of the reefs, and are not conducted within the monitoring study sites. However, lionfish removals at nearby moorings are likely to result in emigration by some fish from the study sites, thus lowering abundances there.

The regal demoiselle, a non-native species from the Indo-Pacific, was observed in study site surveys in 2018 and 2019 at EFGB and WFGB. No regal demoiselles were observed in EFGB or WFGB 2022 surveys, but they were observed in high densities during Stetson Bank surveys in August 2022 (O'Connell et al., 2024). The suspected mode of introduction of this species was the inter-ocean transfer of oil platforms (Robertson et al., 2018). This species could compete with and displace native reef fish such as brown chromis (Robertson et al., 2016), but these impacts have not yet been confirmed. Sightings from EFGB and WFGB fish surveys were reported to the U.S. Geological Survey invasive species sightings database, and FGBNMS will continue to monitor this species.

Chapter 5:
Water Quality



Scientists collect and sort water samples on the deck of the R/V *Manta*. Photo: G.P. Schmahl/NOAA

Water Quality Introduction

Several water quality parameters have been continuously or periodically recorded at EFGB and WFGB from December 2019 through December 2022. Salinity, turbidity, and temperature were recorded every hour by data loggers installed in or near the study sites at depths of approximately 24 m. Temperature loggers co-located with specific repetitive photostations at depths of 30 m and 40 m at each bank collected hourly readings; these sensors were recovered September 8 and 9, 2022 and the remaining sensors were recovered in August 2023.

Water samples were collected in March 2022 at three different depths within the water column and analyzed by a U.S. Environmental Protection Agency (EPA)-certified laboratory for select nutrients. Water column profiles were also acquired in conjunction with water sample collections. Water samples are usually collected on a quarterly basis, but cruises in 2022 were canceled or scaled back due to restrictions related to the COVID-19 pandemic. This chapter presents data from moored water quality instruments, water column profiles, and water samples collected in 2022.

Water Quality Methods

Water Quality Field Methods

Temperature and Salinity Loggers

The primary instrument used at each bank for recording temperature, salinity, and turbidity was a Sea-Bird® Electronics 16plus V2 conductivity, temperature, and depth (CTD) sensor (SBE 16plus) equipped with a WET Labs ECO NTUS turbidity meter. Instruments were located at a depth of 23 m at EFGB and 27 m at WFGB. Loggers were secured to mounting anchors and located in sand flats at each bank (see Figure 1.3 and Figure 1.4). The instruments recorded temperature, salinity, and turbidity on an hourly basis. They were exchanged by divers for downloading and maintenance in March 2022 and January 2023. They were immediately exchanged with an identical instrument to avoid any interruptions in data collection. Data were then downloaded and reviewed, sensors were cleaned and confirmed to be operable, and battery duration was checked. Maintenance, as well as factory service and calibration of each instrument, was delayed in 2022 due to limitations on field work as a result of restrictions related to the COVID-19 pandemic.

Onset® Computer Corporation HOBO® Pro v2 U22-001 (HOBO) thermograph loggers were used to record temperature on an hourly basis. These loggers (attached directly to the primary SBE 16plus instrument) provided a highly reliable temperature backup for the primary SBE 16plus logging instruments located at the 23 m and 27 m stations at EFGB and WFGB, respectively. HOBO loggers were also deployed at 30 m and 40 m stations at EFGB and WFGB (attached directly to permanent repetitive photostation markers). Due to reduced field capacity, the loggers at 30m and 40 m were only retrieved once, in September 2022. The remaining data were recovered in August 2023.

Water Column Profiles

Water column profiles from the surface to the reef cap were acquired in March 2022 with a Sea-Bird® Electronics 19plus V2 CTD that recorded temperature, salinity, pH, turbidity, fluorescence, and dissolved oxygen (DO) every ¼ second. The carousel package included a Sea-Bird® 55 Frame Eco water sampler equipped with 12 four-liter Niskin bottles and a Sea-Bird® Electronics 19plus V2 CTD. Data were recorded following an initial three-minute soaking period after deployment, and the resulting profile data were processed to include only downcast data. The CTD was lowered and returned to the surface at a rate of <1 m s^{-1}. The water column profiles were obtained on March 1, 2022. No other profiles were taken during 2022 as a result of challenges accessing the site and technical errors in sensors from extended deployments.

Water Samples

In conjunction with water column profiles using the sampling carousel described above, water samples were collected. The carousel was attached to the R/V *Manta* scientific winch cable, allowing the operator to activate the bottles for sample collection at specific depths. Four Niskin bottles collected water samples near the reef cap on the seafloor (~20 m depth), midwater (~10 m depth), and near the surface (~1 m depth) for subsequent transfer to laboratory collection bottles. A blind duplicate water sample was taken at one of the sampling depths for each sampling period.

Water samples were analyzed for chlorophyll *a* (chl *a*) and nutrients including ammonia, nitrate, nitrite, soluble reactive phosphorus (ortho phosphate), and total Kjeldahl nitrogen (TKN; Table 3.1). Water samples for chl *a* analyses were collected in 1000-ml glass containers with no preservatives. Samples for soluble reactive phosphorous were placed in 250-ml bottles without preservatives. Ammonia, nitrate, nitrite, and TKN samples were collected in 1000-ml bottles with a sulfuric acid preservative. Within minutes of sampling, labeled sample containers were stored on ice at 0 °C and a chain of custody was initiated for processing at an EPA-certified laboratory. The samples were transported and delivered for analysis to A&B Laboratories in Houston, Texas within 24 hours of collection.

Table 5.1. Standard EPA methods used to analyze water samples collected at FGBNMS.

Parameter	Test Method	Detection Limit
Chl *a*	SM 10200H	0.003 mg/l
Ammonia	SM 4500NH3D	0.10 mg/l
Nitrate	SM 4500NO3E	0.04 mg/l
Nitrite	SM 4500NO2B	0.02 mg/l
Soluble reactive phosphorus	SM 4500 P-E	0.02 mg/l
TKN	SM 4500NH3D	0.50 mg/l

Water samples for ocean carbonate measurements, including pH, alkalinity, CO_2 partial pressure (pCO_2), aragonite saturation state, and total dissolved CO_2, were collected following methods provided by the Carbon Cycle Laboratory (CCL) at Texas A&M University-Corpus Christi (TAMU-CC). Samples were collected in ground neck borosilicate glass bottles. Bottles were filled using a 30-cm plastic tube connected to the filler valve of a Niskin bottle. Bottles were rinsed three times using the sample water, filled carefully to reduce bubble formation, and overflowed by at least 200 ml. A total of 100 µl of saturated $HgCl_2$ was added to each bottle, which was then capped. The stopper was sealed with Apiezon® grease and secured with a rubber band. The bottles were then inverted vigorously to ensure homogeneous distribution of $HgCl_2$ and secured at ambient temperature for shipment. Samples and CTD profile data were sent to CCL at TAMU-CC. Ocean carbonate samples were obtained on March 1, 2022.

Water Quality Data Processing and Analysis

Temperature, salinity, and turbidity data recorded on SBE 16plus instruments and temperature data recorded on backup HOBO loggers were downloaded and processed in March 2022 and January 2023. QA/QC procedures included a review of all files to ensure data accuracy and servicing instruments based on manufacturer recommendations. The 24-hourly readings obtained each day were averaged into a single daily value and recorded in duplicate databases. Each calendar day was assigned a value in the database. Separate databases were maintained for each logger type as specified in the standard operating procedures.

Previous reports used hourly sea surface temperature (SST) and sea surface salinity (SSS) data downloaded from Buoy V and Buoy N of the Texas Automated Buoy System database; however, these buoys were removed in late April 2019 and January 2017, respectively, due to lack of support and funding. Therefore, surface buoy readings were unavailable or absent for the 2022 analyses. In lieu of in situ surface data, satellite-derived SST and SSS data for 2022 were downloaded from the NOAA Environmental Research Division Data Access Program data server for comparison to reef cap data. The SST dataset used was “GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v4.1)” and the SSS dataset used was “Sea Surface Salinity, Near Real Time, Miras SMOS 3-Day Mean (smosSSS3Scan3DayAggLoM), CoastWatch v6.62, 0.25°, 2010-present” (JPL MUR MEaSUREs Project, 2015; NOAA Coral Reef Watch, 2022). Satellite-derived one-day mean SST data utilized for WFGB and EFGB in 2022 were available as a level-4 global 0.01-degree grid produced at the NASA Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center under support by the NASA MEaSUREs program. Satellite-derived SSS data were available as a 0.25-degree longitude/latitude level-3 gridded three-day mean dataset from MIRAS satellite observations.

The 30-m and 40-m HOBO loggers were exchanged in September 2022 and again in August 2023, completing the full year’s dataset. Results of chl *a* and nutrient analyses were obtained from A&B Laboratories and compiled in an Excel table. Ocean carbonate analyses were calculated by the CCL at TAMU-CC.

For seawater temperature, salinity, and turbidity, EFGB and WFGB SBE 16plus daily mean data were compared using a paired t-test in R version 2.13.2. Monotonic trends for long-term seawater temperature and salinity data were detected using the Seasonal-Kendall trend test in a Microsoft Windows® DOS executable program developed by the U.S. Geological Survey for water resource data (Hipel & McLeod, 1994; Helsel & Hirsch, 2002; Helsel et al., 2006). The Seasonal-Kendall trend test performed the Mann-Kendall trend test for each month and evaluated changes among the same months from different years over time, accounting for serial correlation in repeating seasonal patterns.

Water Quality Results

Temperature

Surface temperature at EFGB ranged from 20.99 °C to 30.65 °C in 2022. At 23 m, it ranged from 19.87 °C to 29.52 °C (Figure 5.1). The 23-m backup HOBO logger registered temperatures similar to those from the 23-m SBE 16plus (Figure 5.1). The 30 m HOBO logger was lost during recovery.

Surface temperature at WFGB ranged from 20.83 °C to 30.50 °C in 2022. At 27 m, it ranged from 19.80 °C to 29.72 °C (Figure 5.1). The 27-m backup HOBO logger registered temperatures similar to those from the 27-m SBE 16plus (Figure 5.1). In 2022, tropical weather systems corresponded with decreased water temperatures at EFGB and WFGB in summer months.

According to in situ data from EFGB and WFGB SBE 16plus instruments, reef cap temperatures did not exceed 30 °C at either bank in 2022 (a known temperature threshold associated with coral bleaching). No hurricanes or tropical storms occurred in the northwest Gulf of Mexico in 2022. No significant difference occurred between EFGB 23 m and WFGB 27 m SBE 16plus reef cap temperatures in 2022.

Seawater temperature data obtained from loggers at EFGB (23 m) and WFGB (27 m) have been collected since 1990. Though some data gaps occurred due to equipment malfunction and changes in methods and/or instrumentation, long-term trends showed increasing surface and reef cap temperatures at EFGB and WFGB (Figure 5.2). The Seasonal-Kendall trend test on time-series satellite and daily mean seawater temperature data at depth revealed significantly increasing, monotonic trends from 1990 to 2022 at EFGB and WFGB surface waters ($\tau = 0.29$, $z = 8.36$, $p < 0.001$ and $\tau = 0.30$, $z = 8.63$, $p < 0.001$, respectively) and at EFGB (23 m) and WFGB (27 m) datasondes ($\tau = 0.29$, $z = 6.56$, $p < 0.001$ and $\tau = 0.28$, $z = 6.80$, $p < 0.001$, respectively) after adjusting for correlation among seasons (Figure 5.2). Mean temperature on the reef increased by an average of 0.5 °C at EFGB (23 m) and 0.4 °C at WFGB (27 m) from 1990 to 2022.

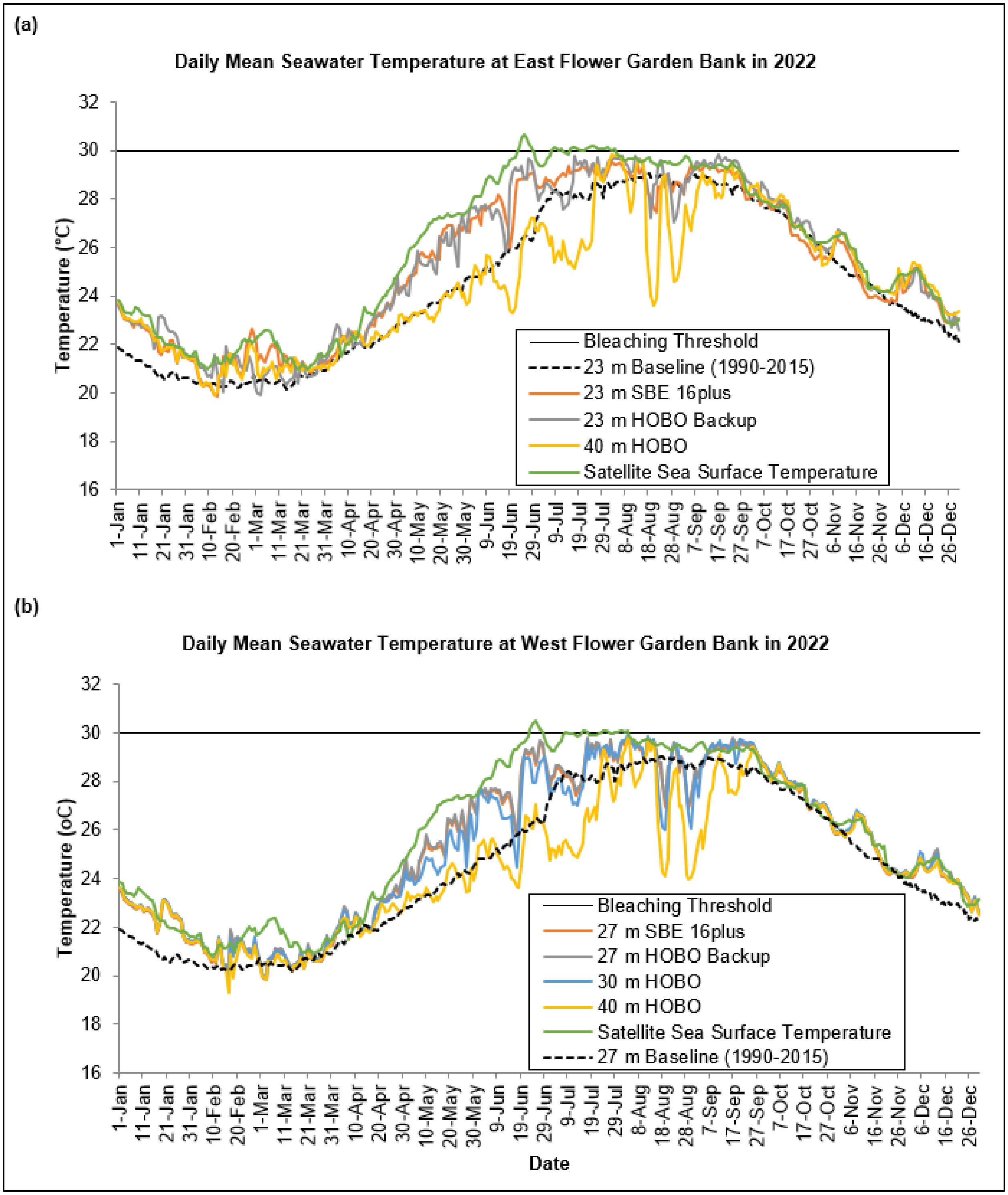


Figure 5.1. Daily mean seawater temperature (°C) at (a) EFGB and (b) WFGB from various depths in 2022, and the 25-year daily mean water temperature baseline. The solid black line at 30 °C is a level known to trigger coral bleaching.

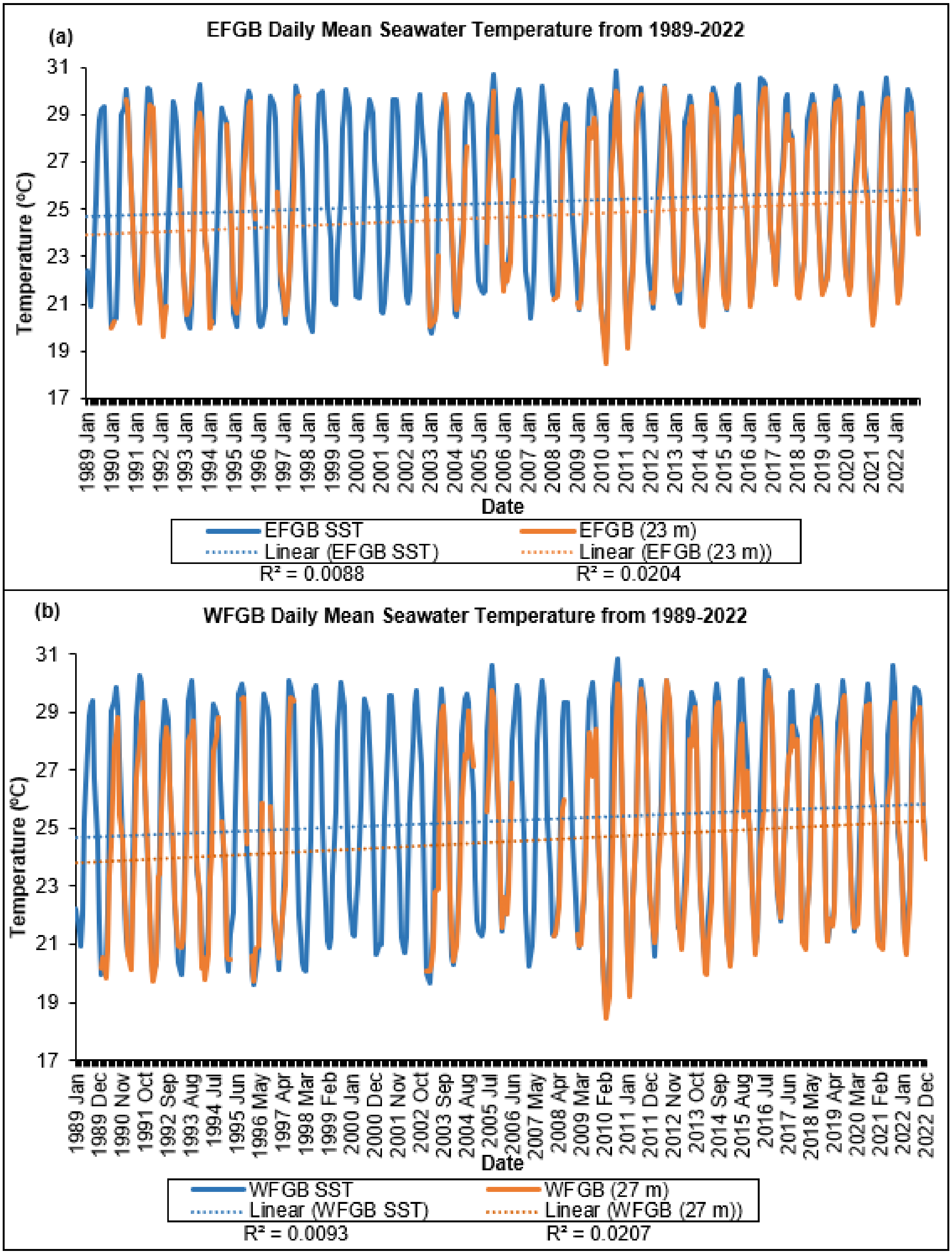


Figure 5.2. Daily mean seawater temperature (°C) demonstrates 12-month seasonal variation from various depths at (a) EFGB and (b) WFGB from 1989 to 2022, as well as a significant increase over time (trend lines).

Salinity

In 2022, salinity at EFGB ranged from 31.01 to 39.75 psu at the surface and 34.11 to 36.61 psu at 23 m (Figure 5.3). At WFGB, salinity ranged from 28.52 to 39.96 psu at the surface and 34.10 to 36.60 psu at 27 m (Figure 5.3). There was no significant difference between EFGB 23 m and WFGB 27 m SBE 16plus reef cap daily mean salinity in 2022.

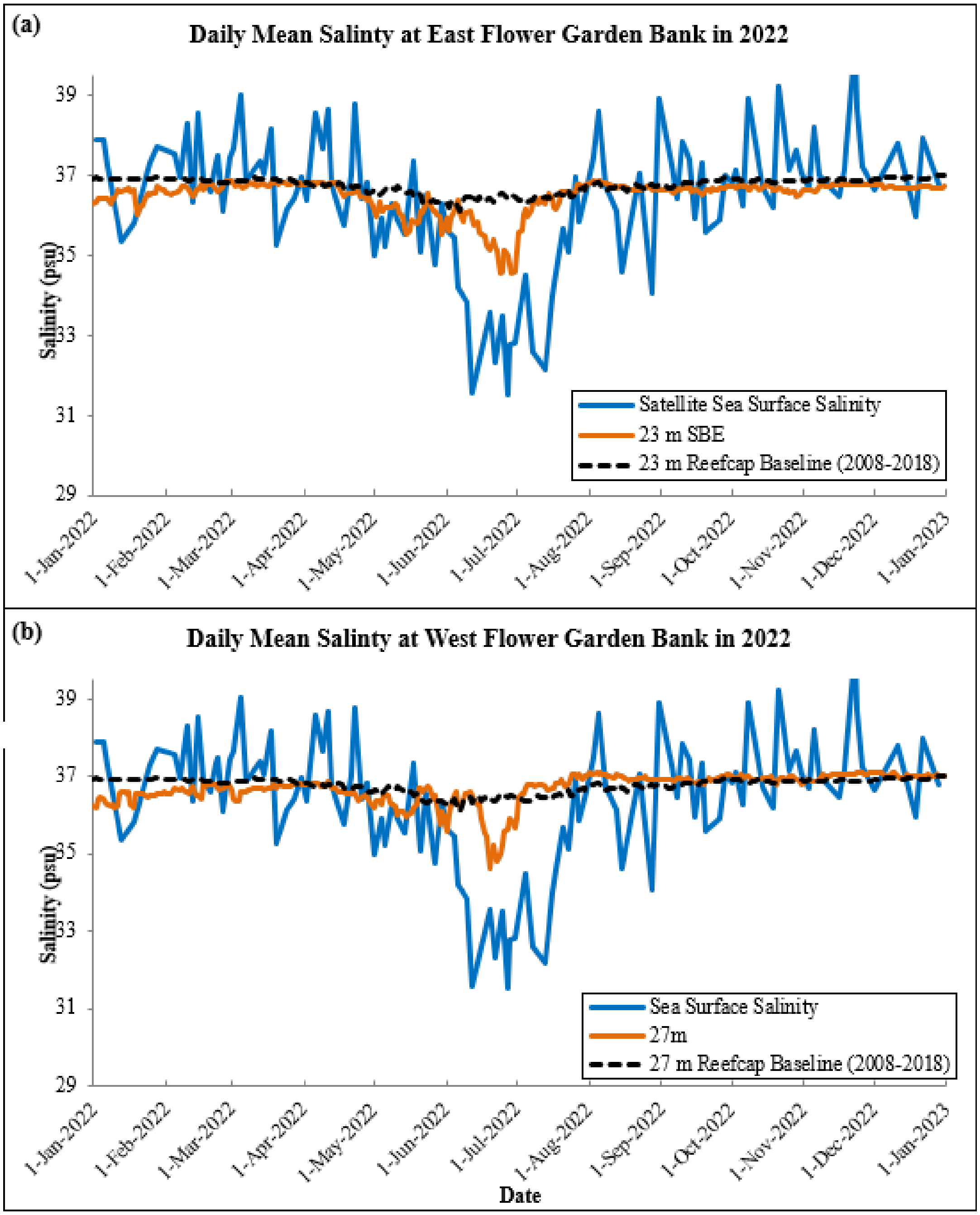


Figure 5.3. Daily mean salinity (psu) at the sea surface, SBE 16 plus reef cap station, and the reef cap 10-year daily mean salinity baseline (2008–2018) at (a) EFGB and (b) WFGB in 2022.

Salinity data obtained from loggers at EFGB (23 m) and WFGB (27 m) have been collected since 2008 with only a few data acquisition disruptions. The data show consistent summer minima, often during June and particularly in surface water, and long-term decreases in surface salinity at both banks (Figure 5.4). The Seasonal-Kendall trend test on time-series daily mean salinity data at EFGB (23 m) and WFGB (27 m) indicated a significantly decreasing, monotonic trend from 2008 to 2022 (τ = -0.42, z = -6.85, p = 0.002 and τ = -0.33, z = -5.61, p = 0.01, respectively) after adjusting for correlation among seasons.

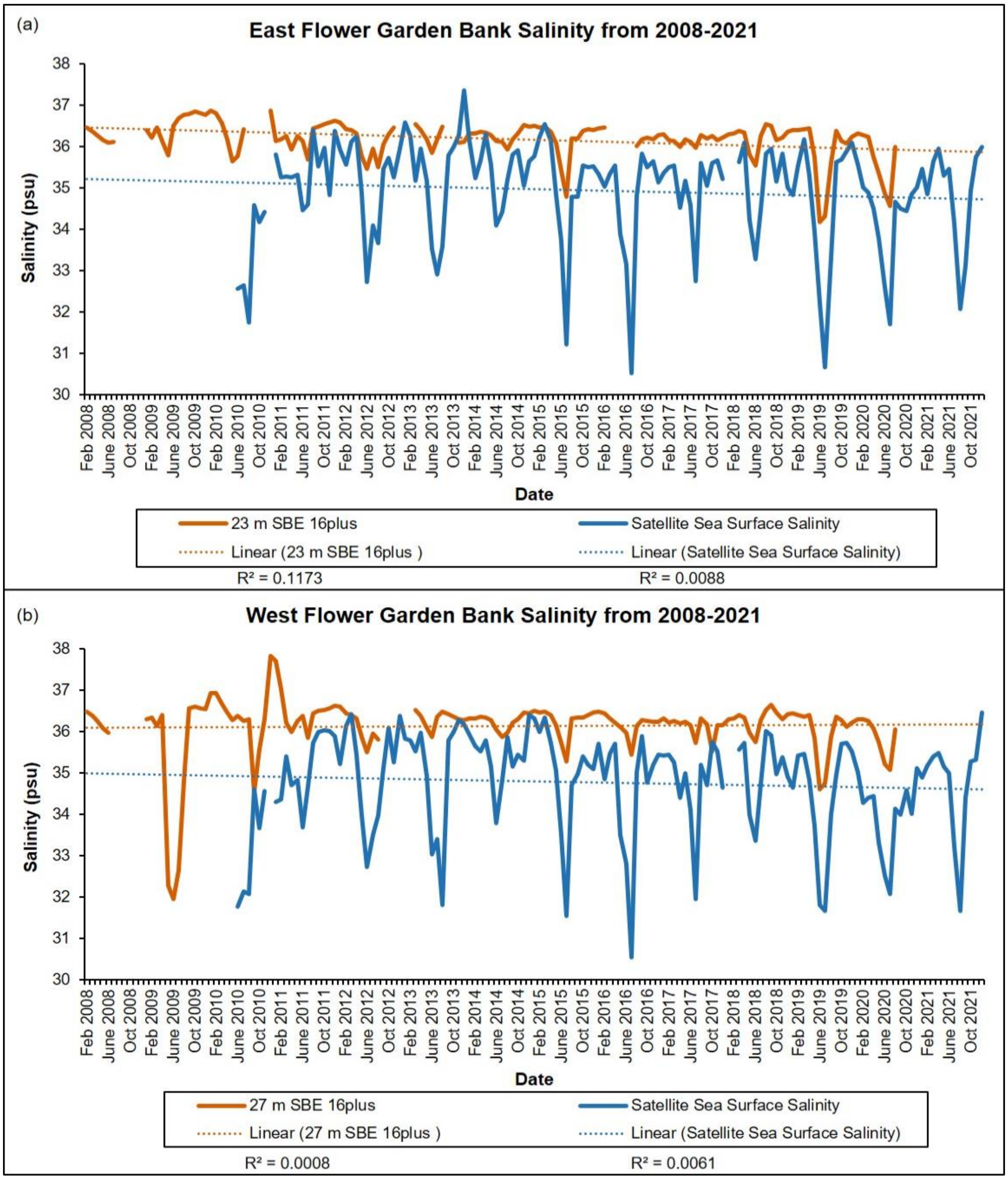


Figure 5.4. Monthly mean salinity, showing seasonal variation and long-term trends at (a) EFGB (23 m) and (b) WFGB (27 m) from 2008 to 2021.

Turbidity

The turbidity sensors at EFGB and WFGB experienced significant malfunctions, resulting in unreliable data throughout 2022. While some data were salvageable at EFGB once a new instrument was deployed, supply chain issues and challenges getting offshore resulted in no functional sensor deployment at WFGB. Therefore, data from EFGB with significant data corruption errors for this time period were removed, resulting in data gaps, and no statistical tests were conducted. Turbidity ranged from 0.12–0.46 ntu at EFGB (Figure 5.5).

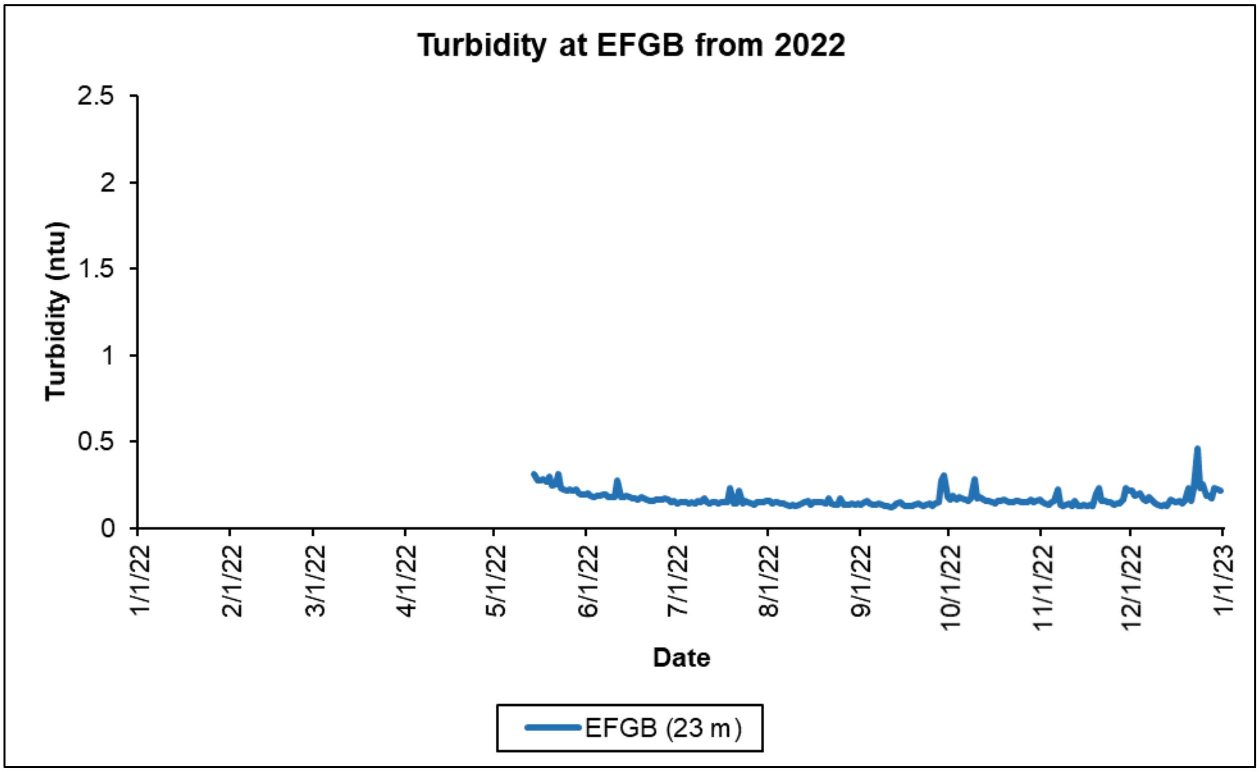


Figure 5.5. Daily mean turbidity (ntu) values in 2022 from EFGB (23 m). No data were available from WFGB due to sensor malfunction.

Water Column Profiles

Water column temperatures at the two banks during the March 2022 sampling differed by about 2 °C. There was a mild thermocline between 10 and 12 m at EFGB, though neither profile varied more than 1 °C from the surface to the reef cap (Figure 5.6). Below 4 m, other parameters suggested a well-mixed water column above the reef cap. Salinity values at the two banks were similar, varying less than 1 psu on average. DO values were variable at the surface and were stable below 4 m at both banks. Turbidity values were slightly higher at EFGB than WFGB from 4 to 6 m below the surface, but were uniform below 8 m. Fluorescence values were slightly higher at WFGB than EFGB (Figure 5.6). A mechanical error occurred with the pH sensor and it was unable to record accurate data during the profiles.

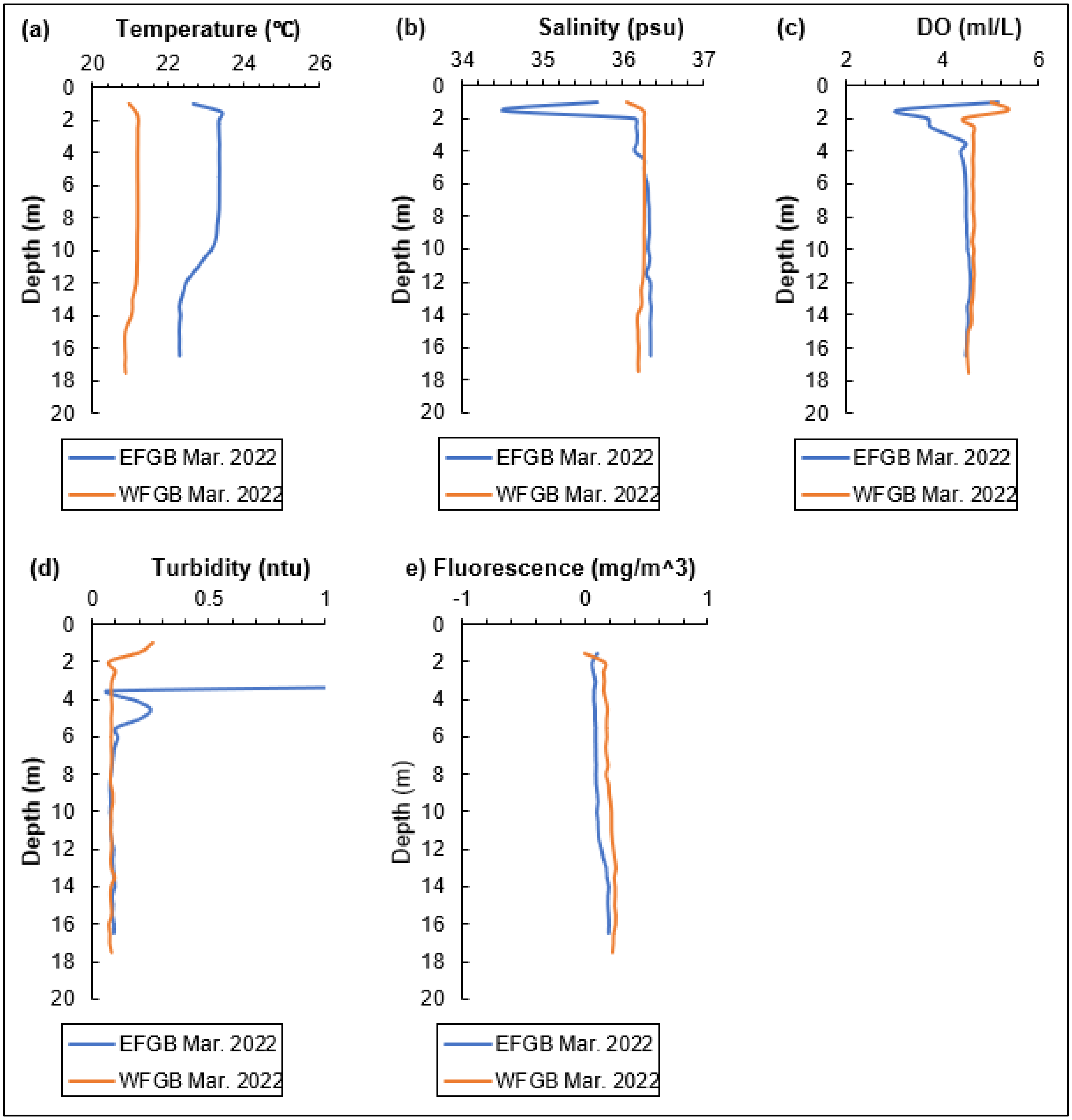


Figure 5.6. EFGB and WFGB (a) temperature, (b) salinity, (c) DO, (d) pH, (e) turbidity, and (f) fluorescence water column profile data in 2022.

Water Samples

The first chl *a* and nutrient samples were taken as part of the long-term monitoring program in 2002. Since then, quarterly nutrient levels have typically been below detection limits, with the exception of occasional ammonia and TKN detections prior to 2012 (Figure 5.7; Figure 5.8). The 2022 nutrient levels from each water column depth were below detection limits in all samples, consistent with oligotrophic oceanic conditions.

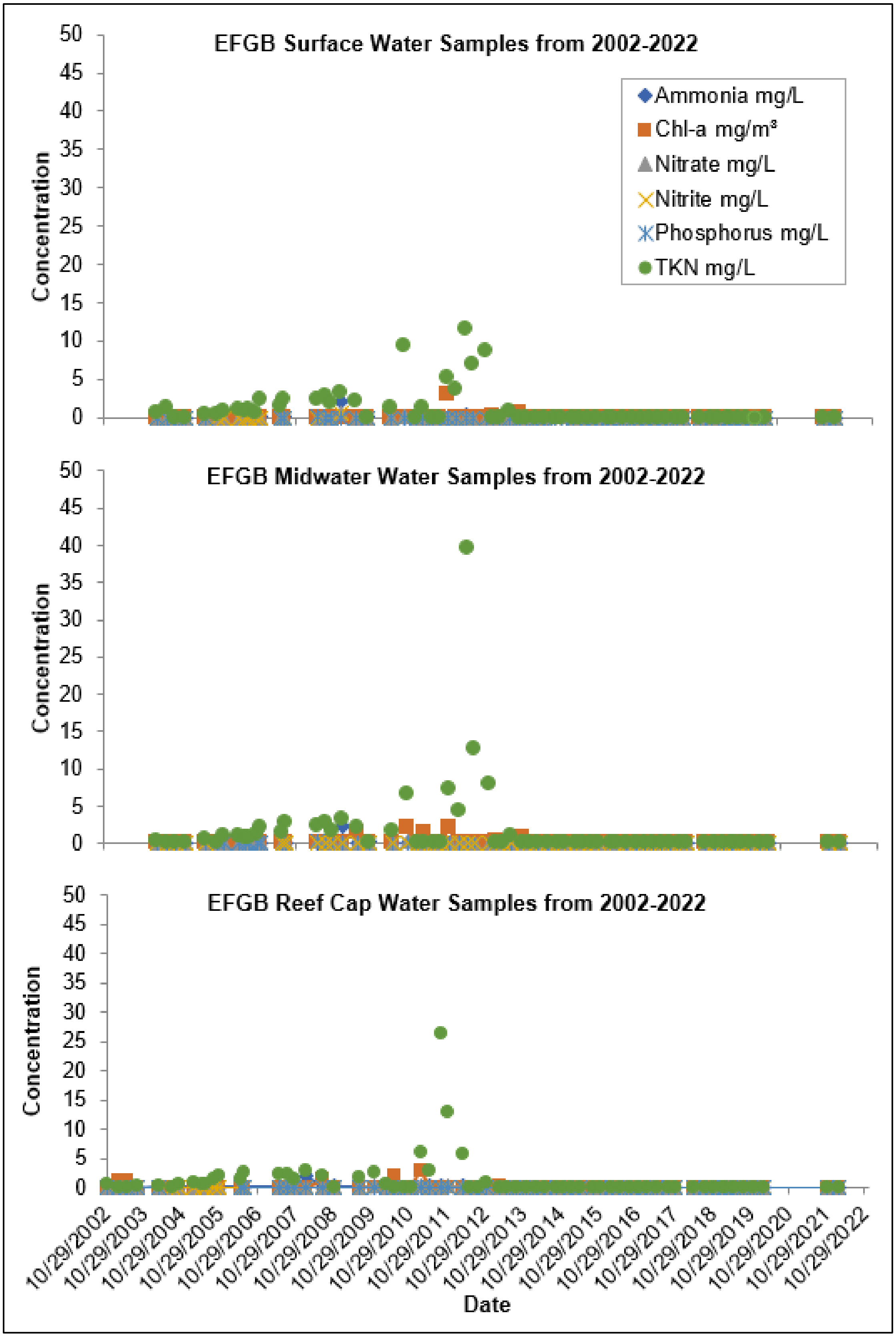


Figure 5.7. Nutrient concentrations from EFGB water samples taken at the surface (~1 m), midwater (~10 m), and reef cap (~20 m) from 2002 through 2022.

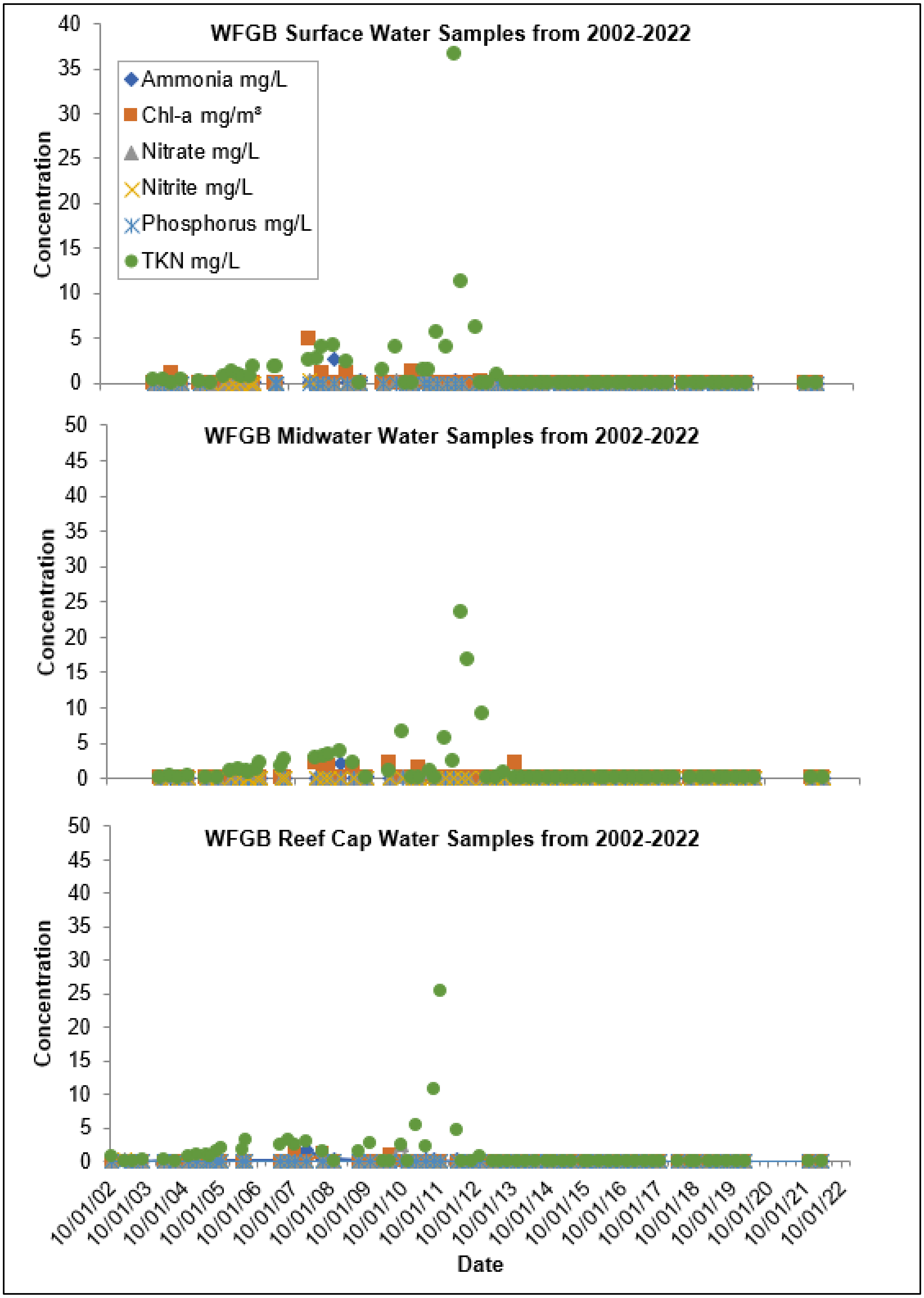


Figure 5.8. Nutrient concentrations from WFGB water samples taken at the surface (~1 m), midwater (~10 m), and reef cap (~20 m) from 2002 through 2022.

Water samples taken on March 1 and August 2, 2022 at three distinct depth gradients (approximately 20, 10, and 1 m) were submitted to CCL research partners at TAMU-CC for analysis of multiple parameters, including pH, alkalinity, pCO_2, $\Omega_{aragonite}$, and total dissolved inorganic CO_2 (DIC; Table 5.2; Table 5.3). Salinity was within a normal range for March 2022 across the system and was not recorded at either EFGB or WFGB in August. Temperatures were similar to those observed since 2013. pH and $\Omega_{aragonite}$ deviations remained fairly small in 2022 and throughout the nine-year period of carbonate chemistry monitoring. 2022 surface water pCO_2 showed less variation and a lower average compared to 2020–2021 values. The lowest pCO_2 values, where the air-sea pCO_2 gradients were greatest, corresponded to the lowest aragonite levels and the highest DIC records in March 2022 at EFGB and WFGB.

Table 5.4. EFGB carbonate sample results for 2022 at three depths. Missing values were not calculated due to the lack of in situ temperature data.

Sample Date	Depth (m)	Salinity (ppt)	Temp (°C)	pH (Total)	Alkalinity (µmol/kg)	DIC (µmol/kg)	pH in situ	$\Omega_{aragonite}$	pCO_2 (µatm)
3/1/2022	20	36.35	22.31	8.029	2395.4	2081.4	8.068	3.406	384.6
3/1/2022	10	36.34	23.31	8.040	2381.1	2055.6	8.065	3.470	383.9
3/1/2022	1	36.35	23.35	8.049	2378.7	2055.2	8.074	3.538	375.9
8/22/2022	20	n/a	29.50	8.052	2391.0	2082.0	7.985	3.741	481.5
8/22/2022	10	n/a	n/a	8.041	2396.0	2095.1	n/a	n/a	n/a
8/22/2022	1	n/a	n/a	8.048	2396.6	2095.7	n/a	n/a	n/a

Table 5.5. WFGB carbonate sample results for 2022 at three depths. Missing values were not calculated due to the lack of in situ temperature data.

Sample Date	Depth (m)	Salinity (ppt)	Temp (°C)	pH (Total)	Alkalinity (µmol/kg)	DIC (µmol/kg)	pH in situ	$\Omega_{aragonite}$	pCO_2 (µatm)
3/1/2022	20	36.18	20.84	8.016	2392.6	2089.1	8.077	3.293	376.0
3/1/2022	10	36.25	21.16	8.029	2397.0	2082.7	8.086	3.387	367.2
3/1/2022	1	36.26	21.18	8.028	2394.5	2077.5	8.085	3.378	367.4
8/2/2022	20	n/a	28.27	8.057	2391.4	2087.5	8.009	3.768	453.7
8/2/2022	10	n/a	n/a	8.065	2391.7	2079.2	n/a	n/a	n/a
8/2/2022	1	n/a	n/a	8.058	2391.4	2079.0	n/a	n/a	n/a

Water Quality Discussion

Limited water quality field work occurred in 2022 due to continued challenges related to the COVID-19 pandemic and vessel mechanical problems (see Chapter 1). Though data collection resumed in 2022, continued COVID-19 outbreaks delayed teams for a number of weeks. In August, a coral disease outbreak at EFGB and WFGB triggered the FGBNMS disease response action plan and forced FGBNMS to reprioritize field efforts. Attempts to reduce the spread of disease within the study sites took priority on all remaining trips of the 2022 season (Johnston, 2021; Johnston et al., 2023).

Seawater temperatures were warm in 2022, but in situ instruments showed that temperatures did not exceed bleaching thresholds (Johnston et al., 2019) at any time during the year.

Significantly increasing monotonic seawater temperature trends from 1990 to 2022 were detected at both banks, suggesting that ocean temperatures at FGBNMS have risen over the past three decades, increasing the likelihood of future bleaching events. No tropical storms or hurricanes that might have affected temperature regimes over the banks occurred in 2022.

Mean SSS fluctuated considerably at both banks. Reef cap salinity was below average for the first half of the sampling period but reached or exceeded the average in the second half. Significantly decreasing monotonic trends from 2008 to 2022 were detected at depth at both banks. Despite annual variation, salinity at depth was within the normal range of variation for coral reefs located in the Western Atlantic (31–38 psu; Coles & Jokiel, 1992). The probable source of low-salinity water at the banks is a nearshore river-seawater mix that occasionally extends to the outer continental shelf, emanating principally from the Mississippi and Atchafalaya river watersheds, potentially subjecting the banks to conditions usually restricted to waters closer to shore (Zimmer et al., 2010).

Laboratory analyses of nutrients remained below detection limits. TKN concentrations, however, trended upwards from 2002 to 2011. This was likely due to organic nitrogen and ammonia forming in the water column through phytoplankton and bacteria cycling within the food chain. It is therefore subject to seasonal community fluctuations, but could also be affected by both point and nonpoint sources. When present, the probable sources of nutrients in the water column were nearshore waters (Nowlin et al., 1998), sediments (Entsch et al., 1983), or benthic and planktonic organisms (D'Elia & Wiebe, 1990).

The water column connects coral reef habitats as well as aquatic and terrestrial systems. Thus, water quality data are critical components of monitoring programs, as they provide information on the incursion of land-based materials that affect critical coral reef ecosystem functions. Despite the fact that not all quarterly water quality data were collected during and following the COVID-19 pandemic (including water column profiles, nutrients, temperature, and salinity from 30 m and 40 m EFGB stations), most important surface and reef cap data were collected. The long battery life and robust sensors on moored SBE 16plus and HOBO instruments ensured large data gaps were avoided; however, the extended periods of deployment resulted in sensor malfunctions that resulted in corrupted data. The availability of satellite data also provided valuable surface information during this time period.

Chapter 6: Conclusions

A coney (*Cephalopholis fulva*) displaying a red and white bicolor variation hovers over a brain coral at FGBNMS. Photo: G.P. Schmahl/NOAA

This report summarizes field efforts for annual monitoring at EFGB and WFGB in 2022. Those efforts were affected by two significant factors. Though COVID-19 policies that restricted operations in 2020 and 2021 changed in 2022, continued outbreaks during the 2022 field season delayed cruises. Furthermore, the August 2022 coral disease outbreak at EFGB and WFGB forced FGBNMS to prioritize disease sample collection and attempt to reduce the spread of disease within the study sites (Johnston et al., 2023).

Fortunately, repetitive photostations, which have been sampled annually since 1989, were invaluable during the disease outbreak, allowing divers not only to continue collecting annual monitoring data, but also to calculate and track disease prevalence on the reef (Johnston et al., 2023). The disease event was also an important test of the FGBNMS disease preparedness plan (Johnston, 2021). It showed that, regardless of the etiology of the disease (stony coral tissue loss disease, a type of white plague, or another disease), the response framework allowed resource managers and research partners to respond efficiently, document the event, and collect samples for diagnostic analyses (Johnston et al., 2023).

Reef-wide transect surveys (in partnership with NCRMP) were conducted for the first time in 2022 as part of the long-term monitoring program, allowing for benthic cover calculations in a random stratified design across the reef caps, not just the study sites. Although coral cover in repetitive photostations and random transect surveys is not comparable, the former is critical in enabling researchers to track individual locations over time (especially during extreme events such as the disease outbreak). The long-term monitoring program benefits from having both random benthic surveys and repetitive monitoring stations.

The reef fish community, which is numerically dominated by the families Labridae and Pomacentridae, has a biomass distribution that is uniform across large and small individuals, with piscivores having the greatest mean biomass among trophic guilds at both EFGB and WFGB. Horse-eye jack dominated the piscivores within EFGB surveys, while great barracuda dominated at WFGB. No manta rays, non-native regal demoiselles, or invasive lionfish were observed in long-term monitoring surveys, though these species are known to occur on each bank.

Seawater temperatures on the reef cap did not exceed 30 °C for 2022 (though satellite data suggested brief exceedances in surface waters), and coral bleaching/paling was observed to be less than 2%. However, a significantly increasing seawater temperature trend from 1990 to 2022 was detected at both banks, suggesting that bleaching events will most likely occur in the future. Salinity and nutrient loads on the reefs were nominal during 2022, and carbonate chemistry indicated that the area acted as a net CO_2 sink.

The FGBNMS long-term monitoring program is one of the longest running coral reef monitoring efforts in the world. For over three decades, it has been a critical tool for understanding the drivers of ecosystem variation at the Flower Garden Banks (Karnauskas et al., 2015). It has also helped FGBNMS and other authorities to preserve the characteristics that sustain the banks' health, and has alerted managers to ongoing and impending changes, enabling timely responses and actions. The monitoring program has been a guiding force for both conservation science and informed management since it began, and continues to support sanctuary education and outreach programs. And while monitoring is sounding alarms about concerning changes, particularly with regard to climate change, it has also provided a target and highlights the possibility that struggling coral reef ecosystems elsewhere in the world could be nurtured back to health by restoring the environmental conditions that characterize FGBNMS.

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Glossary of Acronyms

ANOSIM	analysis of similarity
BOEM	Bureau of Ocean Energy Management
CCA	crustose coralline algae
CCL	Carbon Cycle Laboratory
chl *a*	chlorophyll *a*
CPCe	Coral Point Count® with Excel® extensions
CTD	conductivity, temperature, and depth
DIC	dissolved inorganic carbon
DO	dissolved oxygen
EFGB	East Flower Garden Bank
EPA	Environmental Protection Agency
FGBNMS	Flower Garden Banks National Marine Sanctuary
NCRMP	National Coral Reef Monitoring Program
NOAA	National Oceanic and Atmospheric Administration
PCO	principal coordinates ordination
pCO_2	partial pressure of CO_2
PERMANOVA	permutational multivariate analysis of variance
QA/QC	quality assurance/quality control
SE	standard error
SIMPER	similarity percentages
SSS	sea surface salinity
SST	sea surface temperature
TAMU	Texas A&M University
TAMU-CC	Texas A&M University Corpus Christi
TKN	total Kjeldahl nitrogen
WFGB	West Flower Garden Bank

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