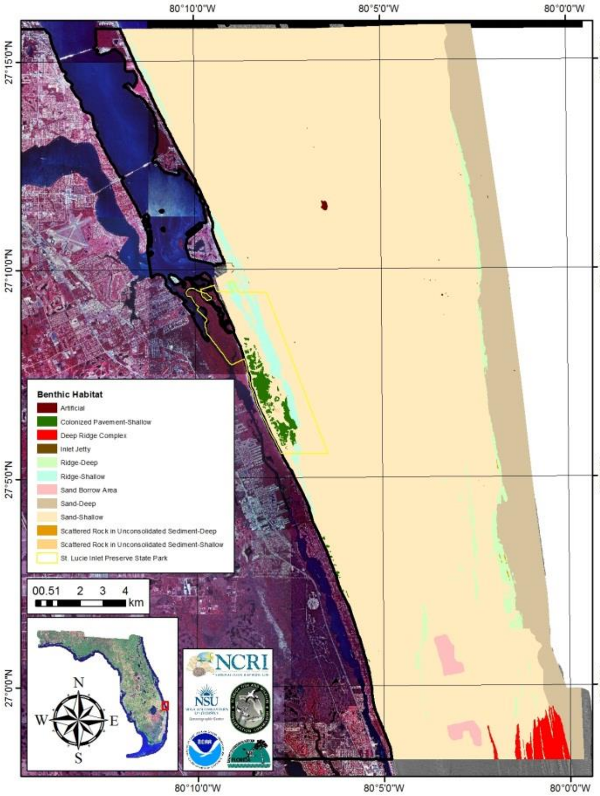
Final Report

(August 30, 2008 - December 1, 2012)

Characterizing and Determining the Extent of Coral Reefs and Associated Resources in Southeast Florida through the Acquisition of High-Resolution Bathymetry and Benthic Habitat Mapping

FWC AGREEMENT NO. 08014



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EXECUTIVE SUMMARY

Effective marine resource management begins with knowing the distribution of resources within the region. Minimal data, and thus limited knowledge, exists about the reef resources of Martin County. The marine benthic habitats in Martin County need to be mapped to characterize and quantify the distribution of its coral and other benthic communities, therefore, the Florida Department of Environmental Protection – Coral Reef Conservation Program, FL Fish and Wildlife Research Institute and the National Coral Reef Institute at Nova Southeastern University have partnered to expand upon previous mapping efforts to identify and classify the benthic habitats in the southeast Florida region (Miami-Dade, Broward, Palm Beach, and Martin Counties). The maps will provide critical information needed to understand the extent of the coral reef habitat throughout Martin County and the southeast Florida region. They will enable managers to enforce impact avoidance and assist in the development of conservation action strategies.

Updating the existing maps is also essential to the region to monitor changes to the resources and provide current data for management decisions. Southeastern Florida has a very dynamic marine system influenced by high energy weather systems (e.g. hurricanes), ship groundings, various construction projects, and artificial reef deployment which change the morphology of the sea floor and thus affect the benthic habitats. Existing Broward benthic habitat maps were drawn based on 2001 LIDAR data, therefore a new LIDAR survey in Broward County will facilitate updating these maps.

The Broward LIDAR dataset was collected by Tenix LADS Inc. between July and August 2008. The data were obtained and processed into high resolution hill-shaded topographic maps. Detailed information regarding this survey can be obtained by contacting Ken Banks at Broward County’s Environmental Protection and Growth Management Department Natural Resources Planning and Management Division.

The marine benthic habitats in Martin County were mapped using the same combined technique approach as was done in the other southeast Florida counties (Walker, Riegl, and Dodge 2008). The mapping area extended seaward from shore to the 30 m depth contour where possible and covered an area of ~350 sq km. Image-based analyses in deeper water were not ideal in Martin County due to poor water clarity; therefore, a high resolution (4 m) LIDAR bathymetric survey was conducted to image the sea floor. This effort was conducted in two phases. Phase 1, where a LIDAR bathymetric survey of the seafloor was conducted, and Phase 2 where habitat maps were created by outlining and defining the features within the bathymetric survey.

Phase 1 mapping began when the project area in Martin County was flown in December 2008 by Blom Aerofilms, Ltd. LIDAR for the project area was acquired over a period of four days and included both topographic and bathymetric LIDAR as well as vertical aerial imagery. These data were processed by Blom. Deliverables for the project included cleaned point cloud, DTM 5m grid, hillshaded geotifs, seabed reflectance data, and 25cm GSD orthophotos.

Gaps in the initial LIDAR data coverage were evident mainly due to poor water quality, temporal, and meteorological conditions. Of the total 341.5 km² surveyed, 51.5 km² contained data holidays and coverage gaps; 15% of the total survey area. Therefore Blom Aerofilms re-flew the areas with major gaps in December 2009 coincident with other work in the United States. The re-flights included a collection of similar data types. The re-flight scheduling and data processing significantly delayed the project, thus a no-cost extension was granted by FWC to extend the project to December 2012.

Benthic habitat maps were produced by delineating seafloor features evident in multiple datasets including the 2008 and 2009 high resolution LIDAR bathymetry and aerial photography collected from Phase 1. Phase 2 started in April 2010 and continued until August 2012. The habitats were classified

according to established NOAA guidelines in coordination with the NOS Coral Mapping Program and use a similar classification scheme when possible.

Of the 374 km² seafloor mapped in Martin County, the polygon totals indicated 95.2% was Sand, 4.1% was Coral Reef and Colonized Pavement, and 0.7% was Other Delineations. The Martin County benthic habitat morphology is very different than the other counties further south. Hardbottom habitats are sparse outside of a shallow, near shore area around St. Lucie Inlet and a few thin deep ridge lines which taper or are buried further north. All of these features are thought to be cemented beach dunes submerged during the last Holocene sea level transgression. Although not confirmed by coring, they do not appear to be composed of a coral-derived framework and they do not exhibit any morphologic signs of historic reef growth like the spur and groove formations of the Outer Reef which terminates in Palm Beach County near Lake Worth inlet (Banks et al. 2007; Walker 2012).

The most extensive, deep hardbottom was the northern end of the Deep Ridge Complex which extends from Palm Beach into southern Martin for about 2 km before it appears to be covered with sediments. Only small, thin portions of the tallest ridges are exposed further north. In southern Martin there are three shore-parallel deep ridge lines. The first deep ridge, nicknamed Three Holes, is located approximately 2 km from shore in 18 m water depth and extends approximately 3.5 km northward in a mostly continuous arrangement. The second deep ridge appears at the same latitude that Three Holes terminates, but it is approximately 6 km from shore in 22 m of water. This feature extends northward in a mostly continuous fashion for about 6 km. The third deep ridge, nicknamed 7-Mile Ledge, is the most conspicuous deep hardbottom feature. Despite its name, in southern Martin this feature is located approximately 6 km (~ 4 miles) from shore in 22 m of water. This is also its widest portion at just about 0.5 km. This ridge extends northward over 23 km with relatively few (4) small breaks or gaps. At its northern terminus, it is located about 12.8 km (8 miles) from shore in 25 m water depth.

Shallow hardbottom habitats extended throughout much of the county, but the majority of the habitat existed near St. Lucie inlet. This was comprised of two habitats, Colonized Pavement-Shallow and Ridge-Shallow. The differences between their delineations were mainly morphological. The Ridge-Shallow has an obvious linear morphology and usually contains higher relief, at least at larger scales. The Colonized Pavement-Shallow is typically lower relief and has no distinct linear morphology. The shallow Martin County ridges extend 2.5 km north of the inlet and 11.5 km south in a shore-parallel orientation. The eastern side resides in about 10 m depth, it crests near 3 m and the western side remains shallow in some parts and drops back to 10 m in others. The shallow colonized pavement is located westward of the shallow ridge in waters 10 m to 4 m deep, sloping upward toward shore. As with other features along the northern Florida Reef Tract, these ridges terminate at the shoreline. The northern terminus is known as Bath Tub Reef and the southern end slips under the shoreline just off Bridge Road on Jupiter Island. Small portions of shallow ridge appear north of the inlet off Jensen Beach. These appear to be ephemeral communities affected by high wave energy and shifting sediments. Beach construction, storm activity, and natural littoral drift all have an effect on the type and arrangement of near shore sea floor habitats and depending on their magnitudes may cause large-scale changes through time.

Approximately 357 km² were identified as unconsolidated sediments that contained different sediment features that were not part of the mapping. The most evident features were large sand dunes throughout the county extending to the northeast. In the south, these dunes appear to be partially or totally burying portions of deep ridge habitats. Elevation profiles revealed these features were up to 11 m high extending over 2.25 miles wide. Little is known about the movement of these features, but given the dynamic environment and the frequently high currents, it is likely that they are migrating across the seafloor, including over the deep ridges.

In collaboration with FWC, FDEP-CRCP, and NCRI, NOAA funded quantitative ground truthing to provide a rigorous determination of habitat types beyond qualitative efforts and valuable information about the composition of the benthic communities for resource management. This was accomplished in August 2012. Data were collected on 16 sites: 7 Ridge-Deep sites, 5 Ridge-Shallow sites, and 4 Colonized Pavement-Shallow sites. The sites were distributed across the seascape as much as possible to provide data on all the main hardbottom habitats and account for latitudinal variation.

A cluster analysis and corresponding non-metric, multi-dimensional scaling (MDS) plot showed that the sites were more similar than not, yet subtle distinctions were evident when the sites were categorized by habitat. The Ridge-Deep sites all plotted on one side of the graph and the two shallow habitats on the other, showing there are likely differences between shallow and deep habitats. Furthermore apart from one site, colonized pavement and ridge did not cluster, indicating a wide range of benthic communities between shallow sites.

A summary of the mean percent cover data by habitat showed many differences in cover. Turf algae were more abundant on the shallow colonized pavement (41.4% ± 11.1) and ridge (52.4% ± 19.6) than the deep ridge (19.1% ± 9.5) and vice versa for cyanobacteria. Cover varied greatly within habitat categories and most cover types were low (> 5%) making it difficult to detect differences at the habitat level. Although percent cover between habitats was muddled by within-habitat variability, the number of biotic cover categories (e.g. macroalgae, hydroids, coral) were significantly different. Colonized Pavement-Shallow had significantly fewer biotic cover categories (5.5 ± 0.96 SEM) than the Ridge-Shallow (7 ± 0.45 SEM) and Ridge-Deep (7.4 ± 0.72 SEM). The number of biotic categories ranged from 4 to 8 on the Colonized Pavement-Shallow, from 6 to 8 on the Ridge-Shallow, and from 4 to 9 on the Ridge-Deep. This indicates the shallow colonized pavement may have less taxonomic diversity than the other habitats.

Rugosity significantly varied between habitats. The Ridge-Shallow mean rugosity significantly higher than the Colonized Pavement-Shallow which was significantly higher than the Ridge-Deep. This result was not surprising because feature relief (albeit at a larger scale) was one of the main criteria used to distinguish between the two shallow habitats.

Although univariate differences between habitats were found (e.g. MDS separation, rugosity, number of biotic categories), multivariate differences of cover types and amounts among sites were not statistically strong between the habitat categories. A one-way analysis of similarity (ANOSIM) was performed to statistically determine the strength of the site categorization by habitat. The strongest result was between the Ridge-Deep and Ridge-Shallow indicating these were most different and supporting the MDS results, however the difference was not very strong. Furthermore the results between Deep-Ridge and Colonized Pavement-Shallow and between Colonized Pavement-Shallow and Ridge-Shallow were very weak.

The lack of strong ANOSIM groupings was likely due to not distinguishing between algal species. Although no species data were collected, it was recognized anecdotally that the algal communities between the deep and shallow hard bottoms were distinct. Previous research showing distinct differences in the macroalgal communities in southeast Florida supports these observations (Lapointe 2007). Lapointe's data show that shallow ridge sites had a large component of Phaeophyta cover (> 50% during certain times) that was not present in the deep habitats, where Chlorophyta was dominant. This was further exemplified by the five sites on the Deep Ridge Complex in north Palm Beach that were dominated by Chlorophyta and Rhodophyta and had very little Phaeophyta if any. Therefore, if macroalgal communities were distinguished in the Martin County quantitative ground truthing, it is likely that the cluster analysis between habitats would have been much more robust.

The MDS plot scatter indicated there may be a cross-shelf pattern to the communities in the Nearshore Ridge Complex ((NRC) combination of Ridge-Shallow and Colonized Pavement-Shallow habitats). A site located on the eastern side of the shallow ridge had a distinct community comprised mostly of macroalgae, turf algae, and palythoa. Sites associated with the shallowest top portion of the ridge (the crest) were most similar to each other. And all of the other shallow sites located on the western side of the shallow ridge grouped in a central axis. It is likely that the distinct ridge profile is providing different conditions across the shelf that are shaping the benthic communities. This could account for larger within-habitat variations because the shallow ridge was not divided into separate habitats to account for the differences across the fore-ridge, crest, and back-ridge.

Stony corals were assessed on the benthic cover transects to gain a better understanding of their distributions and condition throughout the Martin County reef system. A total of 553 colonies were identified, counted, and measured. Nine species were found, but *Siderastrea siderea* (80.3%) and *Oculina diffusa* (15.9%) completely dominated the populations. Stony coral density for the entire county out of 1737 m² surveyed was 0.32 m^{-2}, equating to a coral every 3.1 m². Although many corals were counted, their total size was small. The estimated total area of live tissue (max length * max width – ((max length * max width) * percent total mortality)) for all 553 colonies was 2.8 m². Three species accounted for 97.7% of the total live coral tissue in the transects; *Diploria clivosa* (42.9%), *Siderastrea siderea* (30.2%), and *Oculina diffusa* (24.6%). Although only 8 Diploria colonies were counted, they were the largest colonies and thus accounted for the most live tissue area. Mean max length of most species ranged between 6 and 13 cm, whereas *Diploria clivosa* averaged 39.1 cm. Interestingly, *Siderastrea siderea* had the smallest mean length (4.7 cm), yet was the second highest contributor to live tissue area because of its high numbers (444).

The accuracy assessment of the Martin County major habitats yielded a high level of accuracy as indicated by the overall accuracy (85.6%), the overall accuracy adjusted for known map marginal proportions (adjusted accuracy) (94.9%), and the Tau coefficient (0.713), which adjusted for the number of map categories. Of the 26 classification errors (which excluded artificial sites), 24 were due to Unconsolidated Sediment being found in polygons classified as Coral Reef/Colonized Hardbottom. This yielded a low producer's accuracy (63.1%) for soft bottom, however correction to map marginal proportions yielded a much higher result (99.4%). The converse was also true where a high producer's accuracy for hardbottom (98.3%) was drastically reduced by map proportions (37.8%) due to its low spatial coverage.

The overall accuracy for major habitat was similar to other regional mapping efforts. Overall map accuracy in Martin was less than Broward (89.6%) (Walker et al. 2008), Palm Beach (89.2%) (Riegl et al. 2005), and Miami-Dade (93.0%) (Walker 2009), however it was higher than all of them after adjusting for map marginal proportions. The other mapping efforts did not account for this, but it is an important aspect in Martin County given the disparity between hard and soft bottom areas. Soft bottoms comprised 95.2% of the entire mapped area and hard bottoms only 4.13%. This is much different than Palm Beach (63.9% soft, 35.02% hard), Broward (46.8% soft, 54.2% hard), and Miami-Dade (50.47% soft, 29.65% hard) and likely had a profound effect on the outcome. The map marginal proportion correction is a necessary adjustment in this case and likely captures the true map accuracy better.

The detailed Martin habitats were mapped at a similar level of accuracy, albeit slightly lower than major habitat, as indicated by the overall accuracy (85.0%), the overall adjusted accuracy (91.5%), and the Tau coefficient (0.828). The overall accuracy was 5.5% less than that reported for Miami-Dade (Walker 2009), yet it was 1% higher after correcting for map marginal proportions.

Recent analyses of the spatial distributions of habitats along the southeast Florida coast identified five coral reef ecosystem regions and potential biogeographic boundaries ending in southern Martin County (Walker, 2012). The addition of the Martin County maps allowed for further differentiation in the system, therefore, the new map data were analyzed by the same procedure and included in a new spatial assessment for coral reef ecosystem regions. This assessment statistically analyzed the amount and type of habitats along the coast to derive regions where the number of habitats and their morphology were most similar. Cluster analysis of the 248 cross-shelf transects spread evenly from Miami-Dade through Martin yielded thirteen clusters at the 60% similarity level. These were plotted in GIS to evaluate spatial consistency. The transects in Martin were members of five MDS clusters, however all but Cluster B were exclusive to the Martin area. The Biscayne, Broward-Miami, and South Palm Beach region MDS clusters showed spatial groupings consistent with Walker 2012. The North Palm Beach transects clustered into a few groups that were also spatially clustered. The Deerfield region, which was the weakest result in the previous study, was not evident in this analysis.

The spatial analyses indicated that the seafloor habitat morphology in Martin is distinctly different. In contrast to reef regions further south where coral reef habitats ranged from 13.93% (South Palm Beach) to 52.6% (Broward-Miami) (Walker, 2012), the Martin area contained 4.1% coral reef habitat, most of which was spread throughout the county in a few thin deep and shallow ridges. Martin also has a unique biological composition from other areas of the FRT. Previous research shows distinct differences in the macroalgal communities (Lapointe, 2007) and stony coral communities (Gilliam 2010, Gilliam et al. 2010) in southeast Florida, including 88% lower coral densities and 64% fewer species. For these reasons, a sixth biogeographic coral reef ecosystem region was created north of the North Palm Beach region to distinguish the Martin area.

ACKNOWLEDGEMENTS

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INTRODUCTION

In 1998, the United States Coral Reef Task Force (USCRTF), comprised of federal, state, and territory partners, was established by Presidential Executive Order 13089 to coordinate government efforts to protect, restore, and sustain coral reef ecosystems. In 2002, the USCRTF developed a *National Action Plan (NAP)* to address the growing coral reef crisis. The Plan outlines 13 integrated conservation strategies (goals) within to address the most pressing challenges facing reefs today. The first goal in the NAP is to produce comprehensive digital maps of all shallow coral reef ecosystems in the United States and characterize priority, moderate-depth reef systems by 2009.

With guidance from the US Coral Reef Task Force, resource agencies, the scientific community and the general public, in 2004, the Florida Department of Environmental Protection's Coral Reef Conservation Program (FDEP-CRCP) completed development of a Local Action Strategy (LAS) targeting four threat areas as the focus for immediate action to protect the reefs of southeast Florida. Named, the Southeast Florida Coral Reef Initiative (SEFCRI), a priority goal of the LAS is to determine the extent and condition of the coral reef ecosystem in Miami-Dade, Broward, Palm Beach, and Martin counties – collectively, the southeast Florida region.

The Florida Fish & Wildlife Research Institute (FWRI) has been mapping benthic habitat, including corals, since the early 1980's. These mapped data, stored in FWRI's Geographic Information System, have proved extremely useful to natural resource managers who need to know the location and extent of different habitats to make decisions on issues such as permitting, damage assessment, water quality sampling, and even the delineation of marine protected areas. In the past, this work was focused in the Florida Keys, Biscayne Bay and Florida Bay, where coral cover is greater, and the awareness of coral reefs was higher. Although it is known that coral reefs and coral communities extend northward in the coastal waters off Florida's eastern seaboard through Martin County, until recently, these reef resources received little attention. The southeast Florida benthic habitat mapping completed thus far has been invaluable in documenting the extent and supporting the management of wildlife resources. These coral reef communities are under extreme anthropogenic development pressures and these maps enable managers to enforce impact avoidance. For example, a GIS evaluation of the nearshore anchorage at Port Everglades has enabled resource managers, commercial interests, enforcement agencies, and scientists to agree on an amendment of the anchorage configuration to help lessen the occurrence of ship groundings and reef impacts by ship anchors (Walker 2010). The data are also being used by resource managers to guide decisions on many proposed construction activities and their associated environmental impacts in the area. Once complete, the Martin County mapping data will complement the other mapping efforts and complete the picture of southeast Florida reef resources. The region-wide understanding of the benthic habitats will be used to improve monitoring efforts, resource protection and management decisions.

Effective marine resource management begins with knowing the distribution of resources within the region. Benthic habitat mapping via geographic information systems (GIS), a process by which remote sensing data are interpreted into seafloor habitats, provides this valuable information. Globally, benthic habitat mapping has been employed in many coral reef ecosystems, utilizing many techniques and data types including the interpretation of aerial photography, satellite imagery, bathymetric data, or a combination thereof. Currently in the United States alone, most of the shallow-water (< 30 m) coral reef habitats have been mapped using these techniques.

Coral reefs thrive in warm tropical waters, thus much of the coral reef habitat mapping has focused on tropical and subtropical areas with little regard for higher latitude temperate regions even though coral communities may be present. Recently attention is being focused on higher latitude coral regions to investigate possible range expansions and ecosystem shifts due to global warming (Yamano et al. 2011).

A prime region to study such effects is in southeast Florida, where the third largest barrier reef ecosystem in the world resides, the Florida Reef Tract (FRT).

The FRT spans approximately 595 km of linear coastline from the Dry Tortugas in the southwest to Martin County in the Northeast. The 135 km southern portion resides in an east-west orientation mostly at the same latitude (24.5° N) before it hooks northeast over a 245 km span (25.5° N). Then it extends 215 km north to 27.25° N. This northern extension transitions from a tropical to temperate Holdridge Life Zone (Lugo et al., 1999) where several estuarine biogeographic zones have been identified (Engle and Summers, 1999). Recent analyses of this northern extension identified several biogeographic spatial barriers where the number of benthic habitats attenuated northward along the coast and various habitat metrics differed significantly between 5 sub-regions (Walker, 2012). Most of the shallow-water FRT benthic habitats have been mapped (Walker, 2012, FMRI, 2000); however minimal data and limited knowledge exist about the reef communities of its northernmost reaches off Martin County.

The marine benthic habitats in Martin County need to be mapped to characterize and quantify the distribution of its coral and other benthic communities. Martin County is the northern limit of shallow water reef building corals along the southeast Florida reef tract and has been given little attention in the past. Recently, other high latitude coral reef ecosystems have documented latitudinal shifts in reef species in response to climate change (Yamano et al. 2011). Furthermore, changes in the water flow out of the St. Lucie River from the Everglades restoration project are expected that may potentially provide a positive impact on the recruitment of reef building corals and reef development in the next several years. Baseline documentation of these coral communities is critical to understand the ecosystem’s response to the changing environment.

The FDEP-CRCP, FWRI and the National Coral Reef Institute at Nova Southeastern University (NSU-NCRI) have partnered to expand upon previous mapping efforts to identify and classify the benthic habitats in the southeast Florida region. This region includes four counties: Miami-Dade, Broward, Palm Beach, and Martin. Mapping completed through this partnership to date includes benthic habitat maps for Miami-Dade, Broward, and Palm Beach Counties. This study maps and characterizes the seafloor in Martin County to provide benthic resource data. First benthic habitat mapping was conducted using newly-acquired high resolution LIDAR bathymetry and aerial photography where possible to map the spatial extent of coral reef habitats. The maps were tested for accuracy and quantitative data were collected to characterize benthic cover and stony coral demographics. The benthic mapping data were then analyzed in the habitat biogeographic context of Walker (2012) to determine if a new coral reef ecosystem region designation is warranted.

Updating the existing maps is also essential to the region. Southeastern Florida has a very dynamic marine system influenced by high energy weather systems (e.g. hurricanes), ship groundings, various construction projects, and artificial reef deployment. These events change the morphology of the sea floor and thus affect the benthic habitats. It is not uncommon for hardbottom areas to become buried or exposed by unconsolidated sediments due to storm activity (Gilliam et al. 2008). Ship groundings can reshape large areas of the sea floor on the scale of 1000’s of square meters (Walker et al. 2012). Dredging projects can remove large amounts of sediment for beach construction projects. And artificial reef deployment, whether for mitigation, enhancement, or tourism, can also change the shape of the seafloor. Broward County regularly updates their coastal bathymetry maps to monitor changes to the resources and provide current data for management decisions. In 2008, Broward County flew high-resolution hydrographic survey of the County’s offshore area using a Laser Airborne system covering the entire Broward County offshore region from the surf zone to a depth of 120 feet (40 meters). This survey updates the last LIDAR data collection taken in 2001. These data are needed due to the large number of changes in the region over the past seven years, including many large energy events, ship groundings, construction projects, and artificial reef deployments. The new bathymetry facilitates updating the existing benthic habitat maps based on the 2001 data.

All of these data not only provide new information on the little-studied benthic community composition, but they also serve as a baseline for future community shift and range expansion investigations, assist resource managers in the development of conservation action strategies, and enable impact avoidance enforcement. The maps created from this project will provide critical information needed to understand the extent of the coral reef habitat throughout Martin County and the southeast Florida region, while meeting the priority goals of the US Coral Reef Task Force’s National Action Plan, and the Southeast Florida Coral Reef Initiative. The maps will enable managers to enforce impact avoidance as well as assist in the development of action strategies to conserve reef resources.

METHODS

The marine benthic habitats in Martin County were mapped using the same combined technique approach in the other southeast Florida counties (Walker et al. 2008). Image-based analyses in deeper water are not possible in Martin County due to poor water clarity; therefore, a high resolution (4 m) Light Detection and Ranging (LIDAR) bathymetric survey must be conducted to image the sea floor. This effort will be conducted in three phases. Phase 1 is to conduct a bathymetric survey of the seafloor, Phase 2 habitat mapping is to outline and define the features within the bathymetric survey, and Phase 3 (if funded) will then be conducted to map the densities of organisms with the Phase 2 features. The area to be mapped extends seaward from shore to the 30 meter depth contour where possible and covers an area of ~350 sq km. Only Phases 1 and 2 are currently funded for the Martin County project. A LIDAR bathymetric survey will also be flown for Broward County to update its current maps.

Martin County

Phase 1.—Phase 1 entailed the collection of high resolution bathymetry using Light Detection and Ranging (LIDAR) for an area of heterogeneous benthic habitats to approximately 30 m water depth or LIDAR extinction along the coastal zone of Martin County, Florida. Blom Aerofilms Ltd. was subcontracted by Nova Southeastern University to conduct the LIDAR survey for Martin County. This section was adapted directly from Blom Aerofilms’ report.

General.— The survey proceeded according to the detailed method statement provided in this document. Any of the documents referenced below in this detailed section are available on request from Mr. Julian Millard, the Blom Aerofilms Quality Manager. The basic project parameters were as follows:

Table 1. Project Parameters.

Geodetic Parameters:	
Horizontal Datum	NAD 83
Spheroid	GRS80
Mapping Projection	UTM Zone 17 N
Vertical Datum	NAVD88
Geoid Model	GEOID03
Areas of Interest:	
Martin County	350km²
Survey Parameters:	
Altitude of flight	400m
Flying Speed	150 kts
Flight line spacing	200 m (approximate)
Post spacing (Sea)	4m x 4m nominal per flight line
Post spacing (Land)	1m x 1m nominal per flight line
Accuracy:	
Horizontal accuracy (Bathy)	+/- 2.50m rmse
Horizontal accuracy (Topo)	+/- 0.50m rmse
Vertical accuracy	+/- 0.25m rmse

Deliverables for the project.— The deliverables for this project were as agreed in the project specification and were as outlined in the table below:

Table2. Project deliverables.

Item	Description	Tile Size	Format
1	Cleaned point cloud	5km x 5km	ASCII*
2	DTM 5m grid	5km x 5km	ASCII*
3	Hillshaded geotifs	Single Image	.TIFF
4	Seabed reflectance data	by Flightline	ASCII
5	25cm GSD orthophotos	5km x 5km	.TIFF
6	Report of survey	Hardcopy / digital	.PDF

* ASCII x,y,z, comma separated format as “Lat,Long,Ht,” format.

Flight planning and aircraft mobilization.— Blom Aerofilms Limited obtained the relevant permits from the US authorities and got flight clearance for the areas required. Flight planning was carried out using AHAB Operator Console software.

The aircraft was mobilized from Miami near the BNP survey area. With this in mind a provisional data acquisition date of December 2, 2008 was arranged. Water clarity and transparency at this time of year is heavily reliant on general weather conditions. Forecasting told us that the Martin County coast was currently stable indicating proposed survey dates in the project program could be adhered to although a forecast nearer mobilization was carried out to ensure that this was still the case as weather during the later part of the year can be unstable. It must also be stated that weather conditions and water quality can change with little notice which in turn affected the proposed survey program although every effort was made to avoid disruption.

The flight planning was carried out according to Blom Aerofilms QC document QCP 05.3 – Mission Planning.

Acquisition of HawkEye data.— The aircraft was mobilized to Martin County from Biscayne National Park and entered at Witham Field where it was based for the duration of the project. In the project area an appropriate GPS base station was used to ensure control. The base stations used for the aircraft control was located at:

Project Area	Network	Station	Coordinates
Martin County	CORS ARP	Palm Beach	**Lat:** 26 50 46.65614 N **Long:** 080 13 09.31040 W

The acquisition of the laser data was planned to take approximately 20 hours (4 days on site). This is approximately 6, 3.5 hour sorties. The flying height for this project was at an altitude of 400 meters with a swathe width of approximately 230 meters in order to achieve the required specification. The aircraft was planned to be flown at a rate of 150 knots and in weather conditions that have clear visibility with a wind speed less than 15 knots. An experienced HawkEye operator used the AHAB Operator Console software to direct the pilot towards the selected flight-line. They also monitored the coverage, depth range, and the survey settings during the flight using the Operator Console.

In order to maintain eye safety of people on the ground during this project the navigator and the pilot observed the area to be surveyed. In the event that the laser system passed over a vessel or over an area where people are visible, the laser system power was reduced to prevent damage to the eyes of anybody who might focus on the aircraft with binoculars. At all times the system was operated in accordance with the eye safety certificate.

Calibration.— Prior to any flying or data capture over the three areas the equipment was calibrated to ensure the best possible survey data. Pixel alignment tests were carried out over a designated area to determine accuracy.

Ground survey operations.— There were no specific ground survey operations for this project. The following was agreed in a conference call between the client and Blom Aerofilms on 03 July 08:

Tidal information.— No specific tide gauges were installed for this project. Tidal data held or available to the client will be supplied to Blom Aerofilms where necessary from the NOAA tide station (exported as position, depth and time) for QC and processing checks. The final conversion to NAVD88 will be done using the GEOID03 geoid model. This model contains a reasonable degree of accuracy and contains offshore gravity data.

During the first survey sortie of the coast the cross lines were surveyed and main survey lines were sounded. During the subsequent sorties some cross lines were flown after the main survey lines were sounded as an additional Quality Control step.

Control point for base station.— A suitable GPS base station was used for this project and was located at the location stated above. The base station was monitored by Blom Aerofilms at regular intervals during the course of the survey to ensure stability and reliability of the signal and data download. Should the primary base station above had not been available at the time of survey then a backup CORS station would have been used located in the following location:

Project Area	Network	Station	Coordinates
Martin County	CORS ARP	Okeechobee	**Lat:** 27 15 57.73388 N **Long:** 080 51 19.19263 W

Ground control areas.— There were no GCA areas established for this project. Any available information sources will be supplied by the client and evaluated by Blom Aerofilms as to their accuracy and usefulness in relation to the laser data capture.

It should be noted that Ground control and sea control areas are not essential to the success and accuracy of the final dataset but do help in the processing of the laser and using the QC surfaces to check accuracy.

Geodetic and datum processing.— For this project, Blom Aerofilms will use the following methodology for geodetic processing and positioning of the data.

The initial export of the point cloud will be using UTM Zone 17 N precise coordinates and to the GRS80 ellipsoidal reference surface. This data will then be transformed to NAVD88 using the GEOID03 geoid model to relate the data for each area to the required Datum.

Initial data post processing and production of point cloud.— On completion of the day's flying, the data were downloaded from the aircraft and copied across to a USB 2.0 HDD for checking by the onsite processor. The data were checked for coverage and bottom returns. The aircrew was advised at this time if there was a need for any re-flights due to gaps found at the initial QC stage. Once it was confirmed that all data was captured successfully, the aircraft and crew demobilized back to Norwich.

The data production and initial flow line operated in the following way during acquisition:

- Daily data back up from aircraft to HDD
- Daily data processing (1 day behind acquisition)
- Initial trajectory processing carried out using POSPAC v.5.1
- CSS software was used for the production of the Point Cloud
- QC was carried out to analysis coverage of bottom returns
- Production of initial point cloud.

The point cloud for the bathymetric laser data took place using Coastal Survey Studio (CSS). The SBET from the post processing of the data was inputted into the software and an initial LAS file was created. The laser data from each flight-line was matched to create a seamless point cloud.

At this point the matching of the data and coverage of the data was checked to see if any re-flights were required. On completion of the QC checks the bathymetric data were exported as separate files.

Terrestrial laser data classification.— Before the data was imported into Terrascan in Cheddar for final processing it was checked to ensure the correct number of files were received and all information required to continue processing was present and correct.

If a final SBET trajectory file was required this was also undertaken in Cheddar. All trajectory data were produced in the NAD83 coordinate system and projected to UTM Zone 17 N. This was then used to output a final point cloud from CSS using the parameters that were used in the on-site processing.

CSS outputted two files, one of topographic data and one with the bathymetric data. All data were imported into TerraScan, running in the MicroStation environment. The data were first transformed from UTM Zone 17 N projection to NAD83 horizontal datum, ellipsoidal reference frame and chart Datum using GEOID03 geoid model. This was implemented in the TerraScan software. The final shift to NAVD88 was also then applied.

The topographic data and the bathymetric data were kept separate and the data were processed as follows:

Topographic data were passed through a number of automated macros to classify the laser data into the following classes, ground, low, medium and high vegetation classes. The classified laser data were then checked with the imagery by an experienced editor to remove any remaining bathymetric points and to ensure that the ground was correctly classified.

In order to ensure the quality of the terrestrial laser data, the following QC steps were carried out:

- QC with data provided by the client for possible ground truth
- QC of overlapping and crossing flight lines
- Production of reference surface analysis reports
- QC with the red laser data from the bathymetric LIDAR point cloud

Bathymetric laser data cleaning.— The bathymetric laser data were first checked against the project boundary file. The seaward limit of the boundary was moved when necessary to ensure depths to the 10 m contour below chart datum were issued to the client.

The data were cleaned in Terrascan. The data cleaning met the standards set by Coastal Zone Monitoring standards. During cleaning the following points were removed from the bathymetric LIDAR point cloud:

- Rogue points due to backscatter
- Floating structures
- Deep points with no bottom return
- “spikes”

In order to ensure the quality of the bathymetric laser data the following QC steps were carried out:

- QC of overlapping and crossing flight-lines
- QC with imagery for floating structures and obstructions

Production of final LIDAR deliverables.— On the completion of the cleaning of the bathymetric LIDAR data, both datasets were carefully merged together using TerraScan. The matching of the two datasets along the coastline was quality controlled to ensure that there were no mismatches between the two datasets. Additional QC was carried out to remove any topographic data from the bathymetric data and vice versa.

The final transformation to the projection system as mentioned above was done at this stage after all processing was completed.

All LIDAR Processing was carried out according to Blom Aerofilms QC document QCP 05.11 – LIDAR Processing.

Processing the seabed reflectance data.— Once the laser data acquisition was complete, the processed data was then passed to the system manufacturer for the processing of the reflectance data. The completed dataset, per flight line was returned to Blom Aerofilms for checking and issued to the client.

Imagery processing.— The Hawk Eye II system includes an integrated digital camera that records imagery during the flight. This system was used for the project and at the time of capture a time stamp was registered for each image. By referencing the time stamp against the final SBET trajectory of the plane, the image was correctly positioned initially.

For final orthophoto processing, the imagery was tie-pointed and orthophoto tiles produced. Nominally, these were at 25cm resolution. Orthophotos were produced using the Terrasolid module Terraphoto running within the MicroStation environment. At the time of capture, a time stamp was registered for each image. By referencing the time stamp against the trajectory of the plane, the image was correctly positioned. The imagery was then tie pointed and orthophoto tiles produced. Nominally, these were at 25cm resolution.

It should be noted that the imagery was not high resolution and did not have fully automatic exposure control. Some differences were therefore noticed in the final mosaic.

Phase 2.—

Benthic Habitats.— Benthic habitat maps were produced of the subtidal seafloor from 0 to 30 m depth for Martin County Florida. Several data products were integrated for the production of benthic habitat maps. A comprehensive dataset from previous work at the county, state, and federal level was assembled in ArcGIS to aid in the seafloor feature identification. High-resolution hillshaded images of the Phase 1 LIDAR data were the primary data source used to discriminate seafloor features. These data were accompanied by other datasets from multiple agencies including Martin County Property Appraisal aerial photography, Southeast Florida Coral Reef Evaluation and Monitoring Program monitoring data, and FWRI artificial reef location data. Martin County, FWC, and Dr. Lapointe at FAU's Harbor Branch Oceanographic Institute supplied several datasets of point data that were helpful in identifying/confirming reefal areas in several locations. Post, Buckley, Schuh & Jernigan, Inc. provided shoreline aerial photography from 2009 and 2010 as well as a line shapefile of the nearshore hardbottom edge. Finally, reports, maps, and vibracore were downloaded from the Reconnaissance Offshore Sand Search Oracle database (http://ross.urs-tally.com/database.asp) to help identify sand areas.

The habitats were classified according to established NOAA guidelines in coordination with the NOS Coral Mapping Program and use a similar classification scheme when possible. Polygons were drawn to previous NOAA-mapping criteria of a 1:6000 scale and a minimum mapping unit of 1 acre (Kendall *et al.*, 2002) to match the Broward, Palm Beach, and Miami-Dade habitat maps (Riegl *et al*., 2005; Walker *et al*., 2008; Walker, 2009). The benthic habitat classifications conformed to the NOAA hierarchical classification scheme used in Puerto Rico and the U.S. Virgin Islands NOAA Technical Memorandum National Ocean Service (NOS) National Centers for Coastal Ocean Science (NCCOS) Center for Coastal Monitoring & Assessment CCMA 152 (Kendall *et al.,* 2002, 2003) with some modification. The criteria for habitat classification were defined by their location, geomorphologic characteristics, and biologic communities. A high resolution, hill-shaded, raster image of the LADS bathymetry data was used to map feature location and geomorphology of visible features. Aerial photography was used in shallow water to depict the edges of hard ground and patch reef extents. Conflicts between data types were resolved by expert-driven interpretation based on the agreement of the majority of data types with an emphasis on the most recent data.

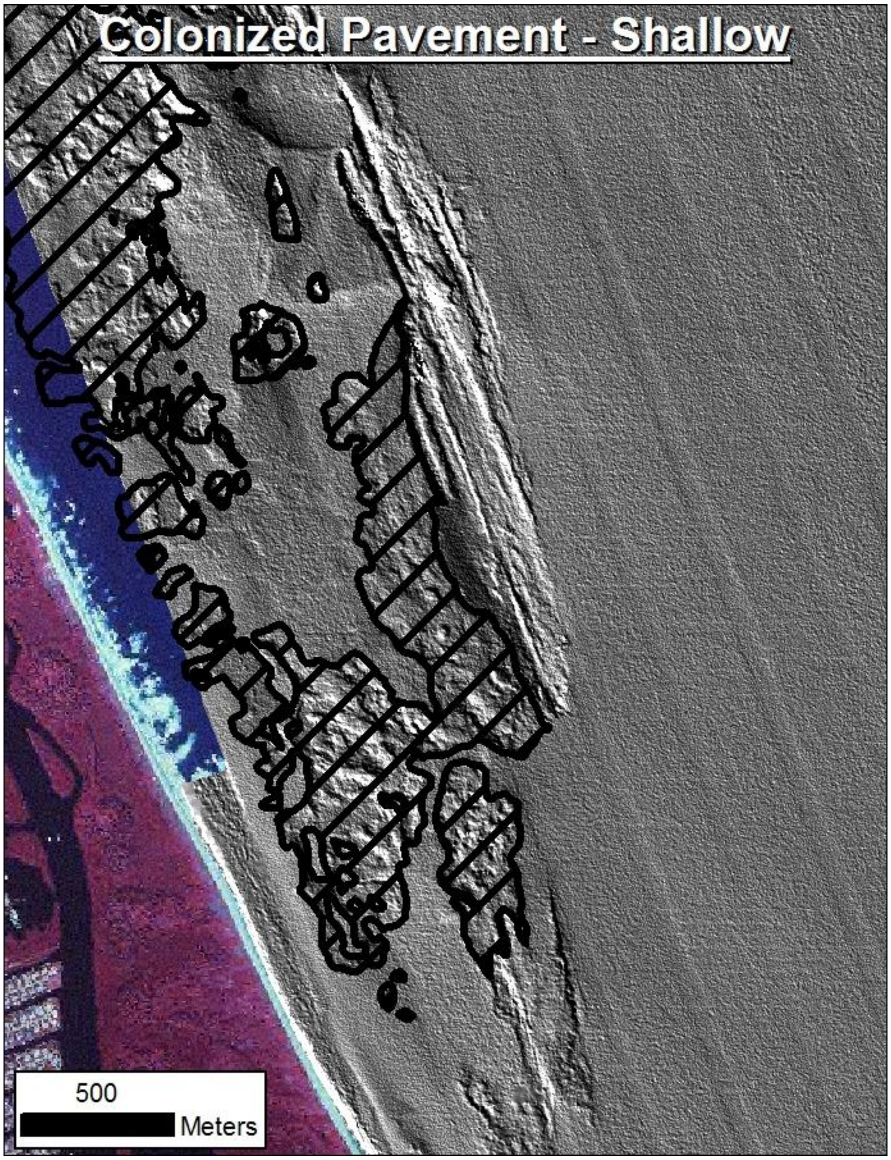
Photographic examples of many of the habitats are provided in Appendix 1.

Coral Reef and Hardbottom: Hardened substrate of unspecified relief formed by the deposition of calcium carbonate by reef building corals and other organisms (relict or ongoing) or existing as exposed bedrock.

Coral Reef and Colonized Hardbottom: Substrates formed by the deposition of calcium carbonate by reef building corals and other organisms or existing as exposed bedrock. Habitats within this category have some colonization by live coral.

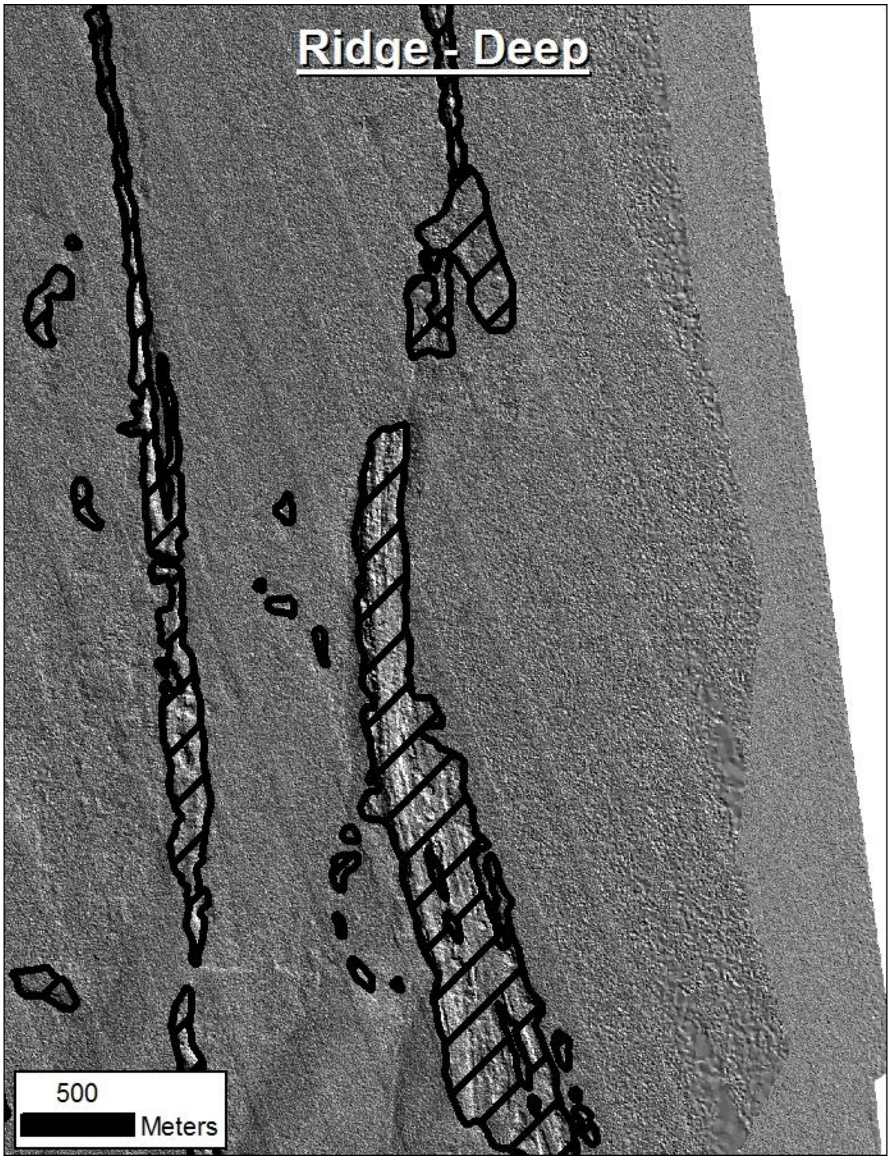
Colonized Pavement: Flat, low-relief, solid carbonate rock with coverage of macroalgae, hard coral, gorgonians, and other sessile invertebrates that are dense enough to partially obscure the underlying carbonate rock.

Colonized Pavement-Shallow: Colonized pavement in water shallower than 10 m. This category includes rubble in many areas; however, consolidated rubble fields are a less frequent feature in shallow water. Especially inshore of the ridge complexes, limited rubble is found and a wide, contiguous area of pavement is encountered. This area can have variable sand cover, which shifts according to wave energy in response to weather. Thus, some of the colonized pavement will always be covered by shifting sand and the density of colonization will be highly variable.

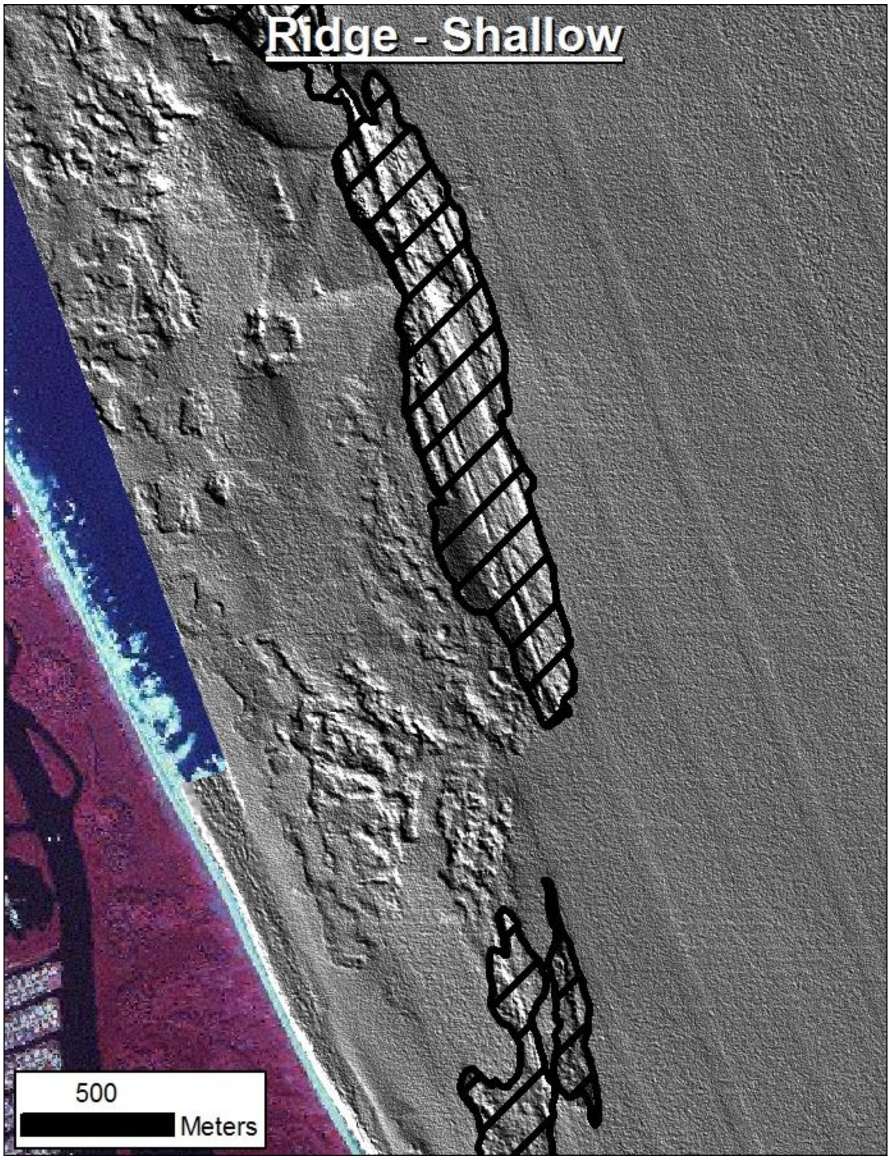


Ridge: Linear, shore-parallel, low-relief features that appear to be submerged cemented ancient shoreline deposits. Presumably, they are an extension of the foundation upon which the linear reefs grew further south and consist of early Holocene shoreline deposits; however, verification is needed. The biological cover is similar to that of colonized pavement with macroalgae, scleractinians, gorgonians, and other sessile invertebrates that are dense enough to partially obscure the underlying carbonate rock.

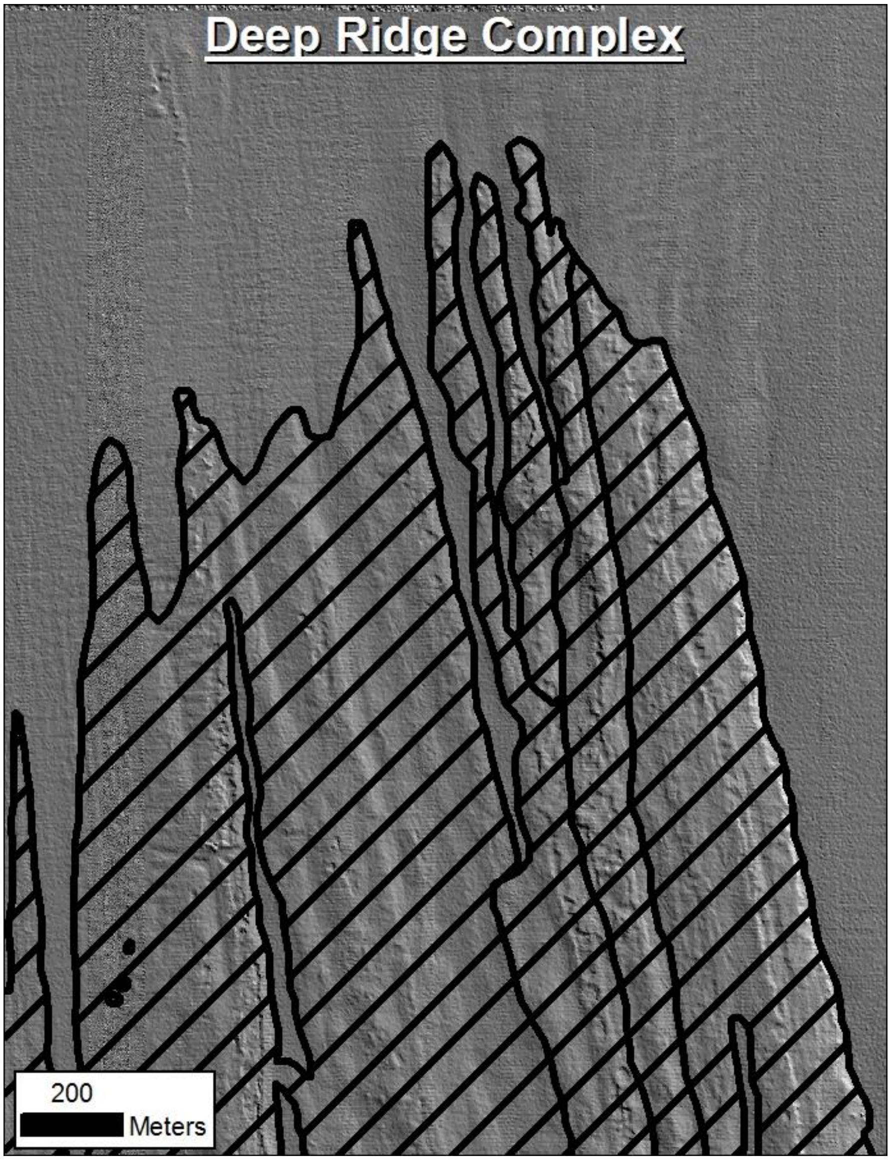
> **Ridge-Deep:** Linear, often shore-parallel, low-relief features that mostly occur deeper than 20 m. It consists of hardbottom with sparse benthic communities in most parts likely due to variable and shifting rubble and sand cover. Some parts contain exposed ledges where large fish (e.g. Goliath grouper, Nurse Shark) may congregate.



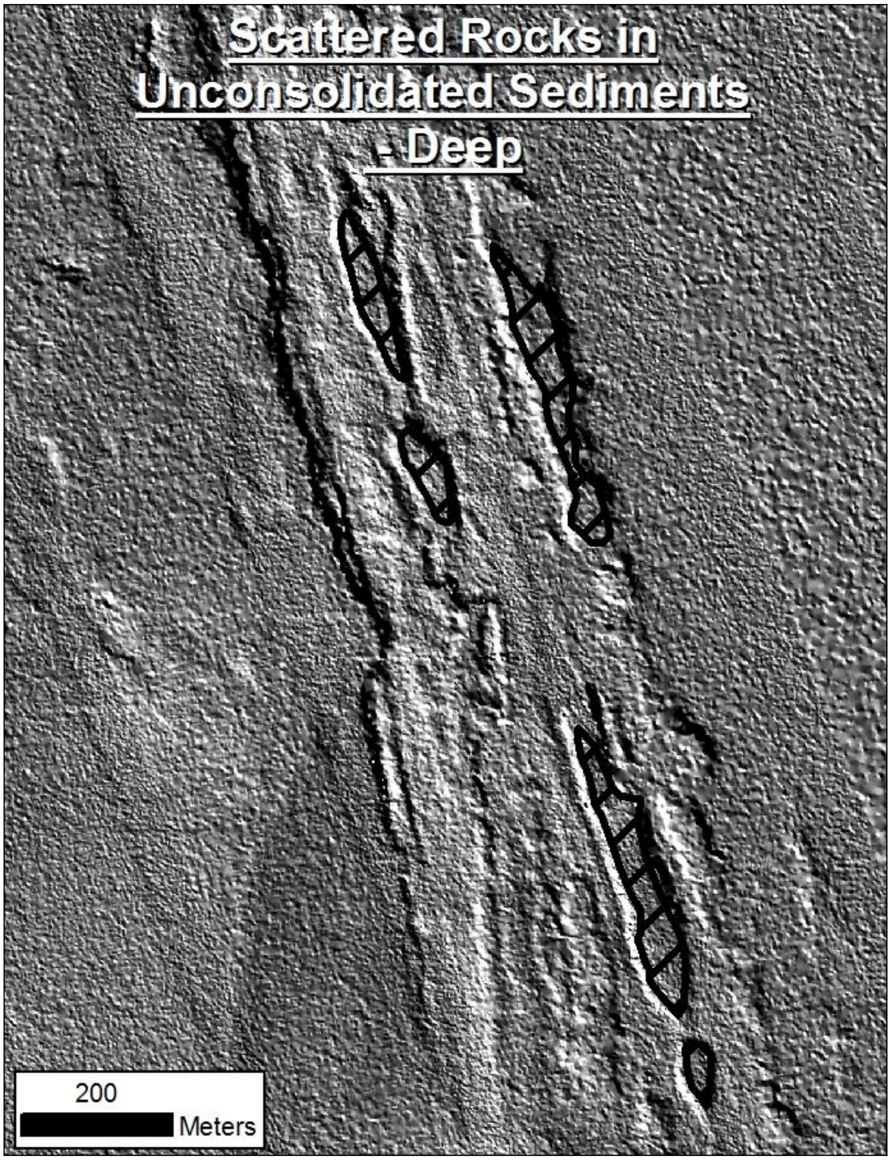
Ridge-Shallow: Ridges found in water shallower than 10 m near shore that are geomorphologically distinct, yet their benthic cover remains similar to the shallow colonized pavement communities on the surrounding hard grounds.



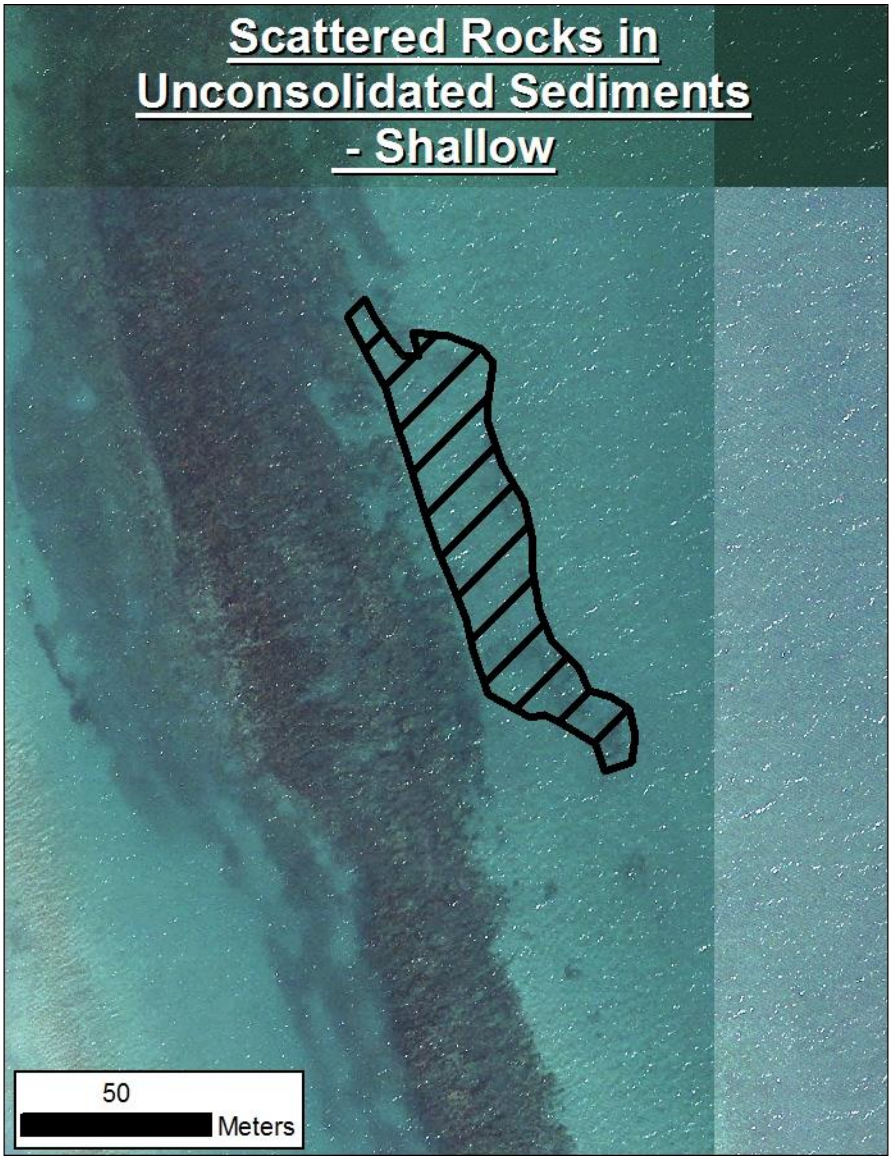
Deep Ridge Complex: A complex of ridges found in deep water in northern Palm Beach and Southern Martin Counties. These features reside in depths from 20 to 35m and are presumed to be of cemented beach dune origin. Most of this habitat consists of low cover, deep communities dominated by small gorgonians, sponges, and macroalgae, but denser areas exist, especially near areas of higher relief. Some areas, particularly between ridges, may contain large areas of unconsolidated sediments.



Scattered Rock in Unconsolidated Sediment-Deep: Primarily sand bottom with scattered rocks that are too small to be delineated individually in water deeper than 20 m.



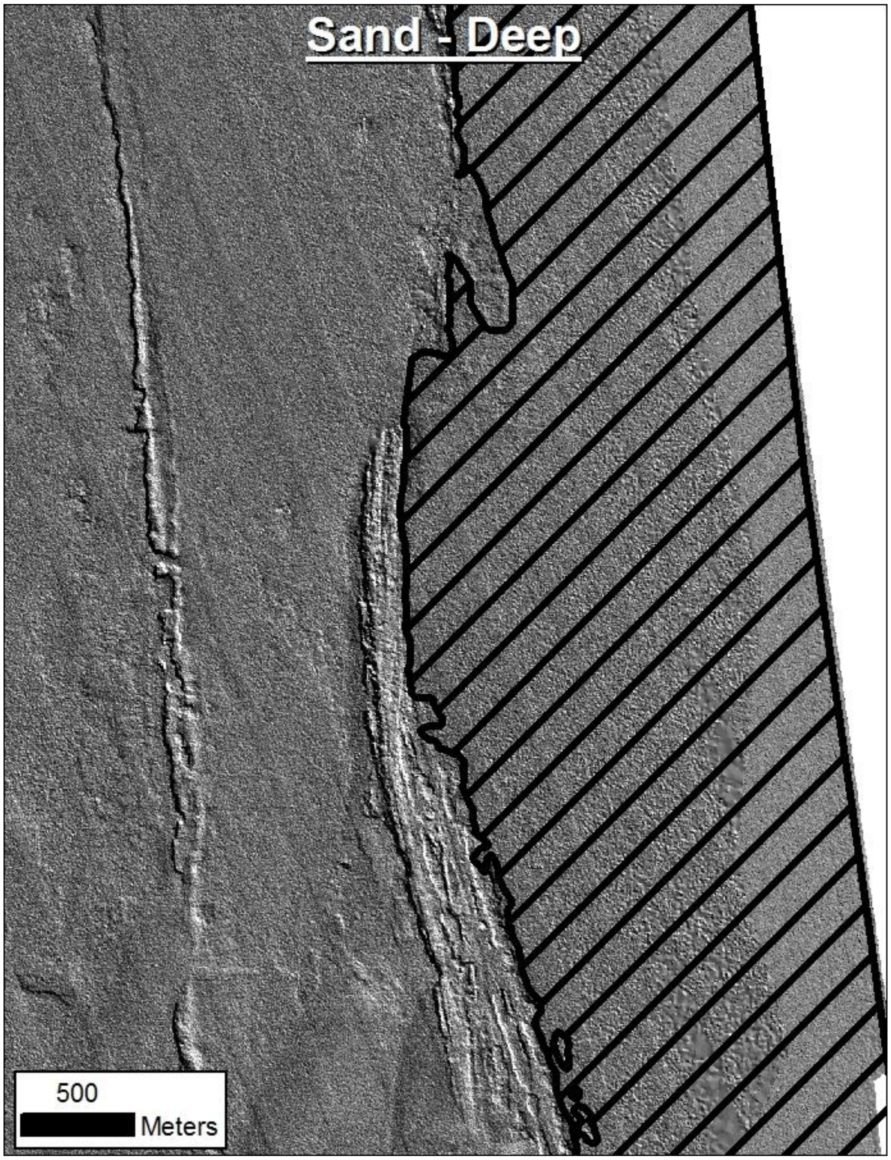
Scattered Rock in Unconsolidated Sediment-Shallow: Primarily sand bottom with scattered rocks that are too small to be delineated individually in water shallower than 20 m.



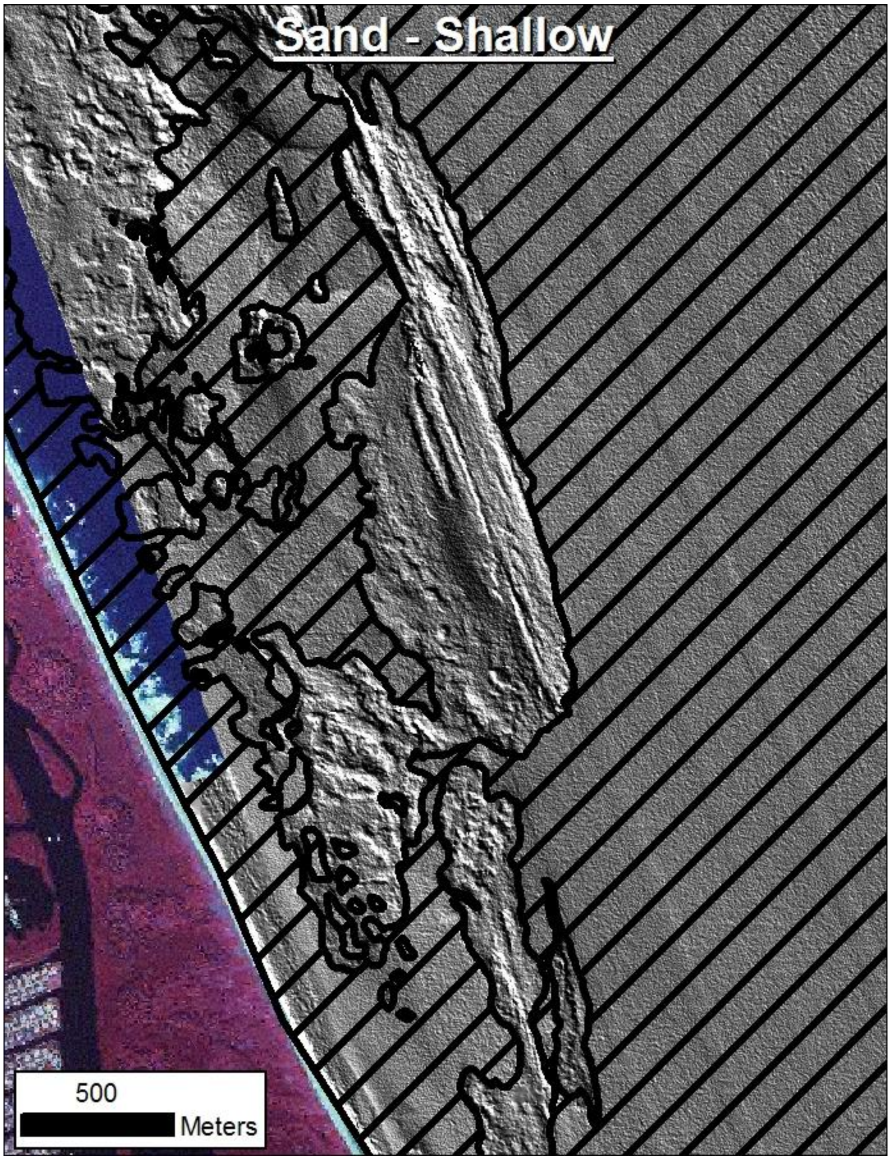
Unconsolidated Sediments: Unconsolidated sediment with less than 10 percent cover of submerged vegetation.

Sand: Coarse sediment typically found in areas exposed to currents or wave energy.

Sand–Deep: Sand deeper than the 25 m contour exposed to a lower energy environment that can have finer grain size, sparse *Halophila* spp., and a rubble component. This habitat can contain a high cover of turf and low-lying benthos in some areas.

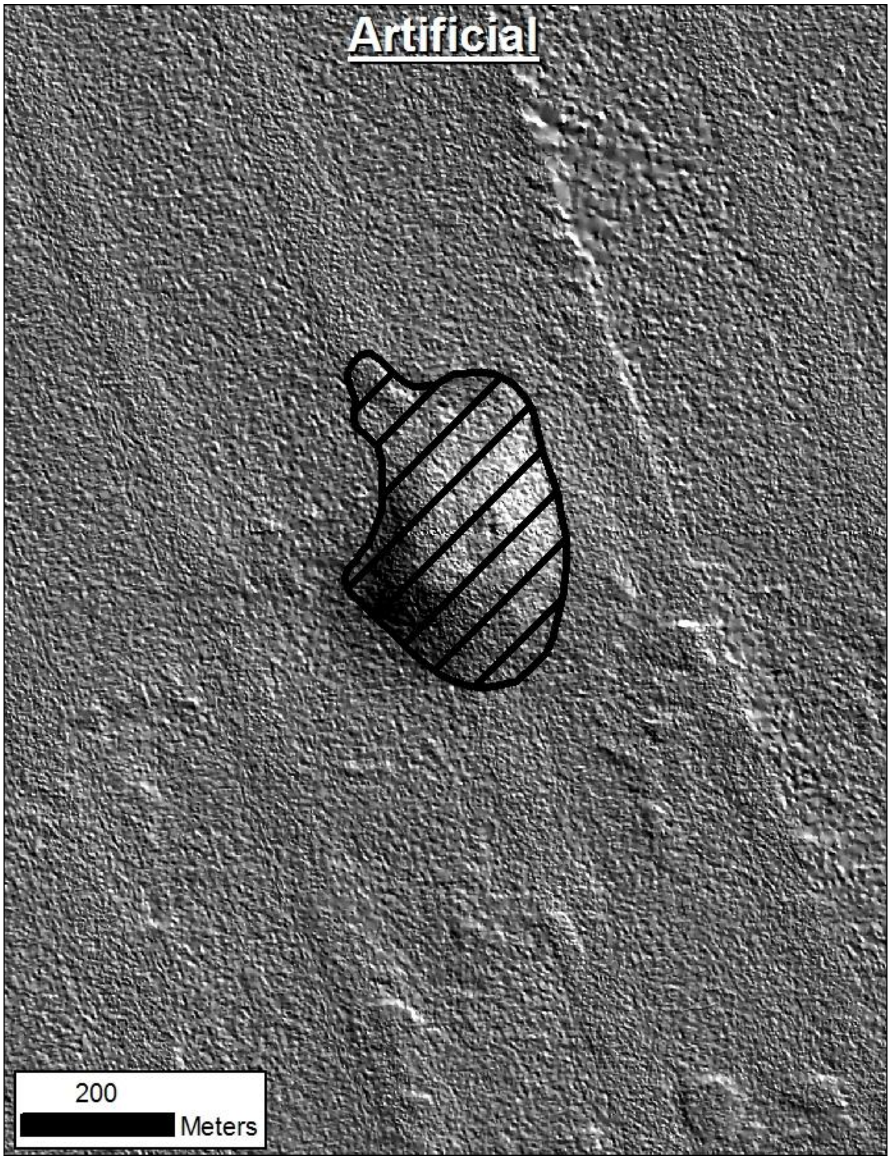


Sand–Shallow: Shallow water (<25 m) sediment exposed to a higher energy environment. Large, mobile sand pockets are found on the areas of consolidated hardgrounds. It is believed that the sand movement is a deciding factor in the generation of benthic patterns.

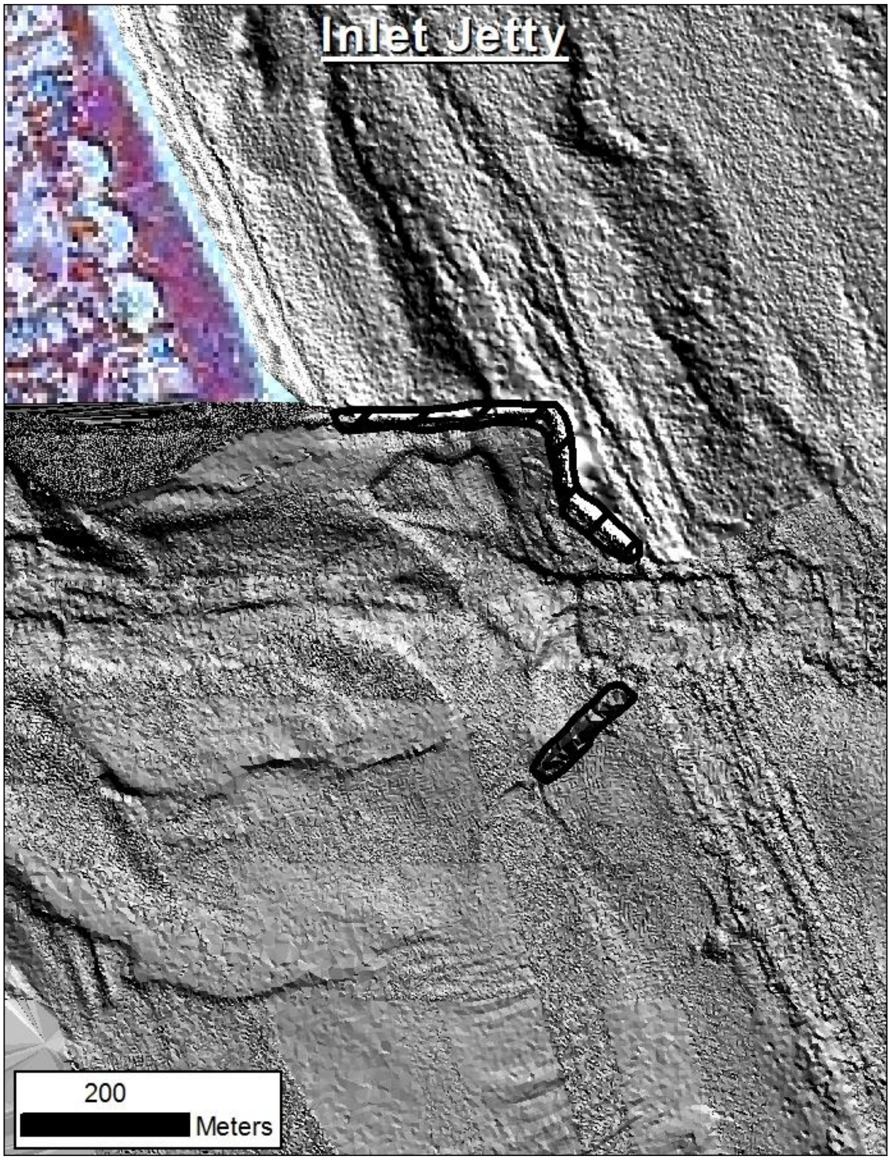


Other Delineations:

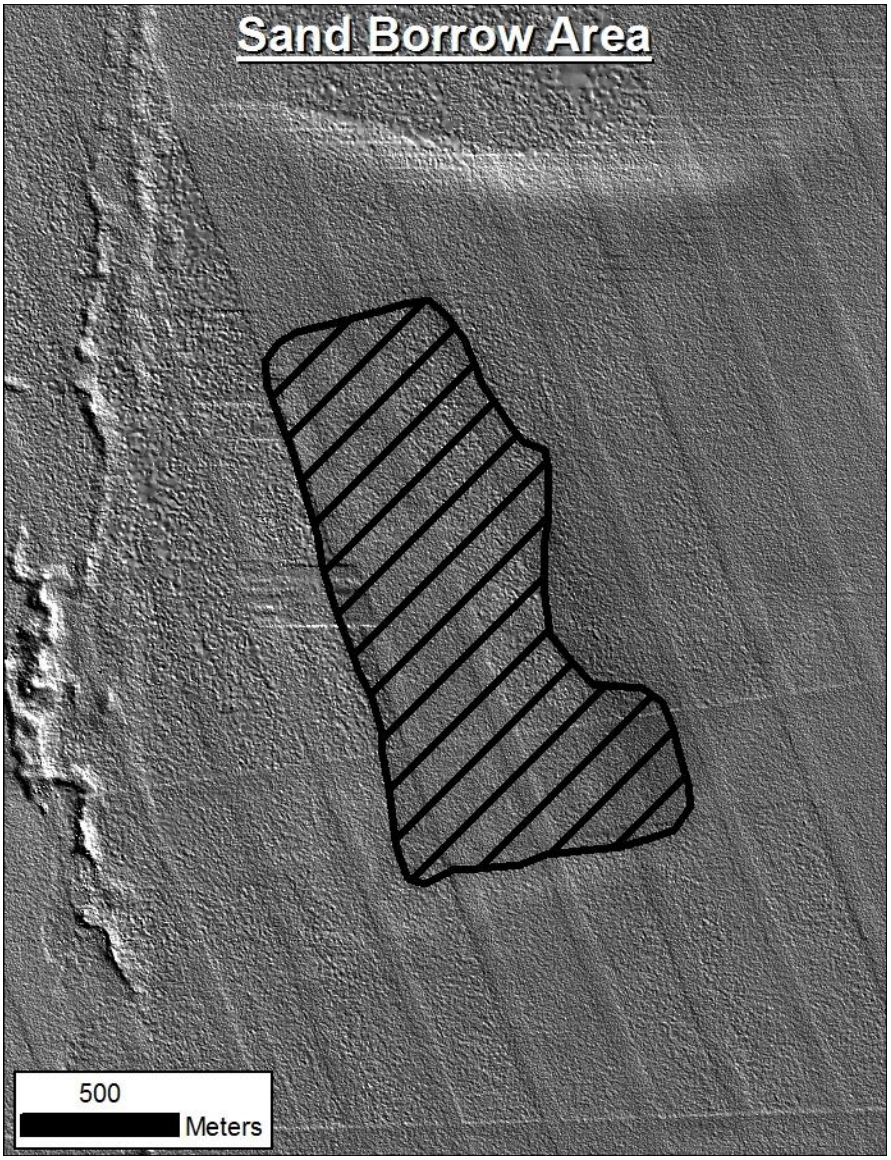
Artificial: Manmade habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil.



Inlet Jetty: Artificial structures placed at the inlet channel primarily to block wave energy and reduce erosion.



Sand Borrow Area: Pits excavated during previous sand dredging projects for beach nourishment.



Qualitative Ground validation (Ground truthing).— A ground validation plan was developed to aid in the interpretations of the different topographic features evident in the bathymetry. The first round of ground truthing was accomplished between May 9 and May 11, 2011. Five cross-shelf transects were placed in targeted areas along the coast that spanned as many habitats and unique topographic signatures in the bathymetry as possible. A location was determined every 200 m along that line in GIS yielding a total of 276 target ground validation sites.

At each site, a Sea Viewer 950 underwater, color video drop camera with a Sea-trak global positioning system (GPS) video overlay connected to a Garmin Wide Area Augmentation System (WAAS) GPS (~3 m accuracy) was used to collect ground truthing video data. Color video was taken at each target location by dropping the camera over the side of a stationary/slowly drifting vessel approximately 0.5-2 m from the bottom. Fifteen second to two minute video clips were recorded directly to an 80 GB digital video recorder in MPEG4 video format at 720 x 480 resolution and 30 frames per second. Video length depended on the habitat type and vessel drift. Videos of large expansive sand habitats were generally short while reef habitats, especially edges, were longer. The GPS location at the start of each video, at the end of most videos longer than 30 seconds, and at the middle where distinct habitat changes occurred, were entered into a database and plotted in GIS. These data were then categorized according to major habitat type at each location. This resulted in a GIS point layer of 315 points at 288 sites along the 5 cross-shelf transects with the video name and habitat description of each point. The categorized points were displayed in GIS according to the major habitats identified in the videos and compared to the other map data. These data were then used to correct any false categorizations in the draft polygonal habitat layer and calibrate the remaining delineations.

The initial ground truthing showed a high percentage of sand. Over 90% of the points were sand habitats. For the video data, these were further divided into four sand habitats to help show possible cross-shelf patterning. These categories were Sand (59%), Sand with algae (21%), Sand with shell hash (6%), and Sand/Rubble (4%). These habitats were not part of the final classification scheme, but indicated that differences exist in the sand both cross-shelf and latitudinally. For example, almost all of the sand with shell hash was found on the northernmost transect line and showed spatial clustering. The sand with algae was mostly limited to the deep areas and also showed spatial clustering. Rubble was found in most of the videos that contained hard bottom, but it was also present in small quantities in sand habitats. Like the previous mapping efforts, it was not possible to map rubble as its own category.

The 288 ground validation sites along the 5 cross-shelf transects were valuable in helping understand the relationships of topographic signatures in the bathymetry to certain habitats. These data identified the need to verify certain other targeted areas, especially those outside of the cross-shelf transects. The map data were visually scanned to identify unknown and questionable locations. A total of 144 additional targeted sites were visited throughout the county.

This ground validation was difficult to plan. Scheduling conflicts and high seas impeded most scheduling attempts throughout fall 2011 and winter 2012. On February 16, 2012 ground validation was attempted with minimal success. Boat malfunctions and bad weather limited the data collection to 20 locations. Soon after, FWC boat engines were stolen, delaying scheduling further. On July 2 and 3, 2012, 124 ground validation sites were visited completing the qualitative ground validation. The habitat at each location was identified and was used to guide the final map classifications.

Quantitative ground validation.— In collaboration with FWC, FDEP-CRCP, and NCRI, NOAA CRCP provided supplemental funding for quantitative ground validation to enhance the present Martin County benthic habitat mapping by further quantitatively assessing and characterizing the mapped hardbottoms. Quantitative ground truthing provides a rigorous determination of habitat types beyond qualitative efforts and valuable information about the composition of the benthic communities for resource management. This effort was accomplished between August 13 and 16, 2012. General site locations were selected from the 2012 FDEP-CRCP reef visual census database which were determined by a statistically robust random sample design (Smith et al. 2011). This design included stratifying across habitat classes throughout the county. Although fish data were not collected, it was thought that collecting benthic data near the fish surveys would be beneficial to both projects.

Methodology for benthic assessments was adopted from those used in the Mesoamerican Barrier Reef System Project (Almada-Villela et al., 2003) and the widely used Atlantic and Gulf Rapid Reef Assessment (AGRRA, 2000). Data at each site was collected on four 50 meter point-intercept transects at an intercept density of 0.25 m for a total of 480 (120 x 4) points per site. At each point, divers identified the organism under the transect tape by major functional groups (hard coral species, turf algae, macroalgae, sponge, zoanthid, etc.) or bare substrate type. Whenever possible all stony corals within 1 m of the transects were recorded for colony size (length, width, height), live tissue area (length x width of live tissue), percent mortality, presence of bleaching, and presence of disease. Finally, rugosity was estimated along each transect by measuring the distance along the bottom contour to the linear distance. All four measurements were combined to create a rugosity index for each site by dividing the contour distance by the linear distance.

A cluster analysis and corresponding non-metric multi-dimensional scaling (MDS) plot was constructed using Bray-Curtis similarity indices (PRIMER v6) of the benthic cover data (square-root transformed) to evaluate benthic cover sites with distinct habitat composition. A one-way analysis of similarity (ANOSIM) was performed to statistically determine the strength of the site categorization by habitat. ANOSIM is a permutation-based hypothesis test analogous to univariate analyses of variance (ANOVAs) that tests for differences between groups of (multivariate) samples from different experimental treatments. The closer the R statistic is to 1, the stronger the categorical groups. Its strength is dependent on the number of samples per category which defines the number of possible permutations. Univariate ANOVA was used to examine differences in rugosity and biological cover category data (i.e., the number of major live functional group categories per site).

Accuracy assessment data collection.— Accuracy assessment target locations were determined in ArcGIS 10.1 after the entire draft habitat map was complete. Target locations for the accuracy assessment procedure were determined by a GIS-based, stratified random sampling technique used in other regional mapping efforts (Walker 2009; Walker and Foster 2009). Unlike previous efforts, the map proportions of all Coral Reef and Colonized Hardbottom and Artificial habitats were used to determine the percentage of assessment sites per habitat. Then 33 locations were added to sand which is comparable to other efforts. This yielded 199 stratified random accuracy assessment target locations to be visited by drop camera and analyzed by confusion matrix approach.

Underwater video from a drop camera was taken at each AA target location. This procedure involved the boat positioning itself within 5 m of the target. A Sea Viewer 950 underwater color video drop camera with a Sea-trak GPS video overlay connected to a Garmin 76CSx GPS with WAAS correction (<3 m accuracy) was then lowered to the bottom. Color video was recorded over the side of the stationary/drifting vessel approximately 0.5-2 m from the seafloor. Fifteen second to two minute video clips were recorded directly to an 80 GB digital video recorder in MPEG4 video format at 720x480 resolution and 30fps. Video length depended on the habitat type and vessel drift. Videos of large expansive sand habitats were generally short while reef habitats, especially edges, were longer. While the video was being recorded, an observer categorized each site according to the video and surrounding area into a database.

Accuracy assessment data evaluation.—The GPS location at the start and end of each video was entered into a database along with the field notes and plotted in GIS resulting in a point layer of 386 locations. These data were then spatially joined to the benthic habitat layer to identify the map classification for each point. Sites that differed between field notes and map classification were evaluated both in GIS and from video to determine possible sources of disagreement. Statistical analyses to determine the thematic accuracy were derived from Congalton (1991), Hudson and Ramm (1987), and Ma and Redmond (1995). Matrices of user and producer map accuracy error, overall map accuracy error, and the Tau coefficient were generated. The Producer's error matrix indicates how well the map producer can classify a given habitat type; the User's error matrix indicates how often map polygons of a certain type are classified correctly; and the Tau Statistic is a measure of the probability that a feature is correctly mapped compared to chance alone. A sampling station was considered correctly classified if the habitat type identified in the field matched the habitat type mapped by the map producer. Overall map accuracy was determined by dividing the total of the correctly classified sampling locations in the error matrix by the total number of sampling locations.

Four benthic habitat classes found in the draft benthic habitat map were excluded from the accuracy analysis; the Inlet Jetty, Sand Borrow Areas, Sand-Deep, and Deep Ridge Complex. The first two were excluded because they are unnatural habitats, although artificial was included because of their ecologic value. The Deep Ridge Complex was excluded because it was mapped and assessed during the Palm Beach mapping effort (Riegl et al. 2005).

Accuracy assessment analyses.—A number of statistical analyses were used to characterize the thematic accuracy of the Martin County benthic habitat map. A total of four error matrices were prepared for the attributes of Major and Detailed Habitat levels of classification. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton 1986). Direct interpretation of these producer's and overall accuracies can be problematic, as the stratified random sampling protocol can potentially introduce bias (Hay 1979, van Genderen 1978, van Genderen 1977). Stratification ensures adequate representation of all map categories, by assigning an equal number of accuracy assessment to each map category, using the draft benthic habitat map as a guide. This caused rare map categories to be sampled at a greater rate (observations per unit area) than common map categories. The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the known map marginal proportions, i.e. the relative areas of map categories. The map marginal proportions were calculated as the area of each map category divided by the total area calculated from the Martin County habitat map polygons. The map marginal proportions were also utilized in the computation of confidence intervals for the overall, producer's, and user's accuracies (Card 1982). The efficacy of the habitat map was further examined by computation of the Tau coefficient, which adjusted the overall accuracies based on the number of map categories, allowing for statistical comparison of error matrices of different sizes (Ma and Redmond 1995). As a classification metric, Tau is a measure of the improvement of the classification scheme over a random assignment of polygons to categories, bounded between -1 (0% overall accuracy for 2 map categories) and 1 (100% accuracy for any number of categories).

The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (true, or ground truthed classification). The overall accuracy (P_o) was calculated as the sum of the major diagonal, i.e. correct classifications, divided by the total number of accuracy assessment samples. The producer's and user's accuracies are both category-specific. Each diagonal element was divided by the column total to yield a producer's accuracy and by the row total to yield a user's accuracy. The producer's and user's accuracies provide different perspectives on the classification accuracy of a map. The producer's accuracy (omission/exclusion error) indicates how well the mapper classified a particular habitat, e.g. the percentage of times that substrate known to be sand was correctly mapped as sand. The user's accuracy (commission/inclusion error) indicates how often map polygons of a certain habitat type were classified correctly, eg. the percentage of times that a polygon classified as sand was actually sand. The distinction between these two types of error is subtle. For example, the user's accuracy for the map category of sand is calculated as the number of accuracy assessment points that were mapped as sand and later verified to be sand, divided by the total number accuracy assessment points that were mapped as sand. But this measure of user's accuracy for mapping sand totally ignores points that were verified to be sand, but mapped as something else, i.e. producer's error.

Considering the uneven distribution of map category area in the map, a simple random assignment of accuracy assessment points would have required an unrealistically large number of points to adequately cover all map categories. The stratified random sampling protocol was used to ensure that each habitat class would be adequately sampled, assigning an equal number of accuracy assessment points to each map category of Detailed Habitat (modifier) within the mapped area. As previously mentioned, this non-random sampling method introduced bias in the producer's and overall accuracies, as map categories with very large areal extents were sampled at the same rate as categories with very small extents.

To remove the bias introduced by the stratified random sampling procedure, the overall and producer's accuracies were adjusted to the known areal proportions of map categories (Card 1982). The known map marginal proportions (π_i) were computed from the GIS layer of the draft benthic habitat map for each of the four error matrices, by dividing the area of each category by the total map area. Then the individual cell probabilities, i.e. the product of the original error matrix cell values and π_i, divided by the row marginal (total map classifications per category), were computed for the off-diagonal elements using the following equation:

$$\hat{P}_{ij} = \pi_i n_{ij} / n_{i-}$$

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row marginals were forced to the known map marginal proportions, i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points. The estimated true marginal proportions were computed as the sum of individual cell probabilities down each column of the error matrix. The π_i-adjusted overall, producer's, and user's accuracies were then computed from the new error matrix, now populated by individual cell probabilities. The values of the π_i-adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by the stratified random sampling protocol. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed from the following set of equations:

Overall Variance = $V(\hat{P}_c) = \sum_{i=1}^{r} p_{ii}(\pi_i - p_{ii})/n_{i-})$

Overall Confidence Interval = $\hat{P}_c \pm 2[V(\hat{P}_c)]^{1/2}$

Producer’s Variance = $V(\hat{\theta}_{ii}) = p_{ii}\,p_i^{-4}[\,p_{ii}\sum_{j\neq 1}^{r} p_{ij}(\pi_i - p_{ij})/n_{i-} + (\pi_i - p_{ii})(p_i - p_{ii})^2/n_{i-j}\,]$

Producer’s Confidence Interval = $\hat{\theta}_{ii} \pm 2[V(\hat{\theta}_{ii})]^{1/2}$

User’s Variance = $V(\hat{\lambda}_{ii}) = p_{ii}(\pi_j - p_{ii})/n_{i-}$

User’s Confidence Interval = $\hat{\lambda}_{ii} \pm 2[V(\hat{\lambda}_{ii})]^{1/2}$

The Tau coefficient is a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond 1995). For a supervised classification scheme there are two possible forms of the Tau coefficient, differing only by the estimation of the probability of random agreement (P_r). In one case it is known *a priori* that the probability of class membership differs among map categories, e.g. a previous map that quantified the disproportionate areal extents of habitat classes. In this case, Tau (T_p) is an adjustment of overall accuracy (P_o) by the number of groups (*r*) and the *a priori* probabilities informing the classification. In the other case it is not possible to quantify the *a priori* disparities of group membership. In the case of the Martin County benthic habitat map there was no *a priori* information available, and thus a Tau based on equal probability of group membership (T_e) was used to evaluate classification accuracy. In this case, the probability of random agreement simplifies to the reciprocal of the number of map categories (1/*r*), and T_e is simply an adjustment of P_o by the number of map categories. As the number of categories increases, the probability of random agreement diminishes, and T_e approaches P_o. Values of T_e were calculated as follows:

Tau coefficient for equal probability of group membership = $T_e = (P_o - 1/r) / (1 - 1/r)$

Because there are only two possible outcomes for each accuracy assessment point, i.e. correct or incorrect, the probability distribution of P_o follows a binomial distribution. But when the total number of accuracy assessment samples within the error matrix is large, i.e. $n > 100$, the probability distribution of P_o approximates a normal distribution (Steel and Torrie, 1960). Given that the distribution of P_o approximates normality, it can then be assumed that the distribution of T_e will also approximate normality (Cohen, 1960). And because the individual row values of P_r are fixed before the map is classified, i.e. equal to 1/*r*, they can be treated as constants and a variance can be calculated for Tau (Ma and Redmond 1995):

Variance of Tau coefficient = $\sigma_r^2 = P_o(1 - P_o) / n(1 - P_r)^2$

Confidence intervals were then calculated for each Tau coefficient at the 95% confidence level (1-α), using the following generalized form:

95% CI = $T_e \pm Z_{\alpha/2}(\sigma_r^2)^{0.5}$

Spatial analyses.— Benthic habitat polygons were statistically tested for any spatial autocorrelation in ArcGIS using Moran's Index to determine any significant patterns in the underlying data significantly different from a random distribution. Map data were then combined with the previous southeast Florida maps (Walker 2012) and statistically examined to determine where the number and size of seagrass, coral reef, and colonized hardbottom habitats significantly differ. Two hundred and forty-eight parallel, cross-shelf vector-line transects spaced 750 m apart were created in GIS throughout the entire mapped region. An intersect was performed between the vector-line transects and the benthic habitat polygons, which broke the transect lines at each point where they intersected with a habitat polygon. The length of each resulting line segment was calculated to determine the linear cross-shelf distance of each habitat (width). A cluster analysis and corresponding non-metric multi-dimensional scaling (MDS) plot was then constructed using Bray-Curtis similarity indices (PRIMER v6) of the cross-shelf habitat width data (square-root transformed) to evaluate regions with distinct habitat composition. The groups of transects that occurred within the clusters with 60% similarity were then categorized in GIS and visually examined to evaluate the clusters for any spatial grouping consistency. Inspection of the benthic habitats where MDS clusters split helped identify the key locations in the habitat mapping data where the regional boundaries were defined. After defining the boundaries, all cross-shelf transects were categorized by the corresponding region. These categories were imported in Primer as factors and a one-way analysis of similarity (ANOSIM) was performed to statistically determine their similarity. The factors were also displayed on the MDS plot to see how the categorization related to the 60% MDS clusters.

RESULTS & DISCUSSION

Martin County

Phase 1.—

Acquisition summary.— The project area at Martin County was initially flown between December 7 and 12 2008, after LIDAR acquisition had been completed in the BNP project area further south in Florida for a separate contract. The project area captured was approximately 350 km² and was acquired over a period of four days and included both topographic and bathymetric LIDAR as well as vertical aerial imagery. Figure 1 below shows an initial coverage plot of the project area at Martin County. Note that re-flights are not shown in the coverage plot.

It should also be noted that the coverage plot shown below includes some noise and turbidity present in the water column and does not constitute a final point cloud product. Initial processing was carried out to remove erroneous and obvious noise but additional processing was conducted later to fully clean the dataset and classify all points according to Blom Aerofilms processing procedures. This is discussed further in the "Project data coverage, quality, and accuracy" section below.

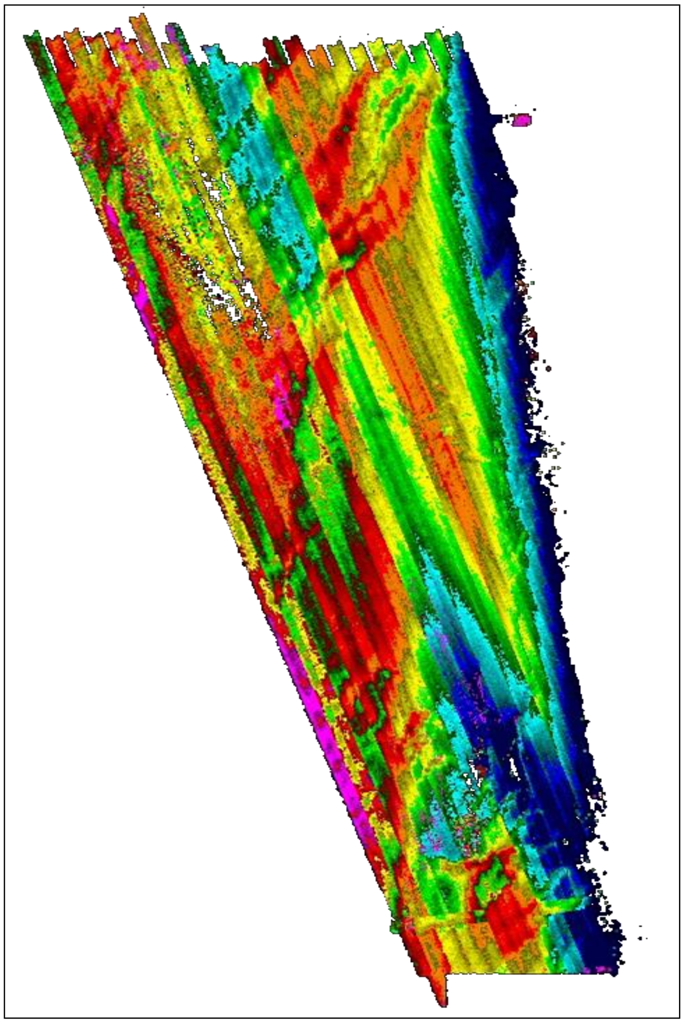


Figure 1. Initial coverage plot of the project area

The LIDAR system arrived in Martin County on the December 7 and was based in Miami due to its proximity to the project site. During this capture phase some poor local weather conditions were experienced which resulted in additional re-flights being carried out in the area to ensure that the project specification was met as best as possible given the timing and local conditions during the survey.

On the 7th of December, low fog and clouds prevented data capture beginning on time. This however did allow the outstanding re-flights to be completed at the BNP survey area that had been identified. The following day poor water clarity was reported which was highlighted by the ground crew for re-flights when the water quality had improved. The 10th of December saw the completion of nine re-flights along with all additional flight survey protocols. At this time, the airborne operator in the aircraft also reported water being present in the photogrammetric hatch onboard the aircraft which required attention during downtime. This problem was rectified as soon as possible with data being checked and highlighted for rework as required. The final day of capture was used to finalize all re-flights and make final quality checks on the data prior to the crew demobilizing back to the UK.

The project was classed as a Risk Category A by Blom Aerofilms at the time of tender which proved to be correct as the survey and topographic geography of the survey area was easy to plan and navigate. A client representative was also onsite during acquisition to examine data capture and the quality of the laser data.

The depths to be achieved from the survey were expected to be between 0 and 30 m which came from assessment of green laser wavelength data using SeaWiffs at the time of tender. The actual depths in any bathymetric LIDAR survey are dependent on water clarity and sea bed reflectivity at time of acquisition. Depths can be maximised to those expected by ensuring acquisition takes place during times of good water clarity and weather conditions. A full indication of average and maximum depths achieved in the project area will be given in the final survey report at the end of the project.

Flight control and ground control.— The survey area was covered with 53 survey lines; including three cross lines. The flying height for the survey was 500 m (approx 1600 ft) as required to achieve specification; flight speed was near 150 knots (approx 290 km/h).

The flight control was achieved using dual frequency GPS. An existing Active Network of control CORS stations was used for the LIDAR mission, with data obtained at a 1Hz rate by Blom Aerofilms. This was carried out in order to maximise the flexibility of the airborne operations during the initial processing stage as detailed below.

The one second RINEX data from the active CORS base stations used for the project was downloaded by Blom Aerofilms as detailed above by the field survey manager onsite during the project. The initial trajectory processing was achieved using POSPac v.5.1 utilising active points (using the weighting strategy implemented in the Applanix software). The GPS RINEX data for the stations detailed was obtained by Blom Aerofilms during the time of survey and used to produce an initial point cloud and shown in figure 4.1 above.

In addition, to confirm the accuracy of the laser data captured in the project area, Blom Aerofilms flew and acquired data over an existing GPS monument that formed part of the existing GPS network. This information acquired during this flight was used during the project processing to confirm the data was to specification and what shifts, if any, were required to the dataset. This was viewed as a suitable solution as there were no additional GCA areas established for the project.

Initial product processing.— The initial processing that was carried out on the dataset is detailed below. Additional processing followed in order to produce final deliverables required for the project and to ensure the project and quoted system specification was met whilst taking into account the timing of the survey.

- GPS data processing using CORS RINEX data available onsite
- Data processing in CSS. Production of initial point cloud
- Export from CSS. Import data in Terrascan for basic cleaning
- Remove very high and low points and obvious noise in water column
- Check coverage. Identify areas for re-flight as required.

Project data coverage, quality, and accuracy.—

Initial data coverage evaluation.—Detailed below are a series of images detailing the level of coverage that was achieved. It should be noted that the level of topographic data coverage in places yields a lower point density due to the local conditions and intensity of the topo laser. This was not the case across the whole project as overlapping flight lines in some areas provided a high point density and a more complete level of coverage. Figure 2 illustrates this point.

The blue points shown in Figure 2 represent hits from the green hydrographic laser that can be used to 'fill in' lower density areas on land where the specification is in question. The issue with using this data as a remedy or substitute for the topo laser points is that the hydro points are not as accurate on land as the hydrographic laser wavelength is designed primarily for water and not land.

Figure 3 shows increased topographic coverage but with data voids caused by trees, buildings, or roads which typically offer a very low reflectivity value causing these gaps to be represented as black spots. There could also be manmade water features such as ponds with low reflectivity. When analyzing the data, it can be obvious what has caused data voids. In this case the gaps in Figure 4 were due to high vegetation on the ground (trees).

Figure 5 shows an area of bathymetric data with lower data density between the flight lines where no flight line overlap exists. This is common and is to be expected as part of a project but achieving complete coverage in areas like this can sometime be challenging if the water quality and salinity is suspect.

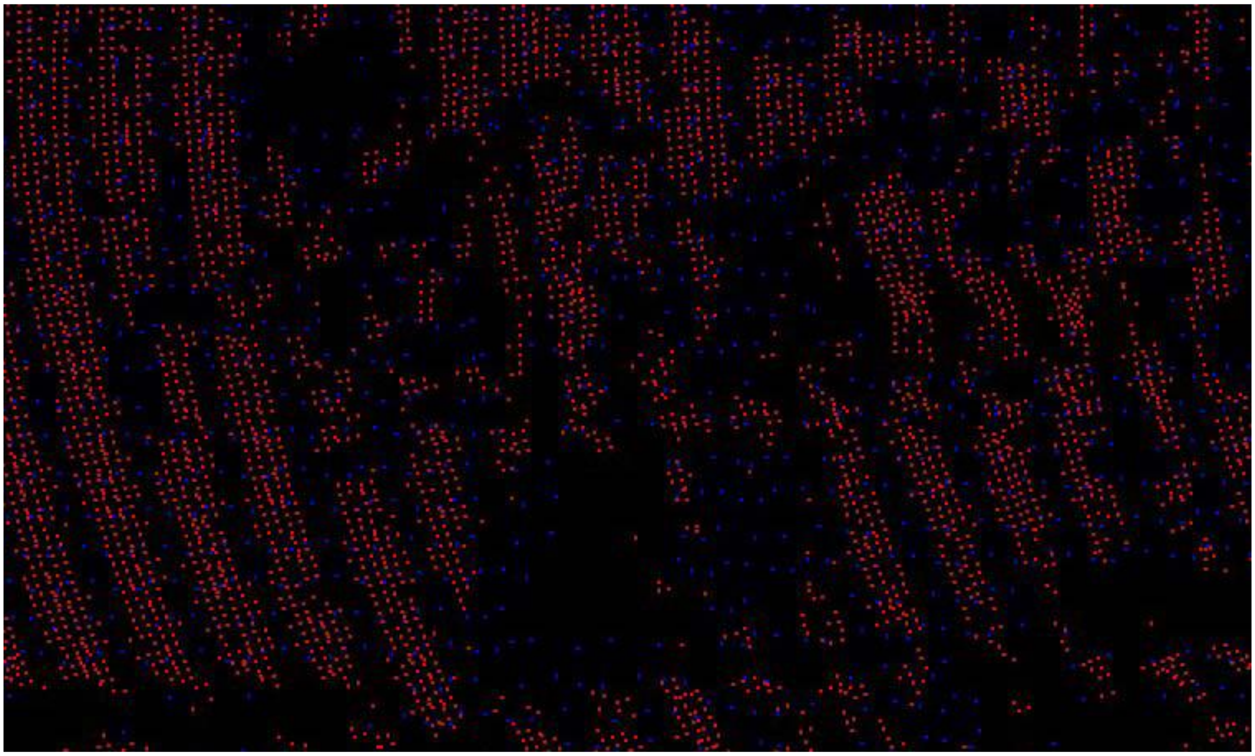


Figure 2. Topographic scanner gaps.

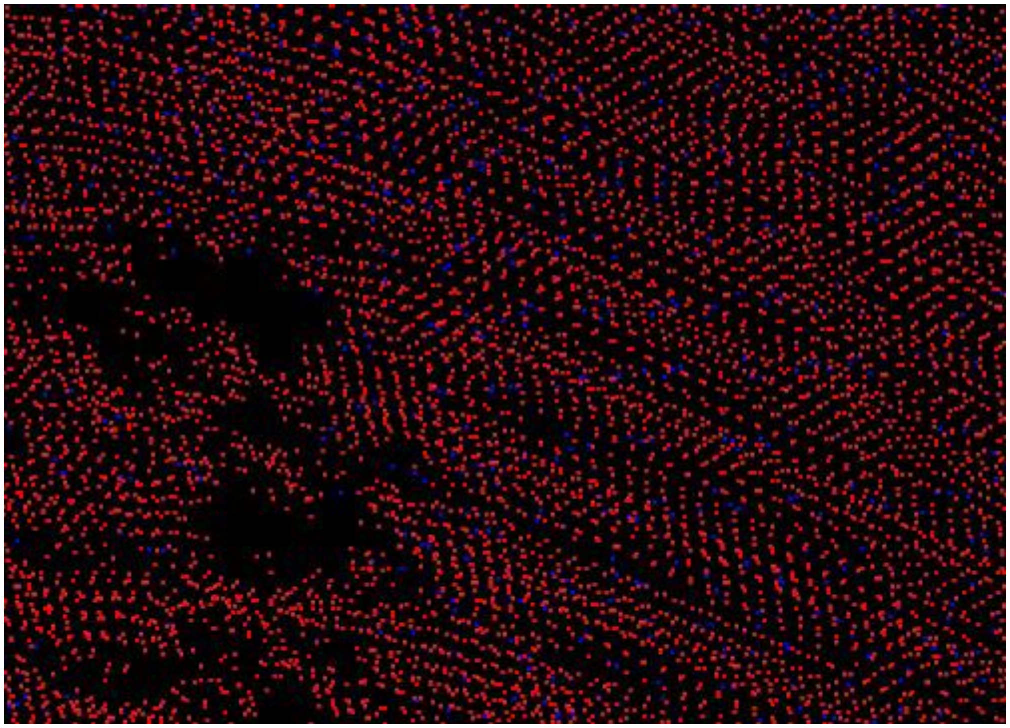


Figure 3. Topographic data gaps.

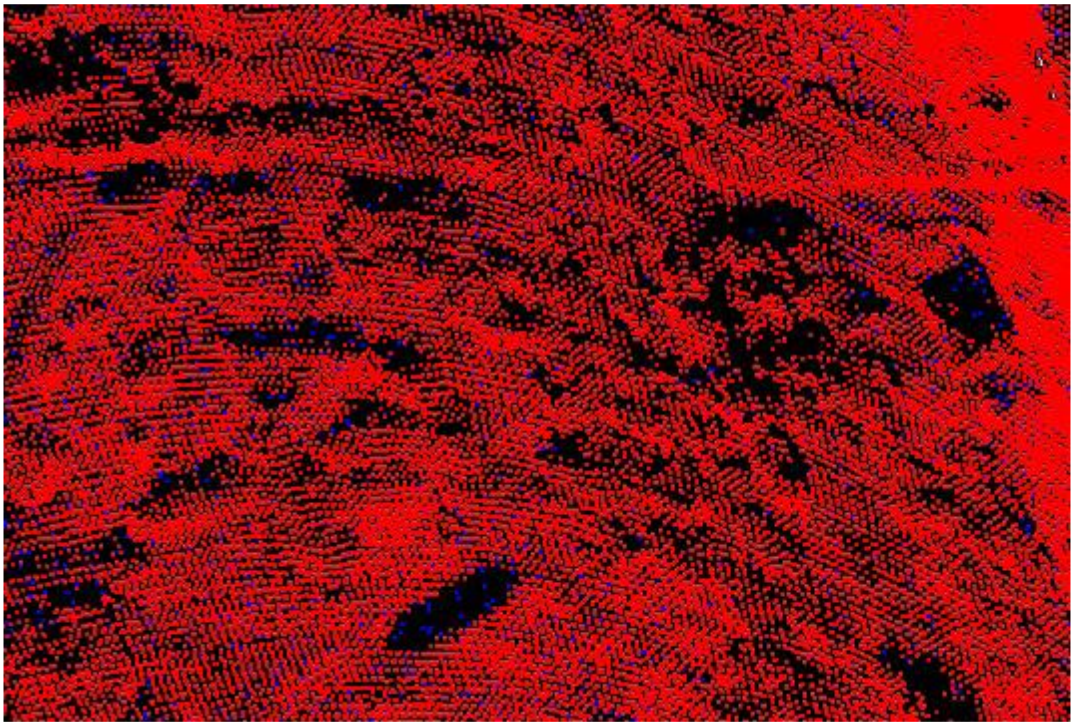


Figure 4. Topographic data gaps caused by trees.

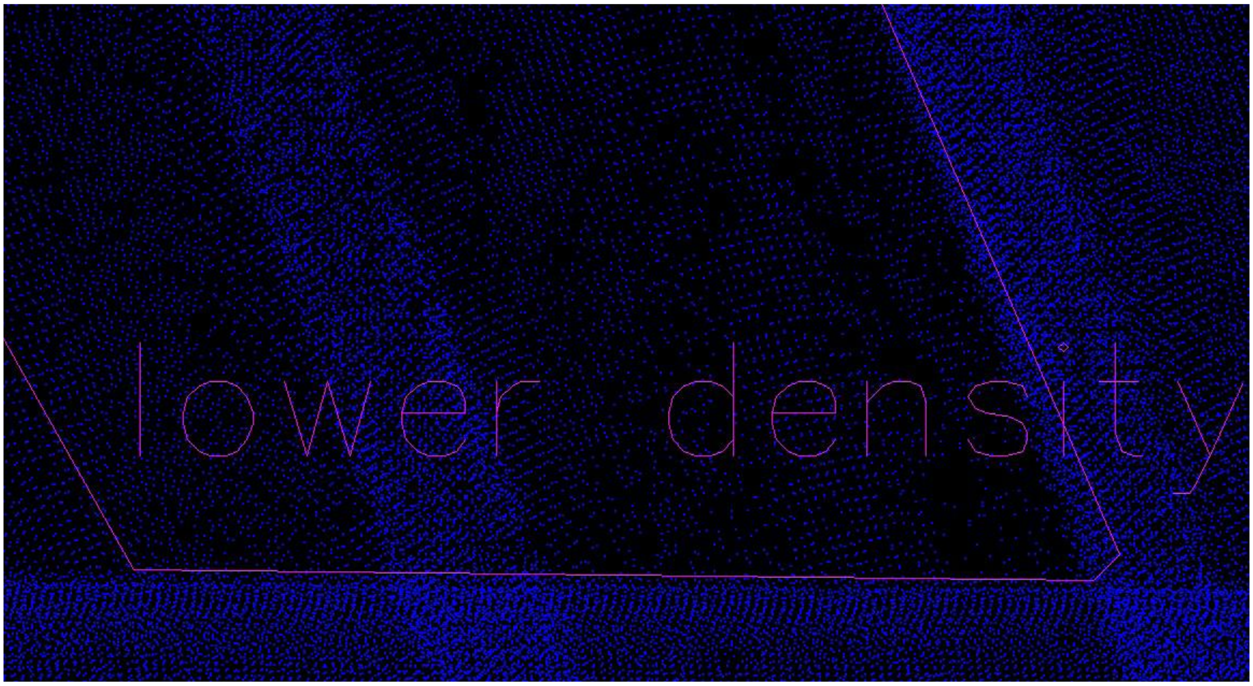


Figure 5. Data density of bottom points.

Many of the data gaps were caused by bad weather conditions onsite at the time of survey, mainly from poor water quality and turbidity, which was especially evident close to the shoreline. The number of these gaps could have been greatly reduced if the survey was conducted during more suitable local conditions (summer), however, this was ultimately unavoidable. Surveys were planned to be conducted in June 2008. Delays causing Blom Aerofilm's late arrival to South Florida were many including a cracked plane windshield, major LIDAR system maintenance, and the precedence of other projects. Surveying was conducted in December because the mobilization costs of the Martin County mapping was shared with the LIDAR collection of Biscayne National Park which had a strict deadline of December 31, 2008 and could not be postponed for better conditions. As expected by project managers and the principal investigator, this was one of the worst possible times of year to survey Martin County.

In terms of coverage per flight line, the project boundary was covered. However, in areas of deeper water out to sea, data coverage and density was reduced. The levels of noise both in the atmosphere and in the water column were extreme and were removed and classified accordingly (Figure 6). Pink points are representative of noise levels which, once removed, left areas in the project with lower density and coverage.

It is common for any ALB system to pick up surface hits on the water and not the seabed where high levels of sea action, surf or foam exist. The traditionally complex intertidal zone, where good shallow water algorithms are required, has to be surveyed during the best possible local conditions. Otherwise, the results gathered are to a degree, useless. Were these areas to be flown in calm conditions, you would expect to gather a seamless profile of the seabed all the way up to the limits of the coast and the beachhead. Instead there were high noise levels resulting in a gap due to water quality not system error.

Figures 7 through 11 are some further examples of where gaps exist due to this issue as shown in Figure 6.

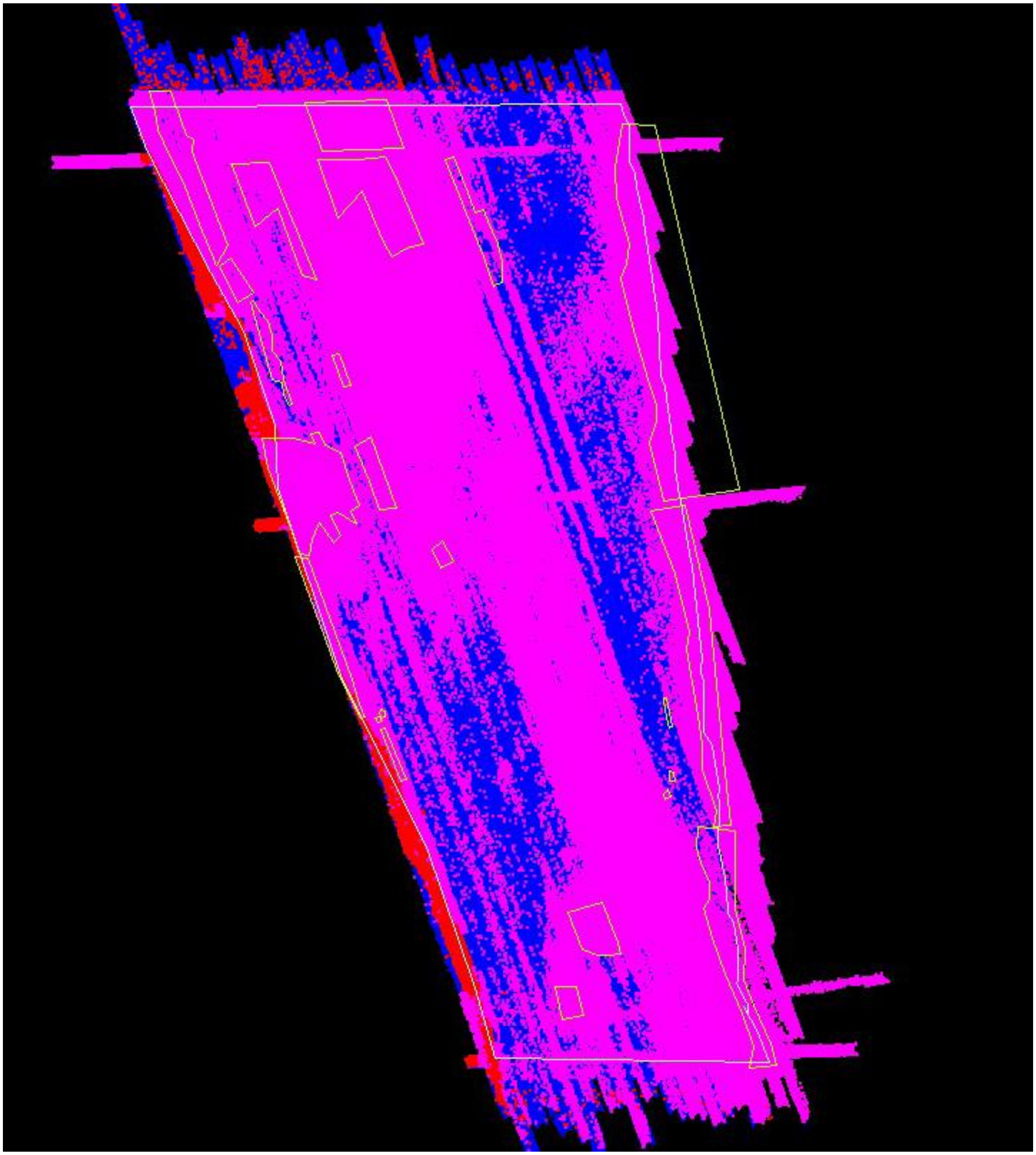


Figure 6. Overview of data gaps. Pink points contained too much noise and may be discarded.

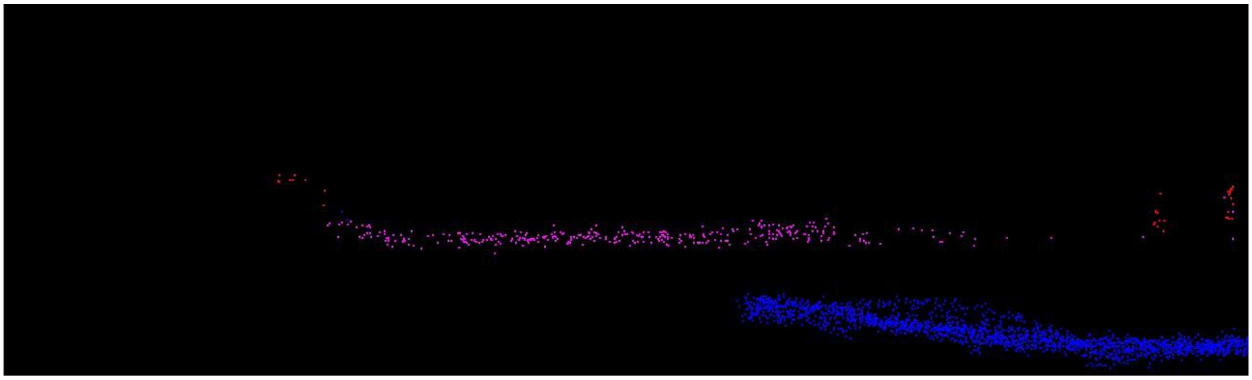


Figure 7. Cross section of the data noise. Blue dots represent good bathymetry data while pink and red dots are noise artifacts.

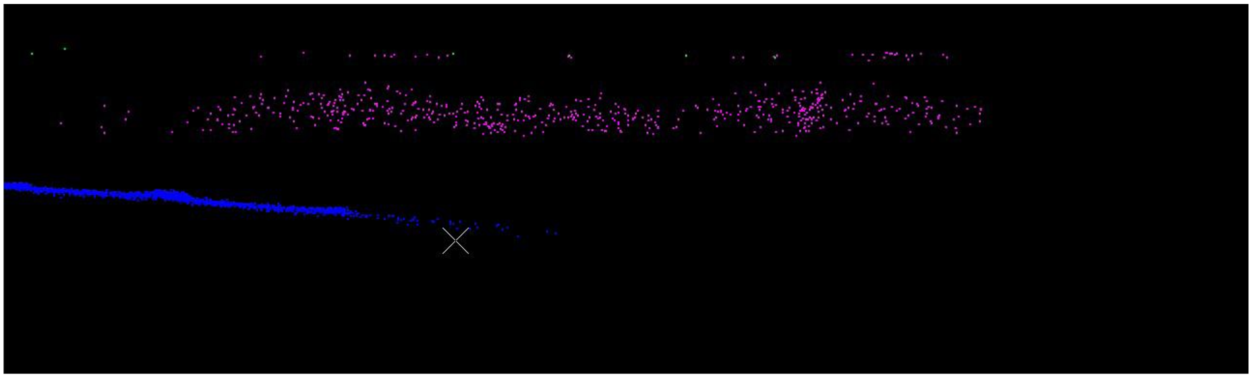


Figure 8. Noise example 2.

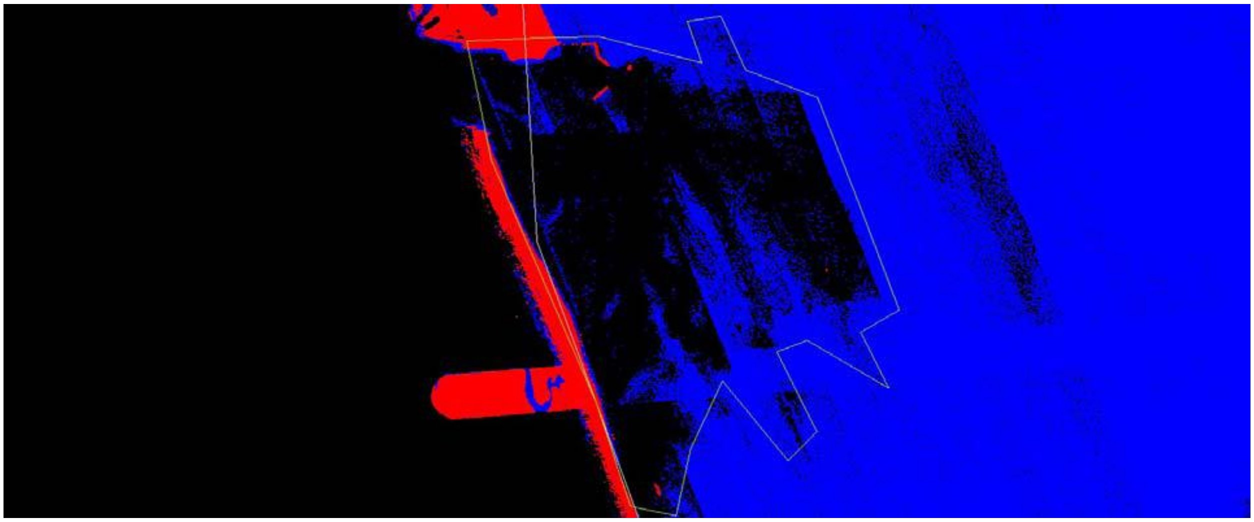


Figure 9. Turbidity Gap 1.

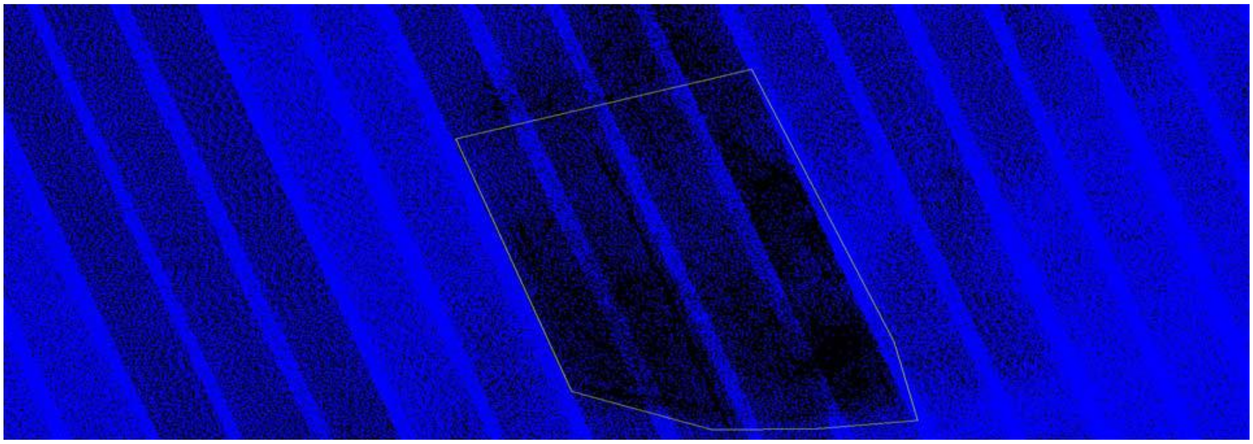


Figure 10. Turbidity Gap 2.

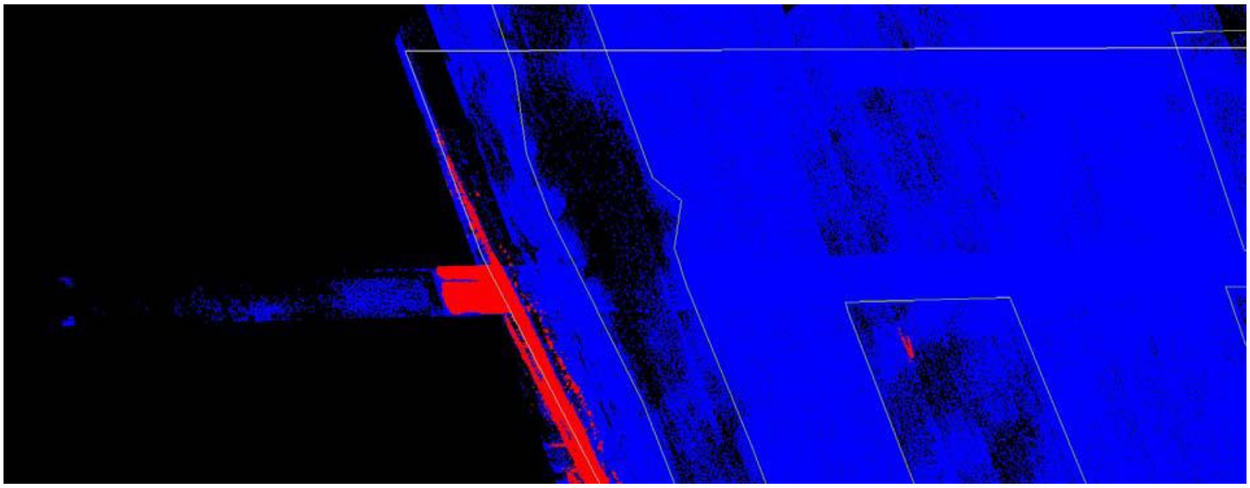


Figure 11. Turbidity Gap 3.

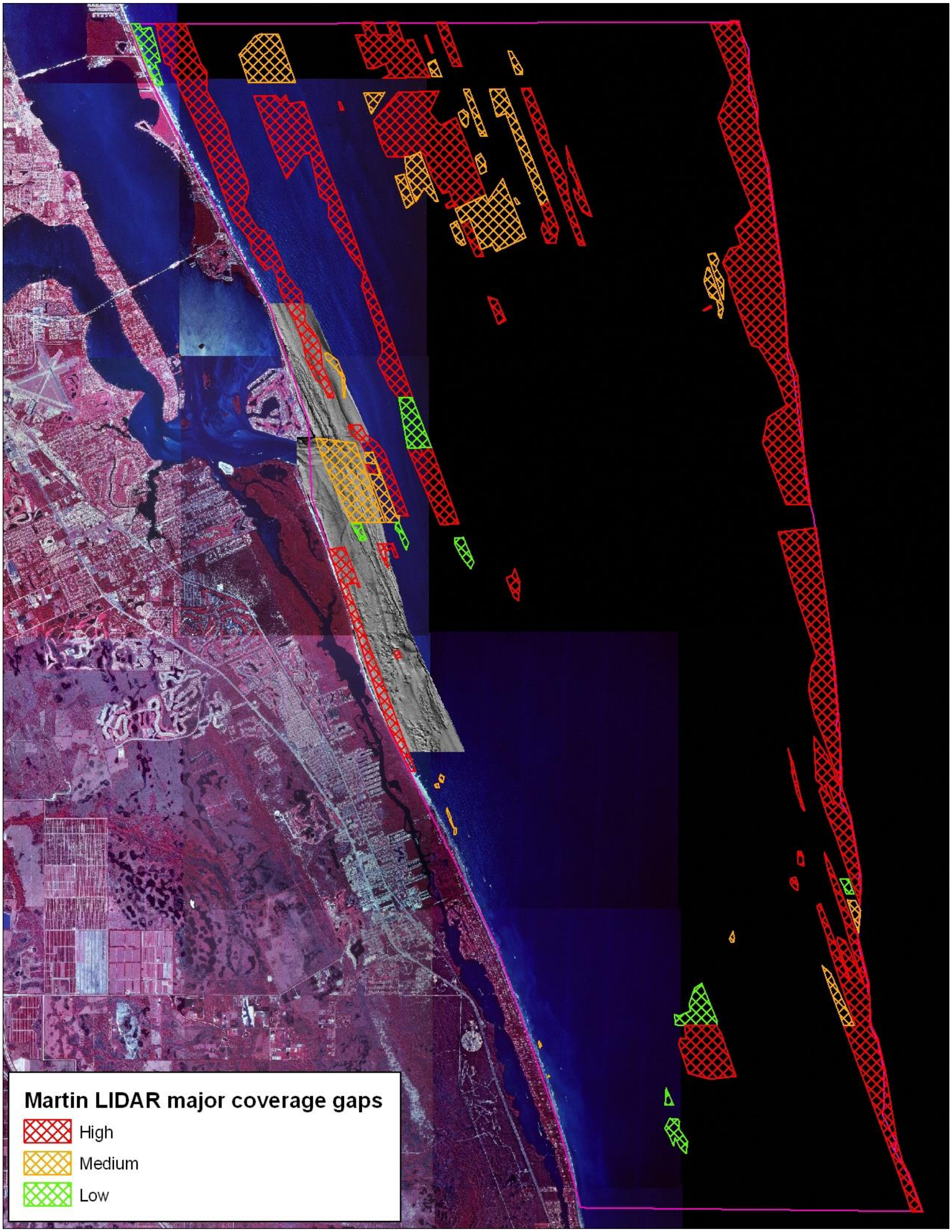


Figure 12. Overview of data gaps (polygons).

The initial data were evaluated for coverage in GIS to determine the extent and severity of the data gaps. Once the noisy data were removed, the clean data were visually evaluated for significant gaps in coverage over the project area in ArcGIS. Vector polygons were drawn around areas with significant gaps in coverage and ranked accordingly (Figure 12). High areas contained significant data gaps in excess of 20 m, Medium areas contained 10 – 20 m gaps, and Low areas contained 5 – 10 m gaps. Most of the data gaps were in the north part of the county and along the 25 – 30 m deep margin where laser extinction occurred due to depth. The areas were calculated and summarized for each group and resulted in a total of 51.5 km² of coverage gaps; 40.7 km² of High, 8.4 km² of Medium, and 2.4 km² of Low. These large areas of high and medium gap coverage were unacceptable for habitat mapping because the bathymetry was the primary data source to create habitat maps in deeper water. Therefore, Blom agreed to perform re-flights to obtain full coverage. See Reflight section below.

Initial data quality and accuracy.— When deciding if the data coverage was to an acceptable level, an analysis of the accuracy was also required to ensure that the project specification was met across the majority of the survey area.

The initial project specification was as follows:

Table 3. Project specification.

Survey Parameters:	
Altitude of flight	500m
Swathe width	330m
Flying Speed	150 kts
Flight line overlap	30m (approximate)
Post spacing (Sea)	4m x 4m nominal per flight line
Post spacing (Land)	1m x 1m nominal per flight line

In order to compute the accuracy achieved across the project a series of 4 x 4 m grids were created and overlaid onto the data to show the quantity of points within these individual grid areas. This provides a snapshot and an immediate view of the accuracies that have been achieved at this stage.

Below are 2 examples taken from the bathymetric data; the first showing a grid where good data density was achieved (Figure 13) and the second showing where the specification was not met due to poor water quality (Figure 14). In areas where poor water quality was evident, the point spacing and density was reduced to where some grids contain no points (laser returns from the seabed).

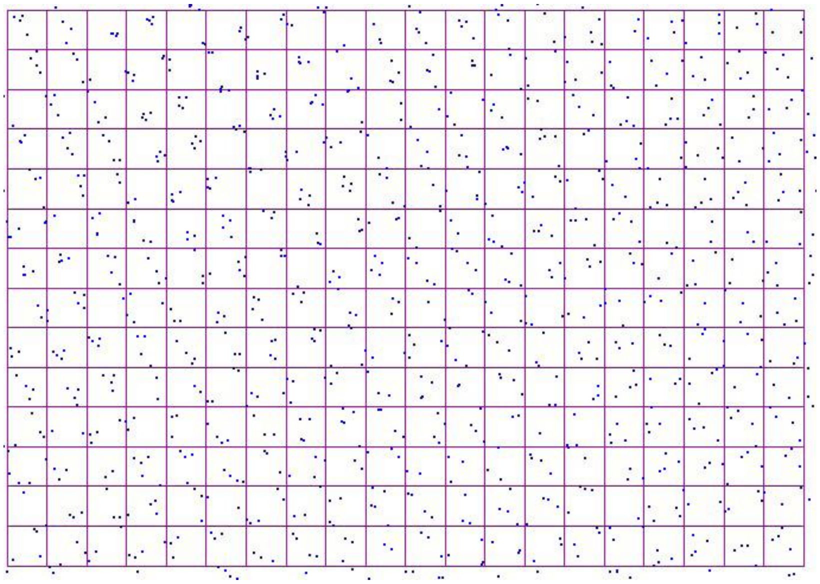


Figure 13. 4 x 4 m grid – data conforming to specification.

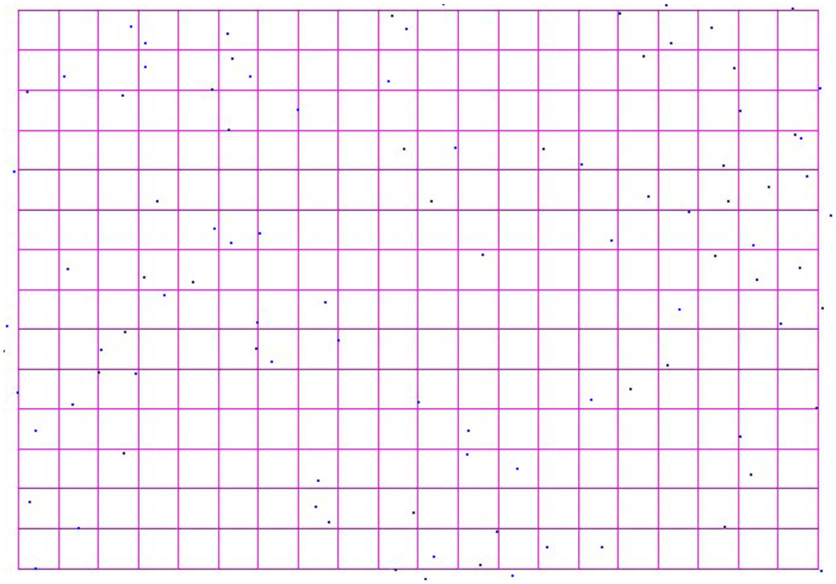


Figure 14. 4 x 4 m grid – data outside specification.

Reprocessed data quality and accuracy.— In May 2009, the previously submitted coverage data was reprocessed and exported with additional matching parameters applied within Blom Aerofilms flowline and software environment which reduced a number of the errors discovered and documented in the initial processed data. This was carried out to produce a better flight line match between differing GPS days where mismatches were evident. The next stage was to ensure the trajectory solutions that were achieved were satisfactory and produced the desired result before laser data classification could begin. Once the results were established as being within specification, laser data classification and cleaning commenced. The stages that were carried out were as follows during this time:

- Additional flight line matching parameters were applied to the data to reduce residual errors (TerraMatch)
- Laser data classification and cleaning (TerraScan)
- Stage 1 reflectivity processing (backscatter)

In order to ensure production based estimates were met, editors were given daily targets to meet which included analyzing and reporting on data quality and issues as they were discovered in the data. The data were also "spot checked" during this time to ensure standards were maintained and that the points were being classified correctly with all noise and erroneous points being classified as such. Blom Aerofilms Quality Management System ensured all editors document the difficulties that were being experienced in line with normal QC procedures. This allowed all parties involved (Processing Supervisor, Technical Manager and Project Manager) to report and flag these accordingly.

During the course of the laser data classification the editors were asked to keep a record of any areas which were suspicious and required further attention. This was only noted on the areas that had been fully classified. A cross section of the area in Figure 15 shows the significant amount of noise classified in the near shore coastal area which has left the resulting gap in the data (Figure 16).

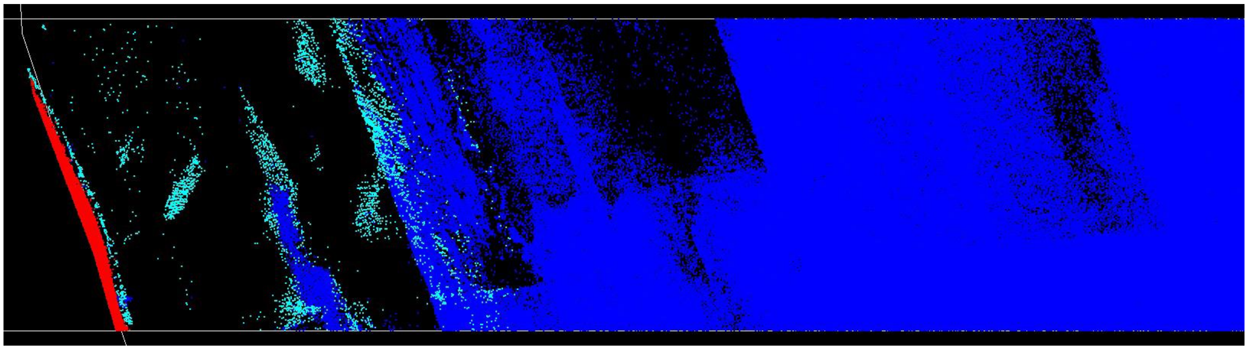


Figure 15. Data gap 2.

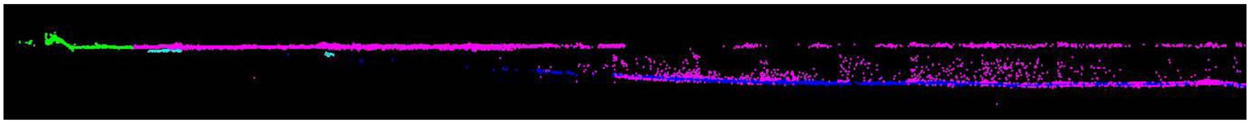


Figure 16. Cross section of noise in Figure 15.

At the very limits of the project boundary there were data gaps which resulted from the laser extinction zone amplified by the turbid waters during the time of survey. These areas were classified as noise as validating the 'pings' in these areas was not consistent as the level of noise generated in the water column raised questions over the accuracy of the points. The following examples from bins 13 and 31 in Figures 17 and 18 below illustrate this. Figure 19 illustrates the level of noise in the data by showing a cross section drawn through bin 31 where the pings in question have been classified as noise (pink).

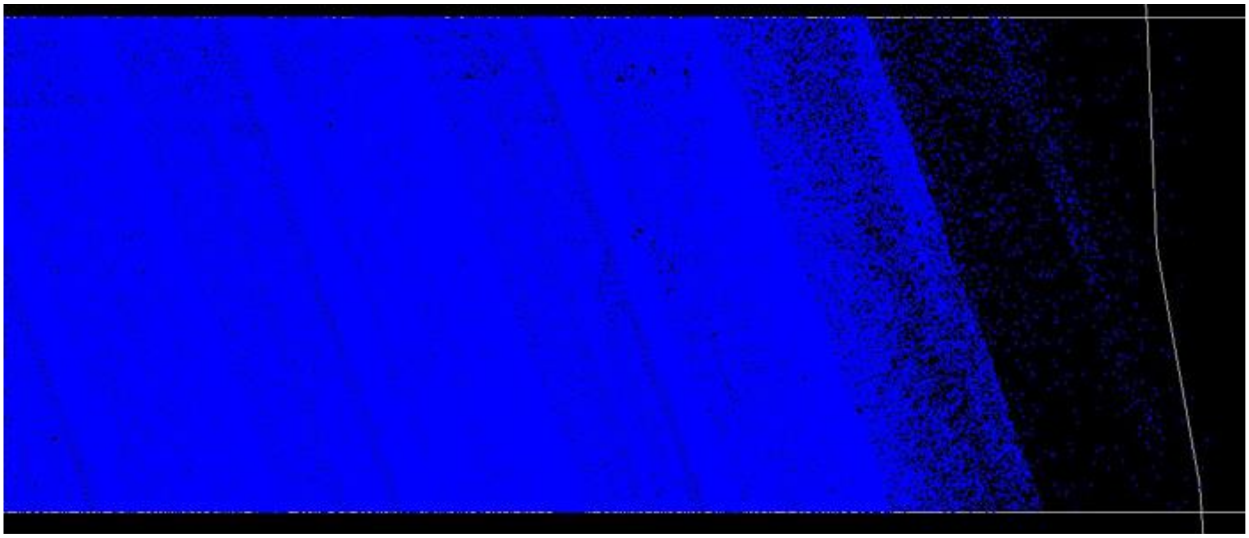


Figure 17. Plan section of project limits – bin 13.

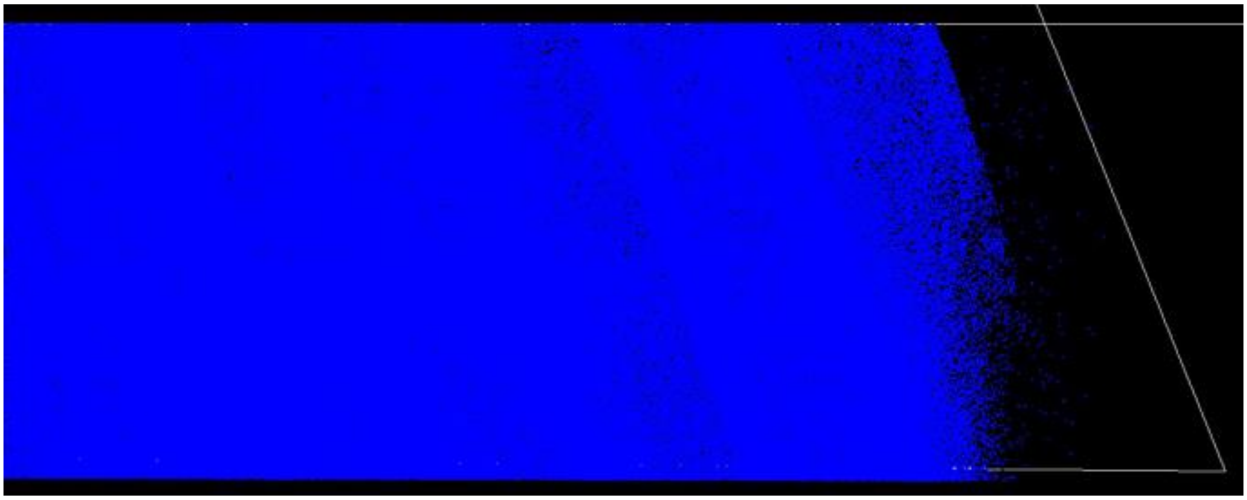


Figure 18. Plan section of project limits – bin 31.

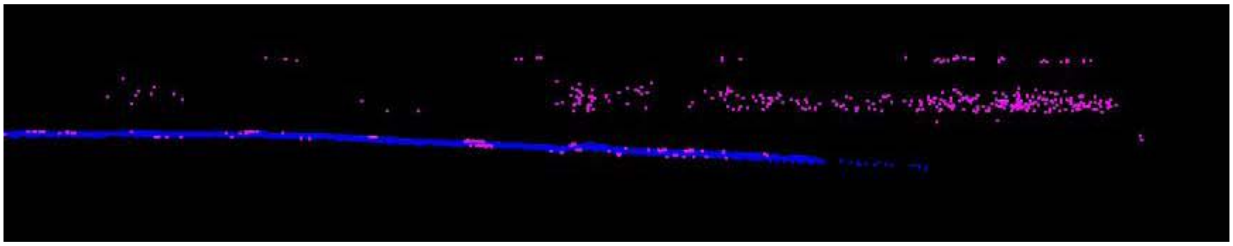


Figure 19. Cross section of noise– bin 31.

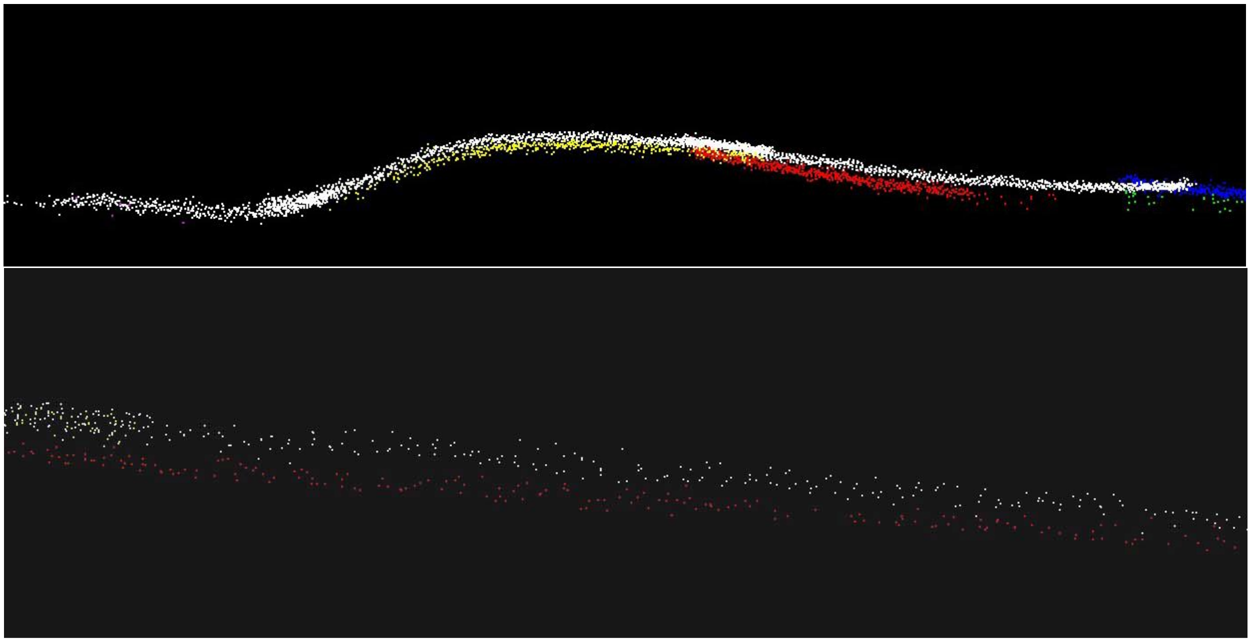


Figure 20. Cross sections of noise from bin 31.

In addition to the basic classification of the laser data, additional flight line matching parameters were also applied to the flight lines in order to improve the vertical accuracy of the data as in places the matching carried out prior to the classification of the data had not produced the results that were expected. Typically, heading, pitch, and roll values are applied in CSS and carried through to the calibrated matched point cloud which is then classified. In this case the deviation of the flight lines was +/-40cm in places which required additional values to be applied manually in TScan on a case by case basis when discovered. Common misalignment issues discovered in the data (shown in Figure 20) were fixed by applying additional values in TScan.

Reflectance data.— Running alongside the laser data classification was the reflectance data processing required as a deliverable for the project. Blom Aerofilms ran this in 2 stages, one of which involved a validation stage carried out at the system manufacturer AHAB. This then formed the basis of the final reflectance product to be delivered with the final laser data. Stage 1 reflectance processing (BAL) is designed to prepare the raw data files to only include the values that will be required for the additional reflectivity information. This is carried out in the CSS environment and delivered to AHAB to then add the reflectivity values to the files for delivery.

LIDAR data processing.— The final 2008 LIDAR dataset was processed in ArcGIS 3D Analyst to create digital elevation models of the point data. Natural neighbor interpolation was used to create surfaces which were then hillshaded to illustrate the relief of seafloor features. The outcomes are illustrated in Figure 21.

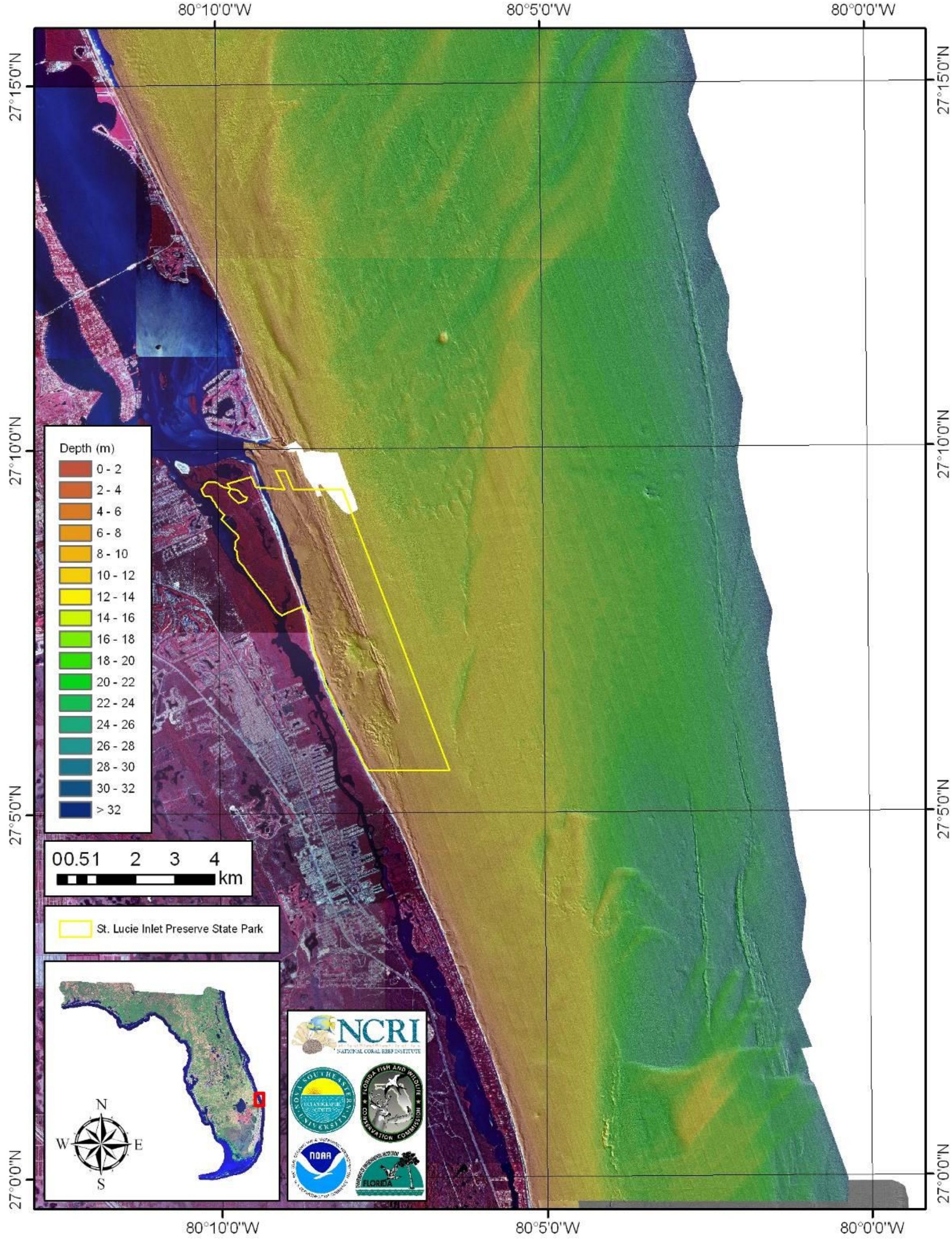


Figure 21. Martin County LIDAR bathymetry hillshaded topographic map of the December 2008 survey colored by elevation.

Phase I *Re-flights.—*

Re-flight acquisition.— As outlined above, the project area at Martin County was originally flown for LIDAR acquisition between the 7th and the 12th of December 2008. Large gaps remained in the original dataset that precluded seafloor mapping in certain areas, thus Blom agreed to re-fly portions of the original survey coincident with other work in the US to attain full coverage. The Martin County LIDAR re-flights were flown during December 24 – 27, 2009.

In order to validate the accuracy and ensure that the two datasets (original and re-flight) would merge when processed, a calibration was required on install which was then checked on arrival at Martin following the transit flight. The purpose of the calibration was to check all the system parameters were functioning and the IMU and lever arm values were consistent with the documented information on record. An overview of the calibration sites flown at Martin are shown in Figure 22 below.

The calibration sites contained the following features which allowed for detailed checking of both the hydro and topo datasets:

- Buildings
- Slopes (golf course bunkers are ideal to calibrate for roll)
- Sand (good for topographic intensity)
- Water (good for assessing the green laser penetration)

The calibration data was then processed independently of the rest and used to ascertain certain values that were then applied to the rest of the data. This was essential in order to appreciate any residual or systematic errors that may have been present in the system and therefore the data. After each of the three flying days, the following actions took place:

- GPS data processing using CORS RINEX data available onsite.
- Data processing in CSS; production of initial point cloud for production of coverage plot.
- Export from CSS and import data in Terrascan for basic cleaning.
- Remove very high and low points and obvious noise in water column.
- Check coverage and identify areas for re-flight as required

The last sortie was then checked and all the data analyzed against the spec for coverage and density and then delivered to Cheddar for final processing.

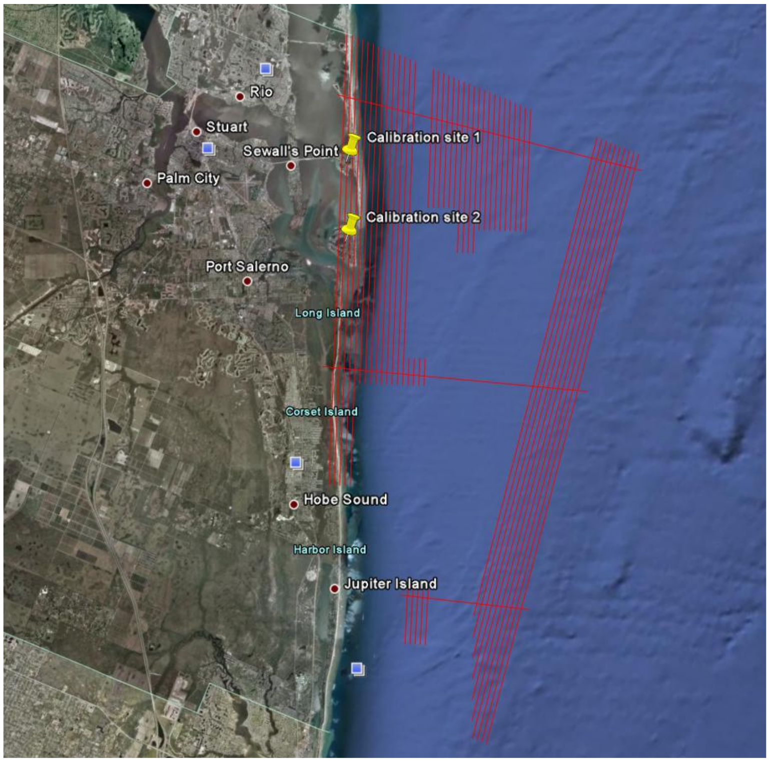


Figure 22. Planned flight lines for re-flights and calibration sites.

Re-flight coverage and data quality.— The following series of screen grabs are indicative of the coverage that was achieved at Martin County and have been partially classified in order to remove the level of noise so the images below are representational of the final data (subject to further cleaning prior to delivery).

As can be seen from Figure 23 most of the areas of concern were flown during day 1. The very outer limits of the project area were yet to be flown. It was estimated that 50-60% of the area was covered in 2 sorties over 5 hours on the December 24th.

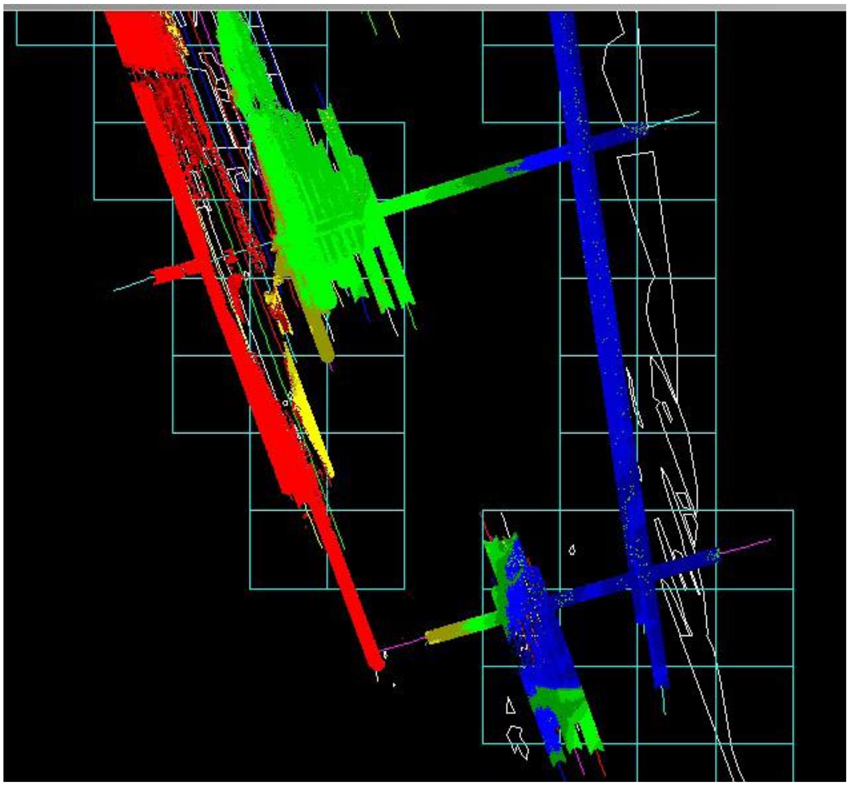


Figure 23. Data coverage collected on December 24, 2009 (by elevation).

During the production of the coverage plots, a great deal of water column noise was picked up by the green laser. These are represented by the pink points and were classified out of the data set prior to production of the coverage plots (Figure 24).

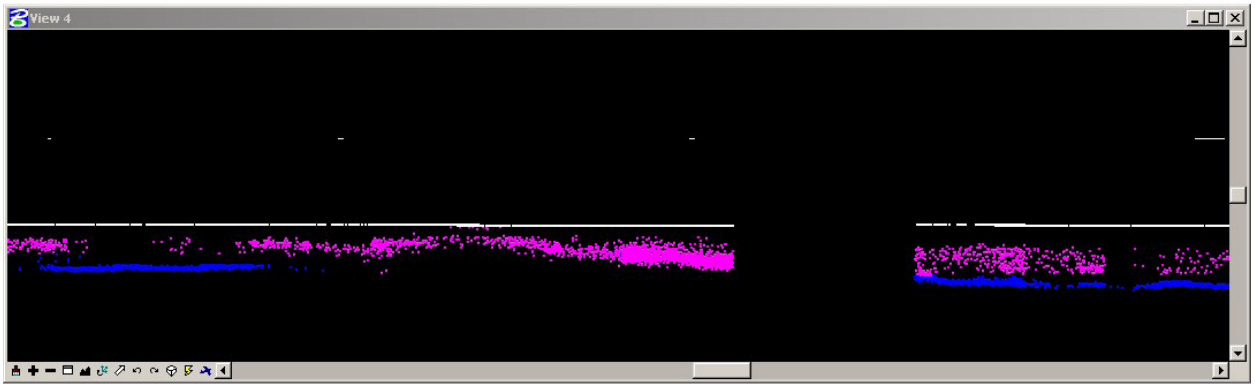


Figure 24. Cross section of water column noise (pink) in the December 24, 2009 data.

The field team also reported a small amount of flight line cusping (Figure 25) which was due to the roll parameter within the calibration file. This was adjusted and reduced during office processing prior to data delivery.

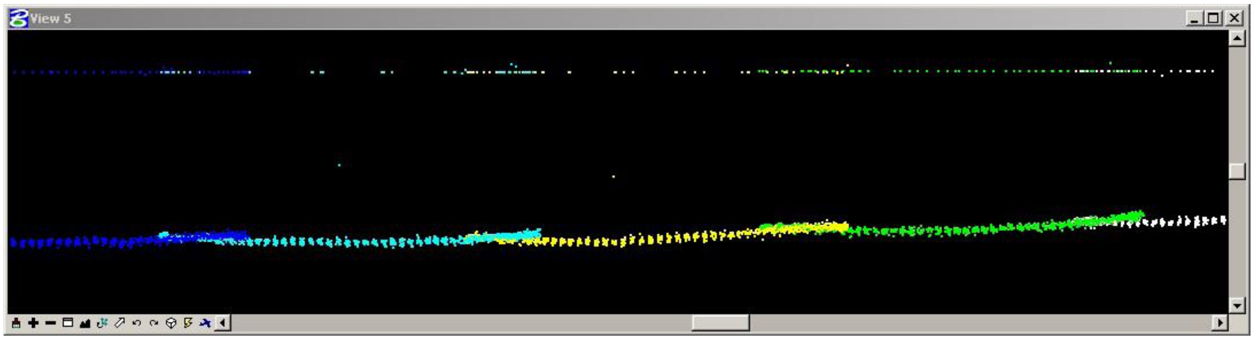


Figure 25. Flight line cusping.

No flying was done on Christmas day as conditions were not stable.

The weather conditions during flights on December 26 were very stable which meant data capture was up to 80% complete (Figure 26). Returns in the outer seaward boundary were down to 35 m which was where conditions hampered Hawk Eye during the mission in 2008. Line 27 was identified for re-flight as very little data was gathered during this pass.

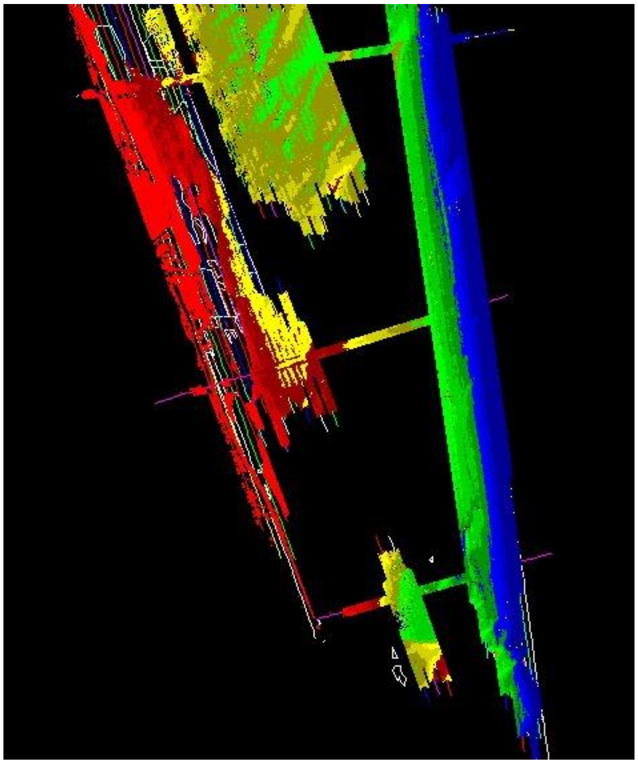


Figure 26. Data density of bottom points.

The last flight was carried out on December 27 and included a re-flight of line 27 which was flown twice, on both occasions returning very little data (Figure 27). The condition of the water within this line had deteriorated since day 1, when this line was flown originally, and is thought to be due to local turbidity and sediment transport. The view was taken not to re-fly this line again because a reasonable effort had been made on two different days to successfully gather the data and time could not be spared to repeat the line. The data that makes up this line was processed in such a way to extract as much data as possible from the software.

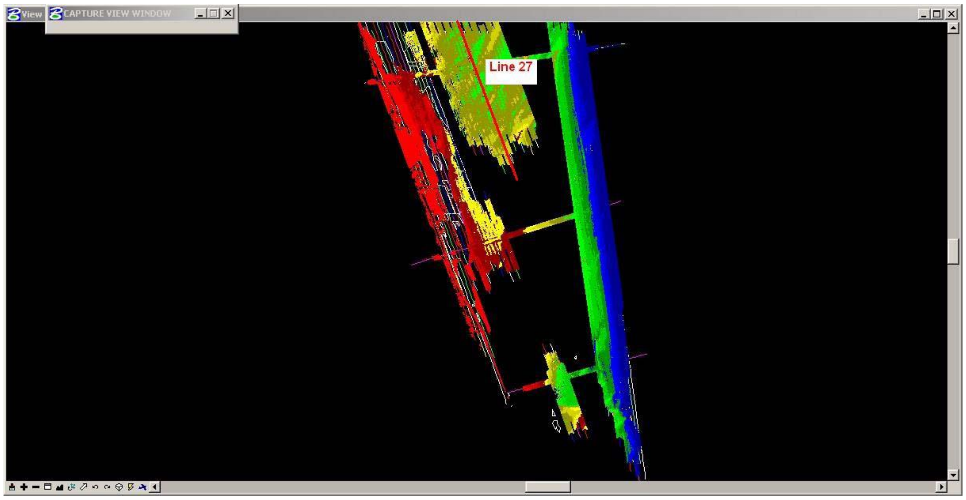


Figure 27. Line 27 re-flight.

All re-flights were completed by December 27, 2009 after a closing calibration flight over a local CORS base station. 11.2 hours of online task time were spent in acquiring the laser data.

All data were captured according to the project specification detailed below. This was checked and cross referenced during QC to ensure that the two datasets (2008 MC and 2009 MC) when merged, provide the best possible coverage of the project area.

Table 4. Re-flight project specifications.

Survey Parameters:	
Altitude of flight	500m
Swathe width	330m
Flying Speed	150 kts
Flight line overlap	30m (approximate)
Post spacing (Sea)	4m x 4m nominal per flight line
Post spacing (Land)	1m x 1m nominal per flight line

Re-flight data processing.— Blom delivered the processed re-flight data on July 9, 2010. The data were reviewed for coverage and converted into digital elevation models and hill-shaded images (Figure 28). The combination of the original and re-flight LIDAR provide approximately 98.5% coverage of the project survey area. Approximately 4.94 km² (1.5% of the total surveyed area) of shallow water LIDAR coverage was not attained during either survey; around the mouth of St. Lucie inlet and along the coast to the south. Regional USACE coastal LIDAR data cover most of these gaps leaving a 1.1 km² data gap around the inlet mouth, which is 0.32% of the total project area. Thus the combination of new and old LIDAR datasets (Blom 2009, Blom 2008, USACE 2006 & 2004, and PB LADS 2002) provided coverage for approximately 362.9 km² of the total 364 km² area of seafloor in Martin County from the 0 to 30 m contour.

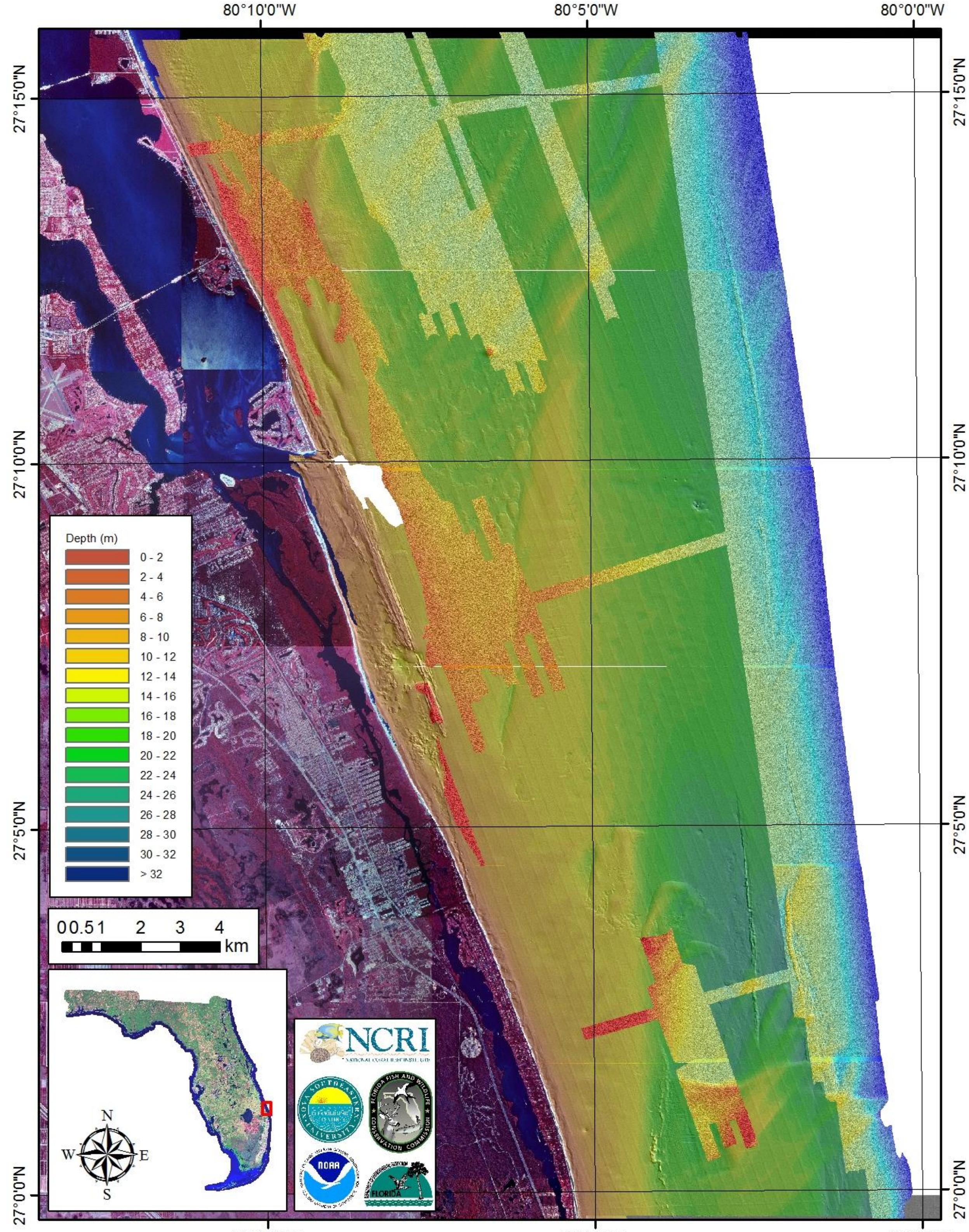


Figure 28. Processed re-flight data for Martin County. The speckled lines illustrate the usable LIDAR data collected during the 2009 re-flight mission.

The near shore area in Martin County was a problematic area to survey using LIDAR apparently due to turbidity. This appears to be a recurring problem for LIDAR surveys in this area where the 2006 SHOALS data, the 2008 Blom surveys, and 2009 Blom surveys contained significantly reduced density, especially near the inlet mouth.

The 2009 re-flight data have proven to be useful in detecting small objects that were not evident during the original surveys (Figure 29). An example is shown in Figure 28 where several small features are obvious in the 2009 data that were not present and would have otherwise been missed. The 2009 data also extend coverage out to deeper waters up to 750 m further offshore than the previous 2008 survey.

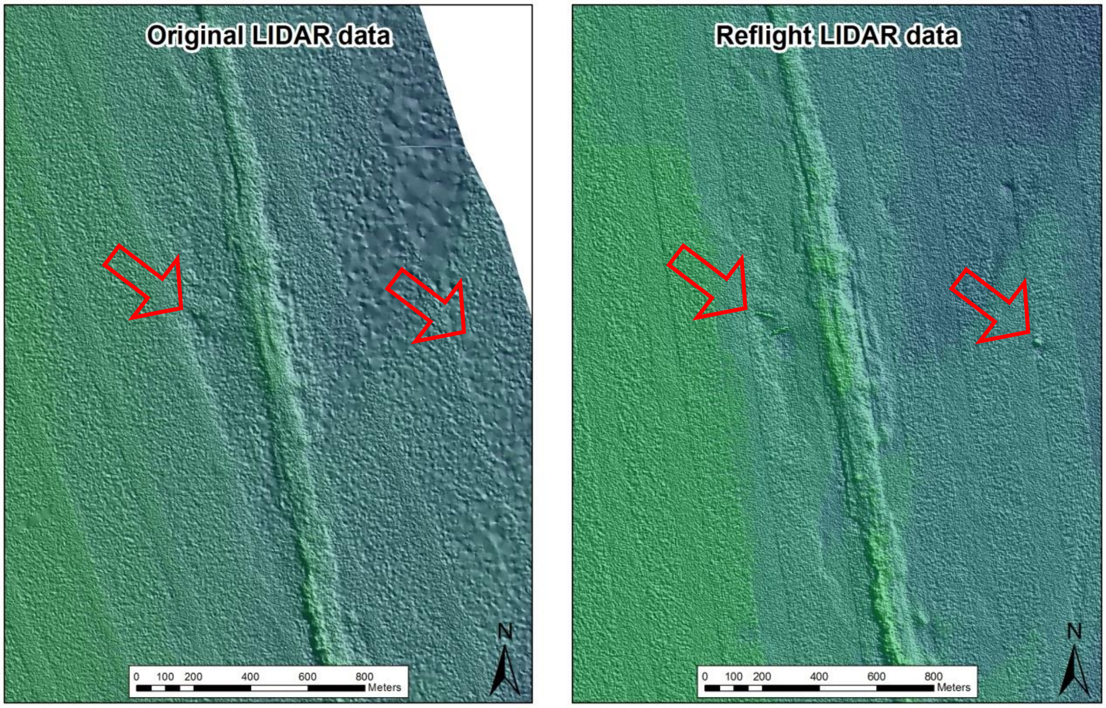


Figure 29. Original (2008) (left) and re-flight (2009) (right) data for Martin County. Several small features are visualized in the 2009 data set that would've been otherwise missed.

Phase 2.—

Benthic habitat map.— Benthic habitat maps were produced by delineating seafloor features evident in multiple datasets including the 2008 and 2009 high resolution LIDAR bathymetry and aerial photography collected from Phase 1. Phase 2 started in April 2010 and continued until August 2012. The habitats were classified according to established NOAA guidelines in coordination with the NOS Coral Mapping Program and use a similar classification scheme when possible. Figure 30 shows the final polygon delineations.

Of the 374.43 km² seafloor mapped in Martin County, the polygon totals indicated 95.21% was Sand, 4.13% was Coral Reef and Colonized Pavement, and 0.66% was Other Delineations (Table 5). These totals are estimates due to some habitats having a large mix of sand within. For example, the Scattered Coral/Rock in Sand category contained varying unknown ratios of sand to hardbottom. This habitat comprised 0.08 km² of habitat, 0.02% of the total area, so the impact of this issue is minimal in Martin County.

The Martin County benthic habitat morphology is very different than the other counties further south. Hardbottom habitats are sparse outside of a shallow, near shore area around St. Lucie Inlet and a few thin deep ridge lines which taper or are buried further north. All of these features are thought to be cemented beach dunes submerged during the last Holocene sea level transgression. Although not confirmed by coring, they do not appear to be composed of a coral-derived framework and they do not exhibit any morphologic signs of historic reef growth like the spur and groove formations of the Outer Reef which terminates in Palm Beach County near Lake Worth inlet (Banks et al. 2007; Walker 2012).

The most extensive deep hardbottom is the northern end of the Deep Ridge Complex which extends from Palm Beach into southern Martin for about 2 km before it appears to be covered with sediments. Only small, thin portions of the tallest ridges are exposed further north. In southern Martin there are three shore-parallel deep ridge lines. The first deep ridge, nicknamed 3 Holes, is located approximately 2 km from shore in 18 m water depth and extends approximately 3.5 km northward in a mostly continuous arrangement. The second deep ridge appears at the same latitude that 3 Holes terminates, but it is approximately 6 km from shore in 22 m of water. This feature extends northward in a mostly continuous fashion for about 6 km. The third deep ridge, nicknamed 7-Mile Ledge, is the most conspicuous deep hardbottom feature. Despite its name, in southern Martin this feature is located approximately 6 km (~ 4 miles) from shore in 22 m of water. This is also its widest portion at just about 0.5 km. This ridge extends northward over 23 km with relatively few (4) small breaks or gaps. At its northern terminus, it is located about 12.8 km (8 miles) from shore in 25 m water depth.

There are shallow hardbottom habitats extending throughout the county, but the majority of the habitat exists near St. Lucie inlet. This is comprised of two habitats, Colonized Pavement-Shallow and Ridge-Shallow. The differences between their distinctions are mainly morphological. The Ridge-Shallow has an obvious linear morphology and usually contains higher relief, at least at larger scales. The Colonized Pavement-Shallow is typically lower relief and has no distinct linear morphology. This distinction was difficult in Martin because it is likely that the Colonized Pavement-Shallow derived from eroding Ridge-Shallow. These two habitats are very similar and can be lumped together as the Nearshore Ridge Complex. They were left separate due to distinctions evident in the quantitative ground truthing data (see below).

The shallow Martin County ridges extend 2.5 km north of the inlet and 11.5 km south in a shore-parallel orientation. The eastern side resides in about 10 m depth, it crests near 3 m and the western side remains shallow in some parts and drops back to 10 m in others (mostly in the south). The shallow colonized pavement is located westward of the shallow ridge in waters 10 m to 4 m deep, sloping upward toward shore. As with other features along the northern Florida Reef Tract, these ridges terminate at the shoreline. The northern terminus is known as Bath Tub Reef and the southern end slips under the shoreline just off Bridge Road on Jupiter Island. Small portions of shallow ridge appear north of the inlet off Jensen Beach. Also, further south along Jupiter Island there are what appear to be small colonized pavement patches however these were not confirmed and recent imagery suggest this environment has significantly changed due to beach nourishment activities. These appear to be ephemeral communities affected by high wave energy and shifting sediments.

The ground truthing effort provided 432 locations of drop camera video recordings that took seven days to collect (Figure 31). These data were integral in the map development, but unfortunately, due to logistical constraints and cost, not all areas were visited for ground truthing. This leaves some areas unchecked, even after accuracy assessment. The nearshore portion is likely to be affected more than deeper, more stable areas. Beach construction, storm activity, and natural littoral drift all have an effect on the type and arrangement of near shore sea floor habitats and depending on their magnitudes may cause large-scale changes through time. Although deemed complete, these maps were created using data from 2008 and 2009 and many changes may have occurred since that time. The maps will need updating as future information becomes available to stay current.

Martin has extensive sediments in the shallow waters offshore. Approximately 356.49 km² were identified as unconsolidated sediments, however there were different sediment features within these polygons that were not part of the mapping. The most evident features were large sand dunes throughout the county. These were most visible in the bathymetric maps as smooth, wavy features extending to the northeast (Figure 21). In the south, these dunes appear to be partially or totally burying portions of deep ridge habitats (Figure 32). An elevation profile of this feature shows an 11 m height extending over 2.25 miles wide (Figure 33). Little is known about the movement of these features, but given the dynamic environment and the frequently high currents, it is likely that they are migrating across the seafloor, including over the deep ridges.

Another interesting sand morphology was the appearance of sand ledges (Figure 34). These areas appeared in the bathymetry as hard ground and thus were visited extensively during the ground truthing, however all of the videos showed extensive sand plains with 0.5 to 1 m drops and rises to other sand plains (Figure 35). No hardbottom was seen around these areas. The origin and formation of these features remains unknown at this time. This has no effect on the outcomes of the habitat map since all these areas were comprised of unconsolidated sediment bottom.

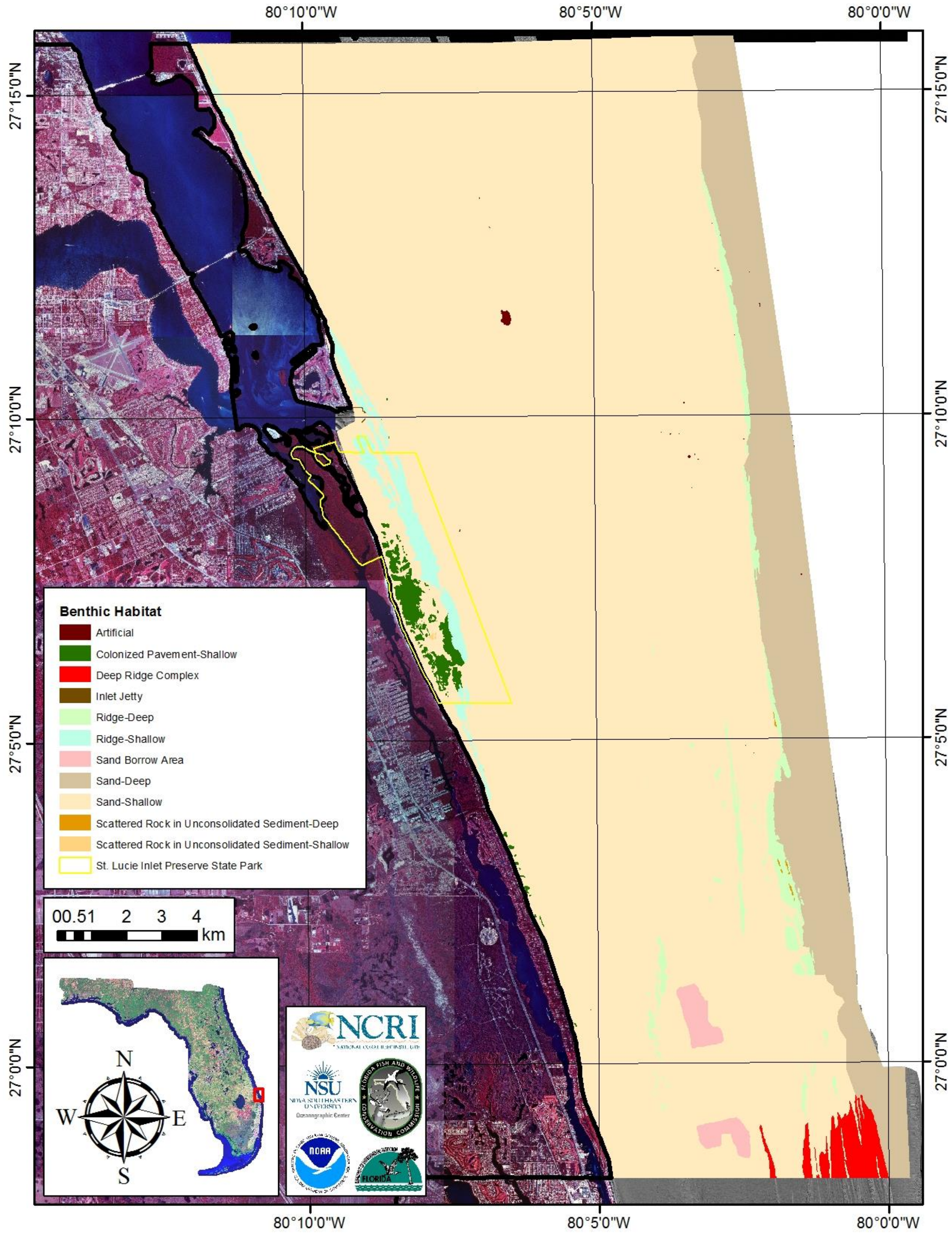


Figure 30. Martin County benthic habitat polygons.

Table 5. Martin County Benthic Habitat Areas (km²)

Habitat	Type	Modifier	Modifier Area (km²)	Type Area (km²)	Habitat Area (km²)
Coral Reef and Colonized Hardbottom	Colonized Pavement	Shallow	2.41 ; 0.64%	2.41 ; 0.64%	15.45 ; 4.13%
	Ridge	Deep	5.11 ; 1.36%	12.96 ; 3.46%	
		Shallow	4.57 ; 1.22%		
		Deep Ridge Complex	3.28 ; 0.88%		
	Scattered Coral/Rock in Sand	Deep	0.05 ; 0.01%	0.05 ; 0.01%	
		Shallow	0.03 ; 0.01%	0.03 ; 0.01%	
Unconsolidated Sediment	Sand	Deep	42.55 ; 11.36%	356.49 ; 95.21%	356.49 ; 95.21%
		Shallow	313.95 ; 83.85%		
Other Delineations	Artificial		0.12 ; 0.03%	0.12 ; 0.03%	2.49 ; 0.66%
	Inlet Jetty		0.02 ; 0.00%	0.02 ; 0.00%	
	Sand Borrow Area		2.35 ; 0.63%	2.35 ; 0.63%	
Total Mapped Area (km²)					374.43 ; 100.00%

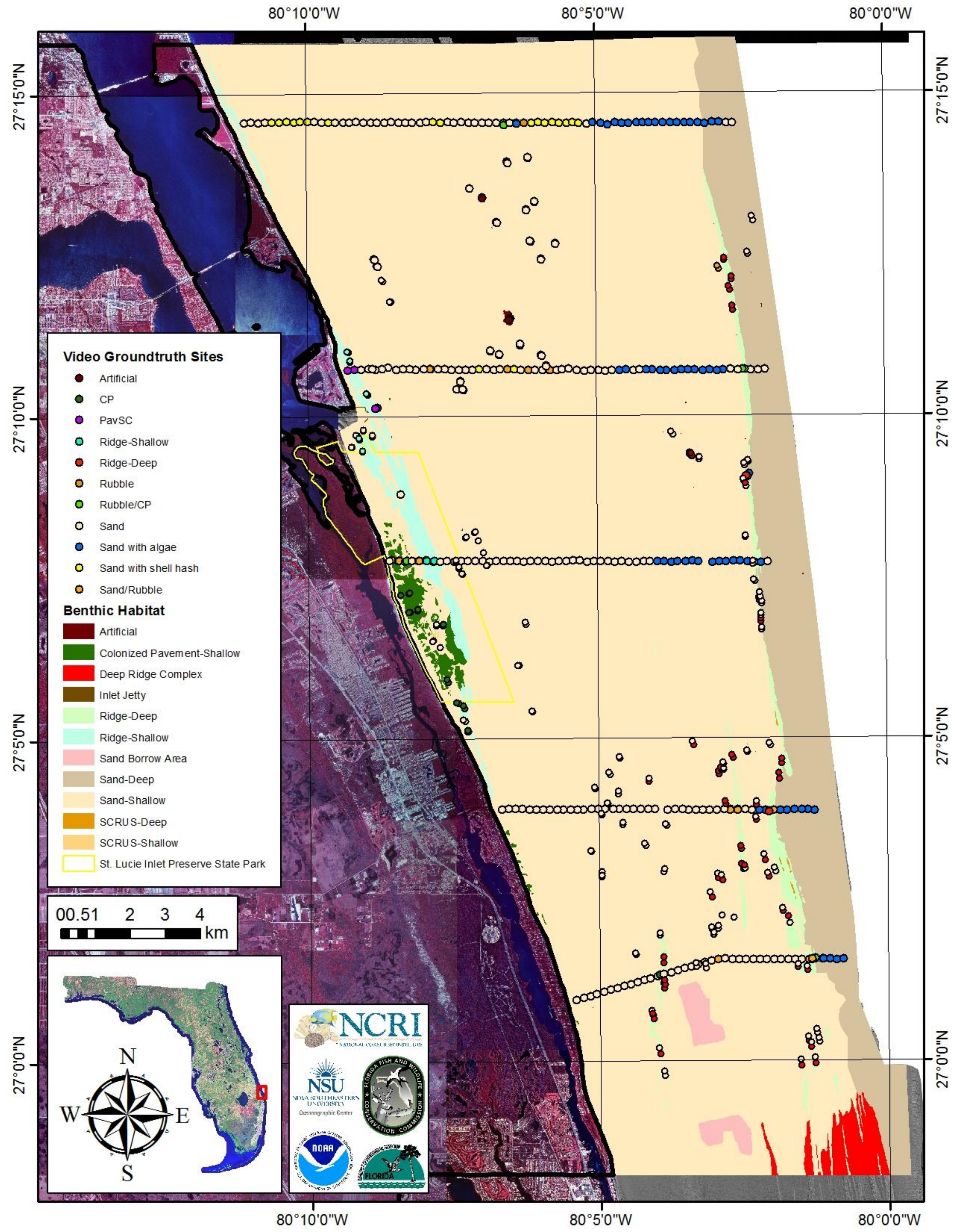


Figure 31. Martin County ground validation sites overlaying the habitat polygons. The ground truthing included classifications on sand that were not included in the final map (e.g. Sand with algae).

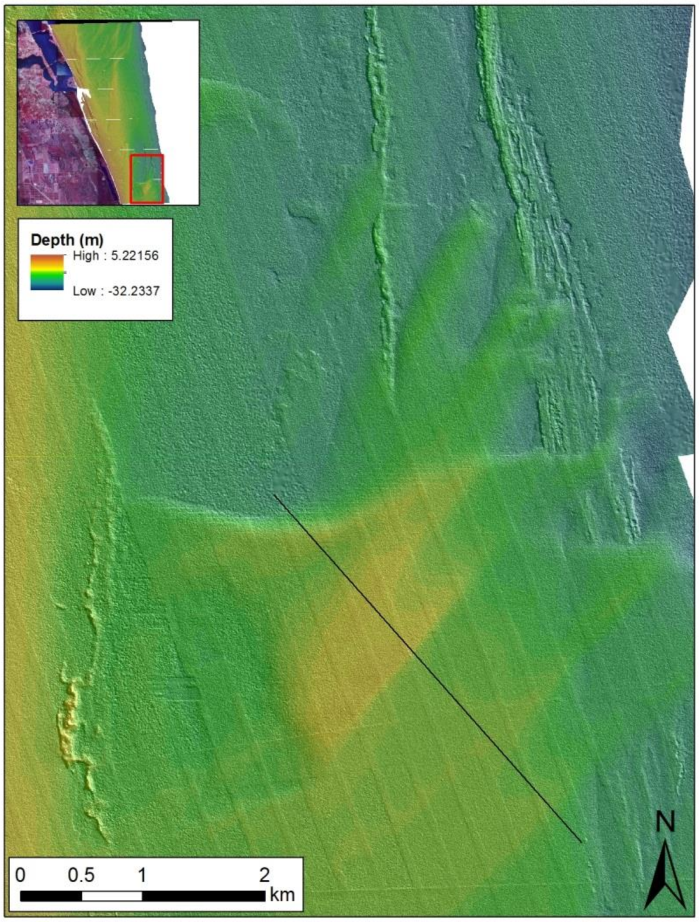


Figure 32. Sand dune features in southern Martin County. The smooth, wavy shallower dunes appear to be burying parts of the deep ridge habitats. The black represents the location of the elevation profile in Figure 33.

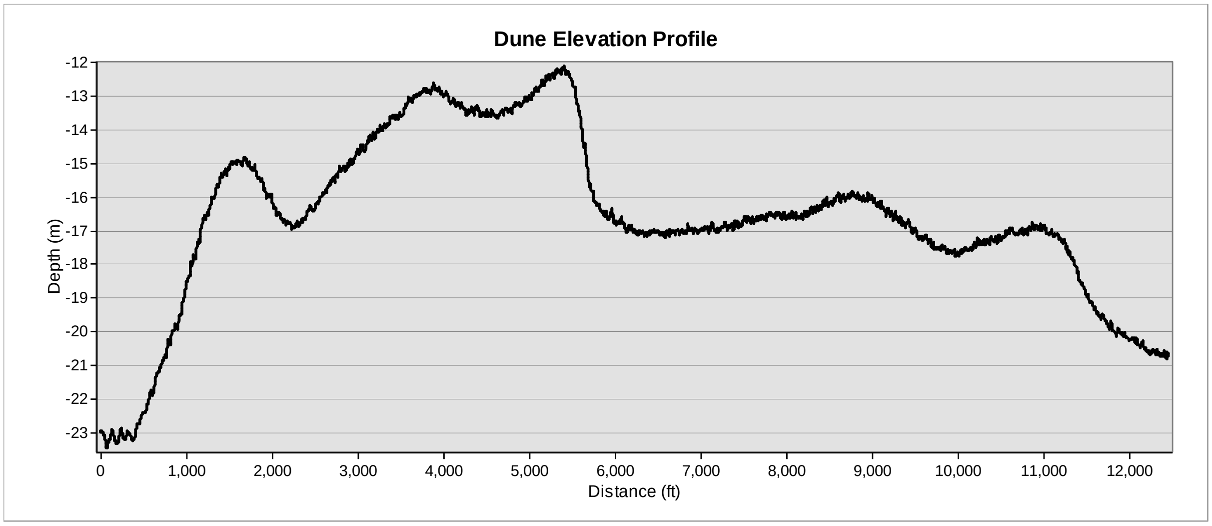


Figure 33. Elevation profile of a large dune in southern Martin County. This dune has an elevation of 11 m and a width of over 2.25 miles. The location is depicted as the black line in Figure 32.

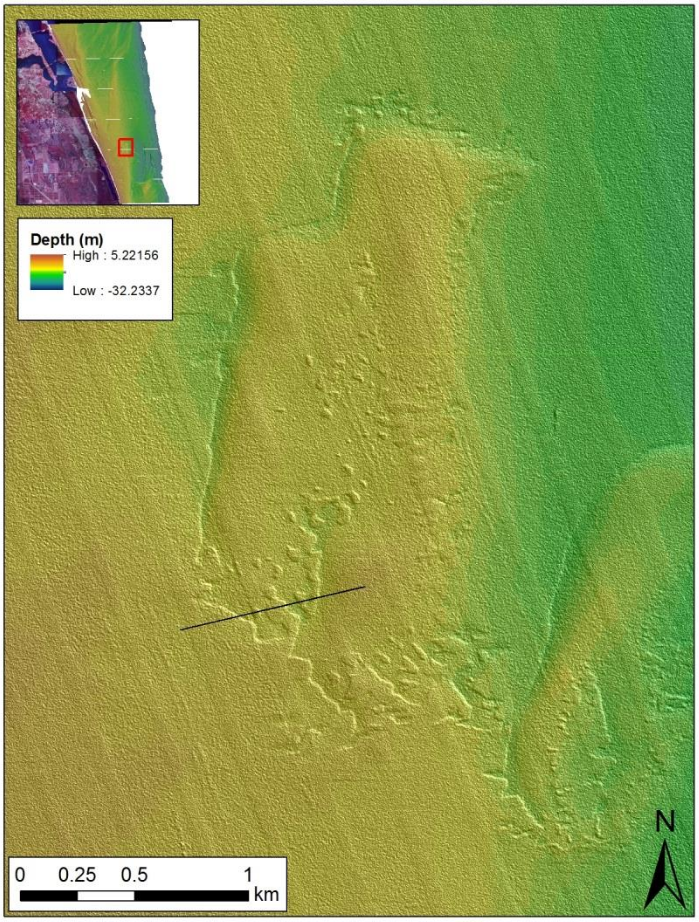


Figure 34. Apparent sand ledge features in southern Martin County. The sharp edges appeared to be hardbottom habitat, yet ground truthing videos confirmed these were composed of sediments. The black represents the location of the elevation profile in Figure 35.

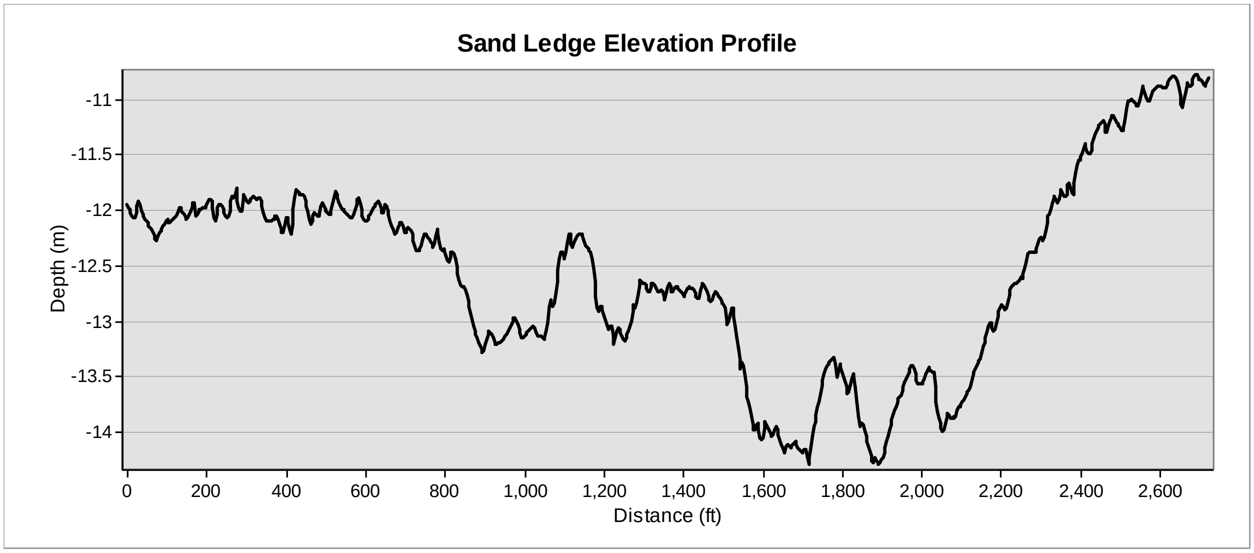


Figure 35. Elevation profile of apparent sediment ledges in southern Martin County. These range in elevation from 0.5 to 1 m.

Quantitative ground validation.— In collaboration with FWC, FDEP-CRCP, and NCRI, NOAA funded this part of the project to enhance the present Martin County benthic habitat mapping by further quantitatively assessing and characterizing the mapped hardbottoms. Quantitative ground truthing provides a rigorous determination of habitat types beyond qualitative efforts and valuable information about the composition of the benthic communities for resource management. This section describes those findings.

Quantitative ground validation was accomplished between August 13 and 16, 2012 (Figure 36). Dives were conducted at 19 locations however data were collected at 16 due to unworkable conditions (high current). Sites 1, 2, and 7 were visited but no data were collected. Data were collected on 7 Ridge-Deep sites (8-13 and 15), 5 Ridge-Shallow sites (14 and 16-19), and 4 Colonized Pavement-Shallow sites (3-6). The sites were distributed across the seascape as much as possible to provide data on all the main hardbottom habitats and account for latitudinal variation. Representative photos from each site (except Site 1 where no photos or data were taken) are provided in Appendix 1.

A cluster analysis and corresponding non-metric, multi-dimensional scaling (MDS) plot was constructed using Bray-Curtis similarity indices (PRIMER v6) of the benthic cover transect data (square-root transformed) to evaluate similarities between habitat types. The sites were defined by the map categories a priori and entered in PRIMER as factors. The MDS plot was then configured to show the habitats and site numbers (Figure 37). The MDS plot is designed to statistically show similarities and differences in multivariate data by plotting them in two dimensions where the relative distance apart is indicative of their similarity. Thus, sites very close together are more similar than those further apart and the sites furthest apart are the least similar. For the most part, the benthic cover sites were more similar than not as evinced by the central clustering in the graph and subtler distinctions were evident when the sites were categorized by habitat. The Ridge-Deep sites all plotted on one side of the graph and the two shallow habitats on the other, showing there are likely differences between shallow and deep habitats. Furthermore, apart from site 17, the two shallow habitats, colonized pavement and ridge, do not cluster and site 19 was very different from sites 16 and 18. This lack of clustering in the shallow ridge habitat indicates a wide range of benthic communities between sites.

A summary of the mean percent cover data by habitat shows the overall differences in cover (Figure 38). For example, turf algae were more abundant on the shallow colonized pavement (41.4% ± 11.1) and ridge (52.4% ± 19.6) than the deep ridge (19.1% ± 9.5) and vice versa for cyanobacteria. The large error bars indicate that cover within habitat categories varied greatly within habitats (0.98% ± 0.54, 4.2% ± 5.3, and 17.4% ± 23.9) and most cover types were low (> 5%) making it difficult to detect differences at the habitat level. Viewing the data by site helps elucidate this variability. For example, the percent cover data by site for the Colonized Pavement-Shallow shows two sites with very low sediment cover (< 5%) and two where it's over 30% (Figure 39). Similarly Site 3 had macroalgal cover of 53.8% while Site 4 had 17.9%. The within habitat variation of percent cover on the Ridge-Shallow sites were also very evident (Figure 40). Macroalgae varied between 6.3% at site 14 to 49.4% at site 19; Sediment ranged from 0% at site 18 to 36.3% at site 14; Cyanobacteria ranged from 0.8% at sites 18 and 19 to 13.3% at site 17; and Palythoa was only found at site 14 but contributed 11.3% to cover. The same was true in the Ridge-Deep where macroalgae ranged from 11.9% to 56.7%, sediment ranged from 6% to 49.8%, and cyanobacteria ranged from 3.3% to 69.6% (Figure 41).

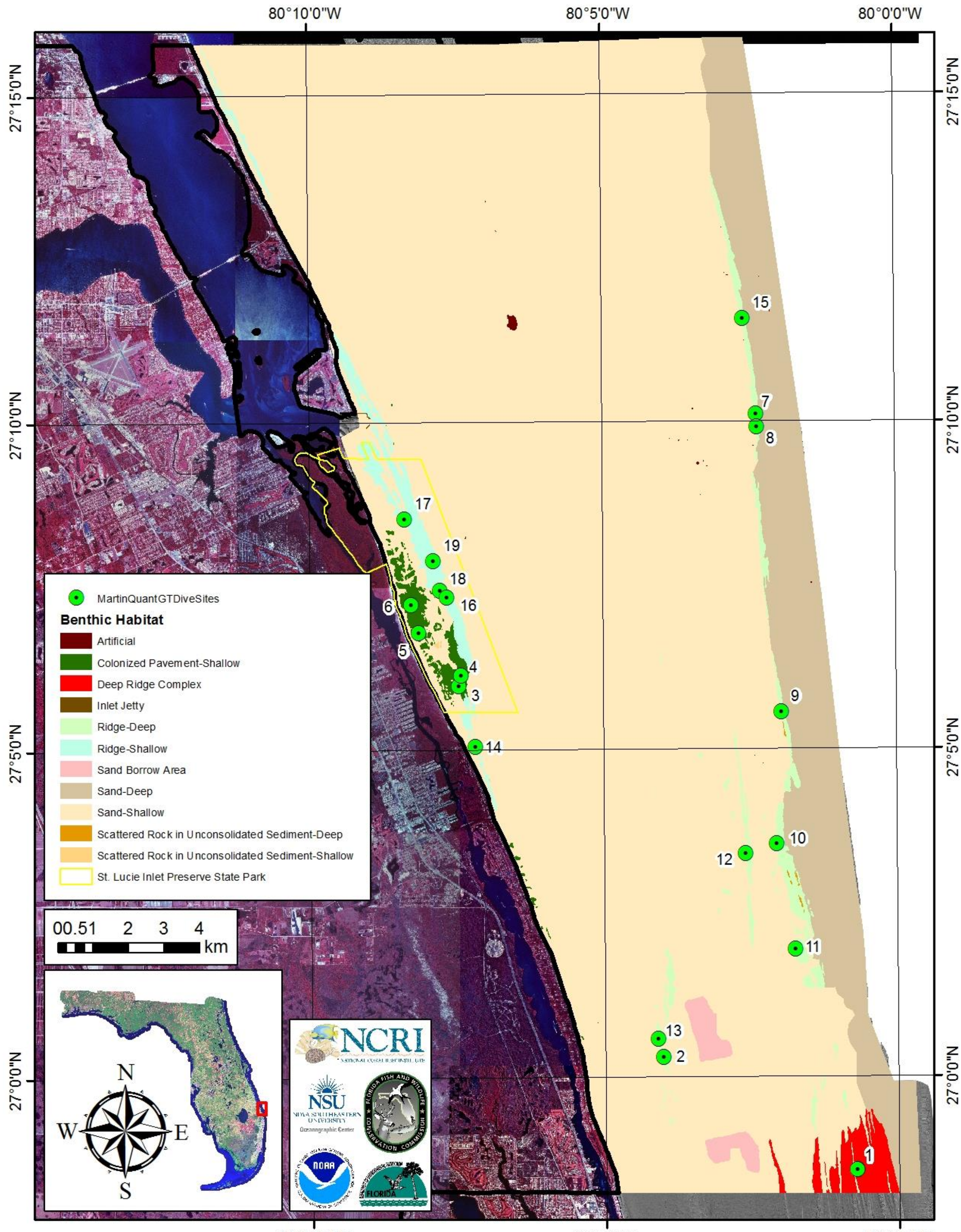


Figure 36. Martin County quantitative ground validation sites overlaying the habitat polygons. Dives at sites 1, 2, and 7 were abandoned due to strong current.

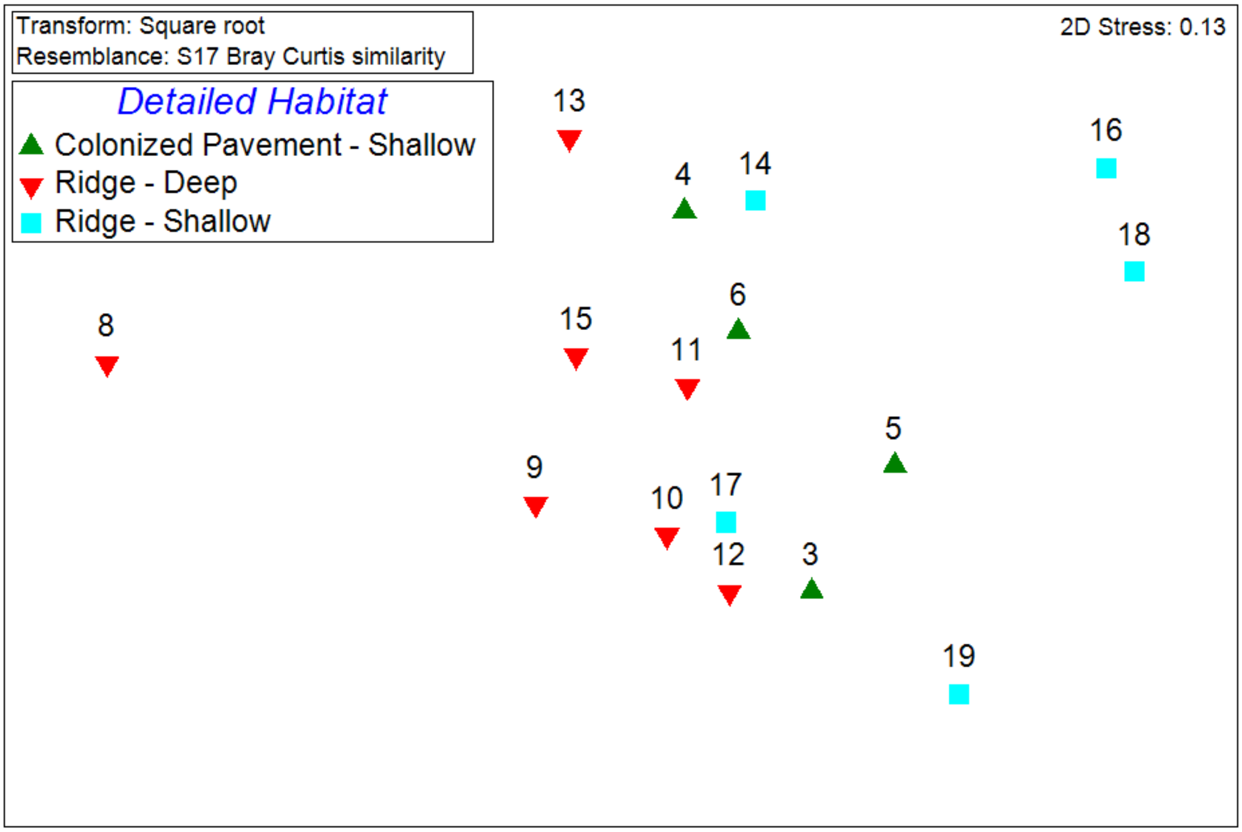


Figure 37. Multidimensional scaling plot of percent cover data for all quantitative surveys.

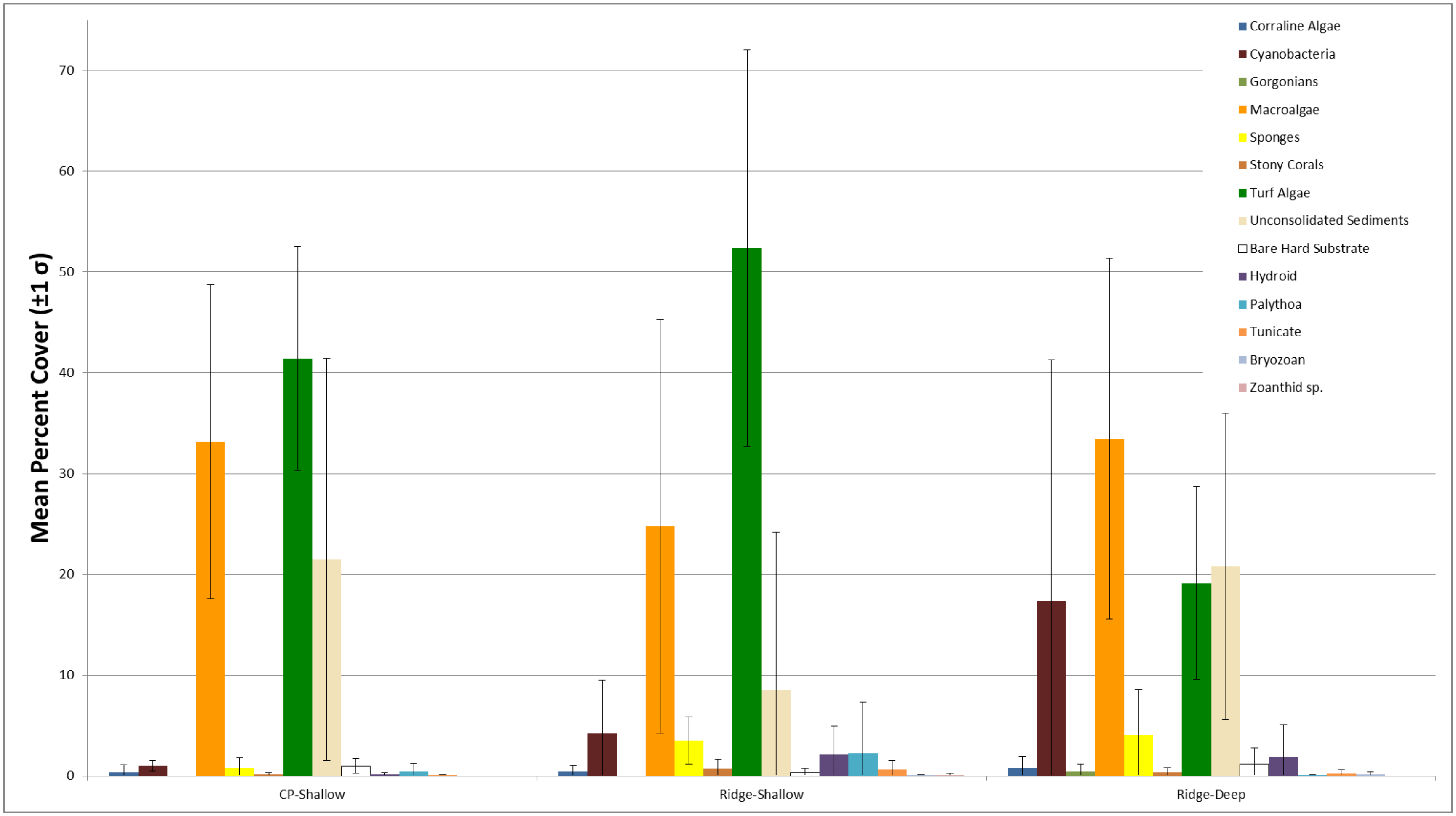


Figure 38. Percent benthic cover data averaged across all sites in the same mapped habitat. Error bars represent one standard error of the mean.

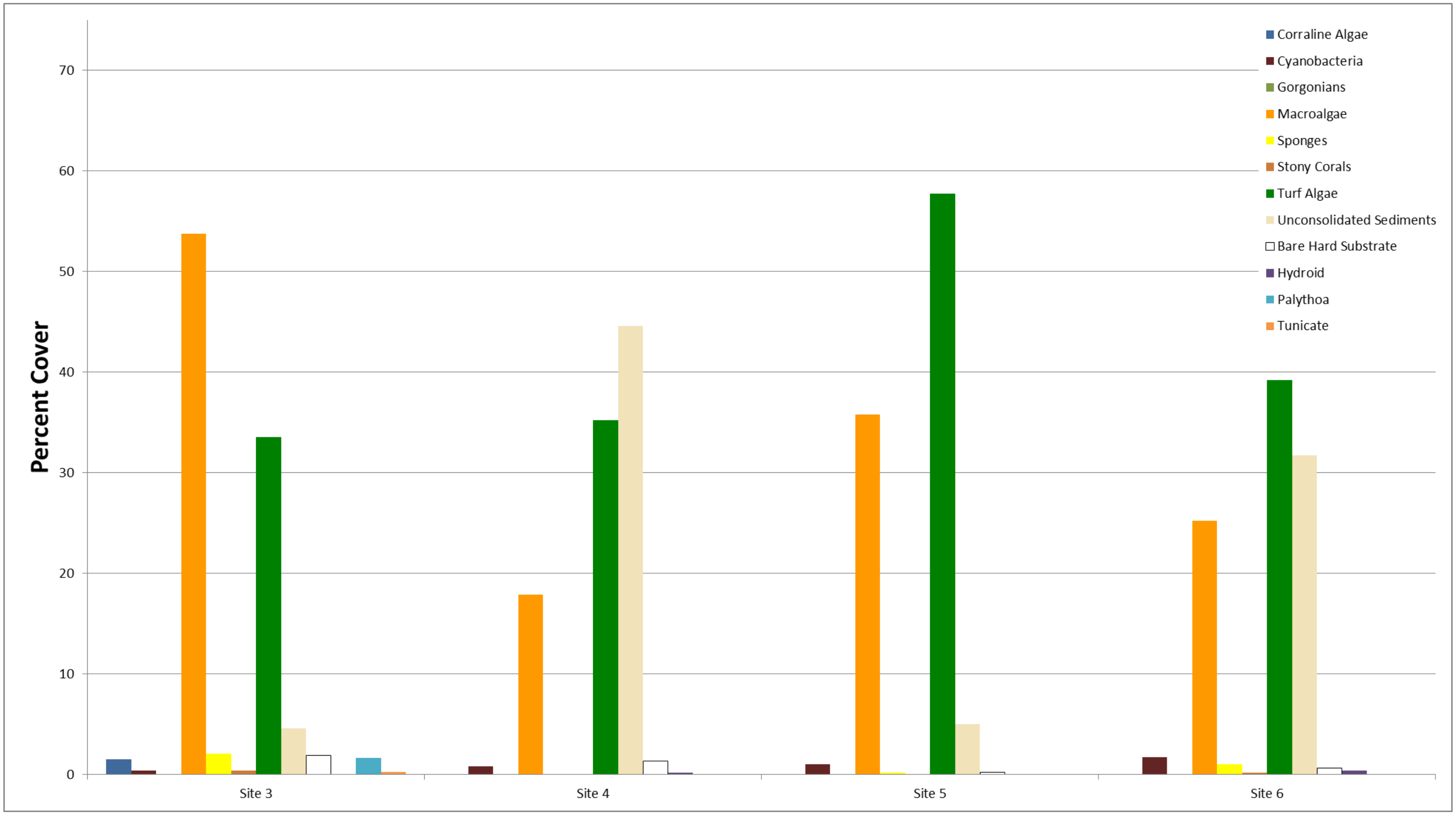


Figure 39. Total percent benthic cover data (4 transects per site) for Shallow Colonized Pavement sites.

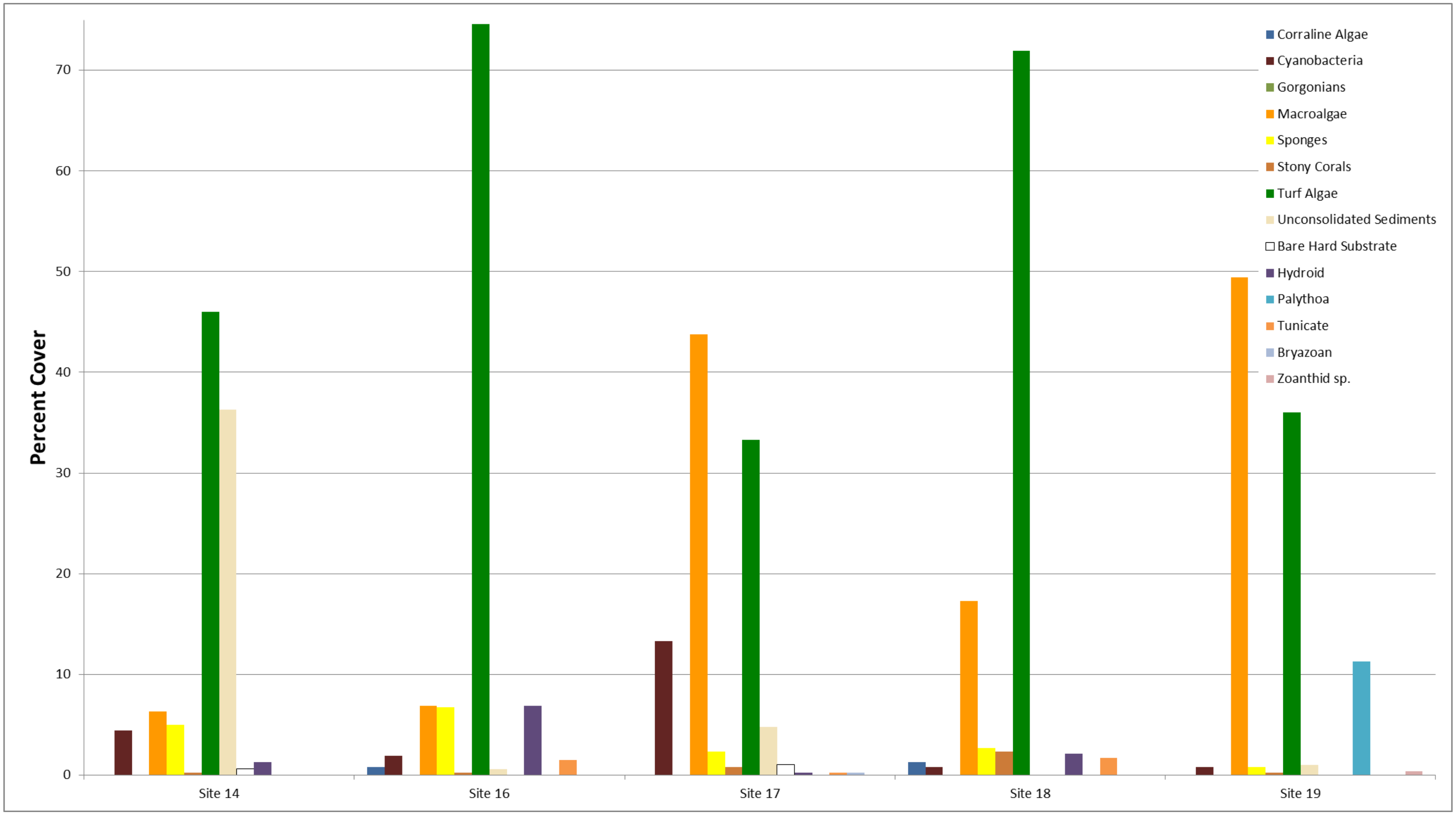


Figure 40. Total percent benthic cover data (4 transects per site) for Shallow Ridge sites.

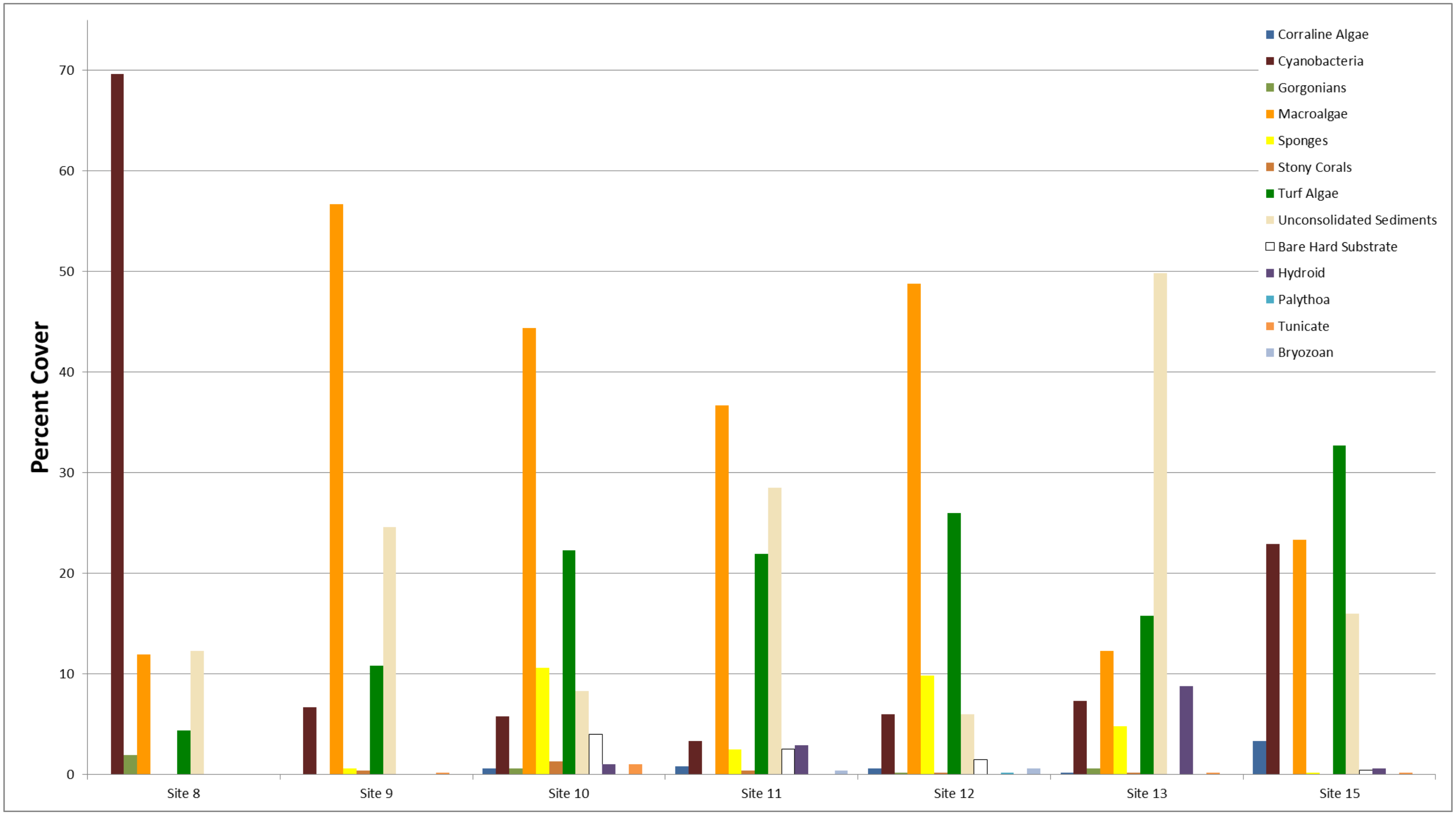


Figure 41. Total percent benthic cover data (4 transects per site) for Deep Ridge sites.

Although percent cover between habitats was muddled by within-habitat variability, the number of biotic cover categories (e.g. macroalgae, hydroids, coral) were significantly different (Figure 42). Colonized Pavement-Shallow had significantly fewer biotic cover categories (5.5 ± 0.96 SEM) than the Ridge-Shallow (7 ± 0.45 SEM) and Ridge-Deep (7.4 ± 0.72 SEM). The number of biotic categories ranged from 4 to 8 on the Colonized Pavement-Shallow, from 6 to 8 on the Ridge-Shallow, and from 4 to 9 on the Ridge-Deep. This suggests the shallow colonized pavement may have less taxonomic diversity than the other habitats.

Rugosity significantly varied between habitats (Figure 43). The Ridge-Shallow mean rugosity was significantly higher than the Colonized Pavement-Shallow which was significantly higher than the Ridge-Deep. This result was not surprising because feature relief (albeit at a larger scale) was one of the main criteria used to distinguish between the two shallow habitats.

Although differences between habitats were found (e.g. MDS separation, rugosity, number of biotic categories), differences of cover types and amounts among sites were not statistically strong between the habitat categories. To analyze this, a one-way analysis of similarity (ANOSIM) was performed to statistically determine the strength of the site categorization by habitat (Table 6). ANOSIM is a permutation-based hypothesis test analogous to univariate analyses of variance (ANOVAs) that tests for differences between groups of (multivariate) samples from different experimental treatments. The closer the R statistic is to 1, the stronger the categorical groups. Its strength is dependent on the number of samples per category which defines the number of possible permutations. The best result was between the Ridge-Deep and Ridge-Shallow indicating these were most different and supporting the MDS results, however the difference was not that strong. Furthermore, the results between Deep-Ridge and Colonized Pavement-Shallow and between Colonized Pavement-Shallow and Ridge-Shallow were very weak.

Table 6. Analysis of Similarity results of site habitat categorization.

ANOSIM - Detailed Habitats	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >= Observed
Ridge - Deep, Ridge - Shallow	0.257	3.2	792	792	25
Colonized Pavement - Shallow, Ridge - Deep	0.159	19.4	330	330	64
Colonized Pavement - Shallow, Ridge - Shallow	0.038	38.9	126	126	49

The lack of strong groupings in the ANOSIM likely has something to do with the way the data were collected. Macroalgae and turf algae were the most dominant cover types at almost all the sites. These two categories are comprised of many different species that make up the algal communities in the habitats. This study did not distinguish between algal species, thus when the data were ranked in the multivariate comparison, all macroalgae species were considered the same. Although no species data were collected, it was recognized anecdotally that the algal communities between the deep and shallow hard bottoms were distinct. Previous research showing distinct differences in the macroalgal communities in southeast Florida supports these observations (Lapointe 2007). In 2007, Lapointe’s 2-year detailed regional study on macroalgal communities showed that Martin County had the highest macroalgal cover and the dominant species in these communities can shift over relatively short time frames. At fixed monitoring stations he documented blooms of *Caulerpa brachypus* and Phaeophytes (likely *Dictyota sp.*) where cover at some sites changed by over 50% in a few months. It appears that there are several spatial patterns in these data that went unexplored. These data show differences in the populations along a latitudinal gradient and between the deep and shallow reefs that are not seen solely by summing up the data for each county. This is not surprising given the multitude of biogeographic changes in habitats and other community constituents along the reef tract (Walker 2012). In Martin, Lapointe (2007) surveyed five sites; three on shallow ridge and two on deep ridge. The three shallow ridge sites had a large component of Phaeophyta cover (> 50% during certain times) that was not present in the deep habitats, where Chlorophyta was dominant. This was further exemplified by the five sites on the deep ridge complex in north Palm Beach that were dominated by Chlorophyta and Rhodophyta and had very little Phaeophyta, if any. Therefore, if macroalgal communities were distinguished in the Martin County quantitative ground truthing, it is likely that the cluster analysis between habitats would have been much more robust.

Inspection of the MDS plot scatter (Figure 37) exhibited subtler distinctions between sites that might explain the high within-habitat variability on the shallow colonized pavement and ridge habitats. There appears to be a cross-shelf pattern to the communities in the Nearshore Ridge Complex ((NRC) combination of Ridge-Shallow and Colonized Pavement-Shallow habitats). Site 19, which was separated from all other sites in the MDS, was located on the eastern side of the shallow ridge (Figure 44) and had a distinct community comprised mostly of macroalgae, turf algae, and palythoa. Sites 16 and 18, which were very similar to each other in the MDS, were associated with the shallowest top portion of the ridge, the crest. All of the other shallow sites (3, 4, 5, 6, and 17) were located on the western side of the shallow ridge crest and grouped in a central axis in the MDS. A depth profile of the NRC shows drastic changes in the seafloor depth over short distances (Figure 45). Going from east to west as wave energy does, the seafloor rises 7 m in a distance of 800 ft (near site 19) to ~2 m depth at the crest (Sites 16 and 18). Then it drops down over 4 m on the western side of the ridge (site 17) before rising and flattening out over the shallow colonized pavement (near site 5 and 6). This type of profile is indicative of many shallow reef systems where differences in communities are driven by depth and energy exposure to form fore-reef, reef crest, back-reef, and lagoon communities. It is likely that although the structure is not comprised of coral, the distinct profile is providing different conditions across the shelf that are shaping the benthic communities. This could account for larger within-habitat variations because the shallow ridge was not divided into separate habitats to account for the differences across the fore-ridge, crest, and back-ridge.

Stony corals were assessed on the benthic cover transects to gain a better understanding of their distributions and condition throughout the Martin County reef system. A total of 553 colonies were identified, counted, and measured (Figure 46). Nine species were found, but *Siderastrea siderea* (80.3%) and *Oculina diffusa* (15.9%) completely dominated the populations. Stony coral density for the entire county out of 1737 m² surveyed was 0.32 m^{-2}, equating to a coral every 3.1 m². Although many corals were counted, their total size was small. The estimated total area of live tissue (max length * max width – ((max length * max width) * percent total mortality)) for all 553 colonies was 2.8 m² (Figure 47). Three species accounted for 97.7% of the total live coral tissue in the transects; *Diploria clivosa* (42.9%), *Siderastrea siderea* (30.2%), and *Oculina diffusa* (24.6%). Although only 8 Diploria colonies were counted, they were the largest colonies and thus accounted for the most live tissue area. Mean max length of most species ranged between 6 and 13 cm, whereas *Diploria clivosa* averaged 39.1 cm (Figure 48). Interestingly, *Siderastrea siderea* had the smallest mean length (4.7 cm), yet was the second highest contributor to live tissue area because of its high numbers (444).

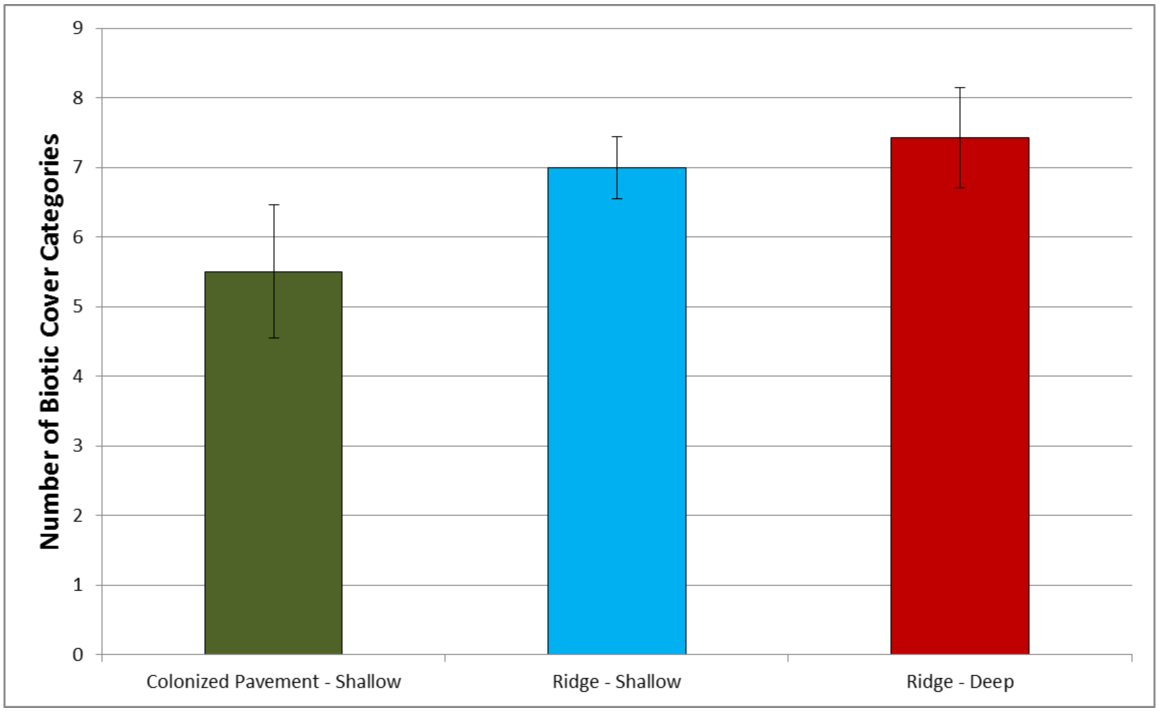


Figure 42. Summary of biotic cover categories at each site by habitat type. Error bars indicate one standard error of the mean.

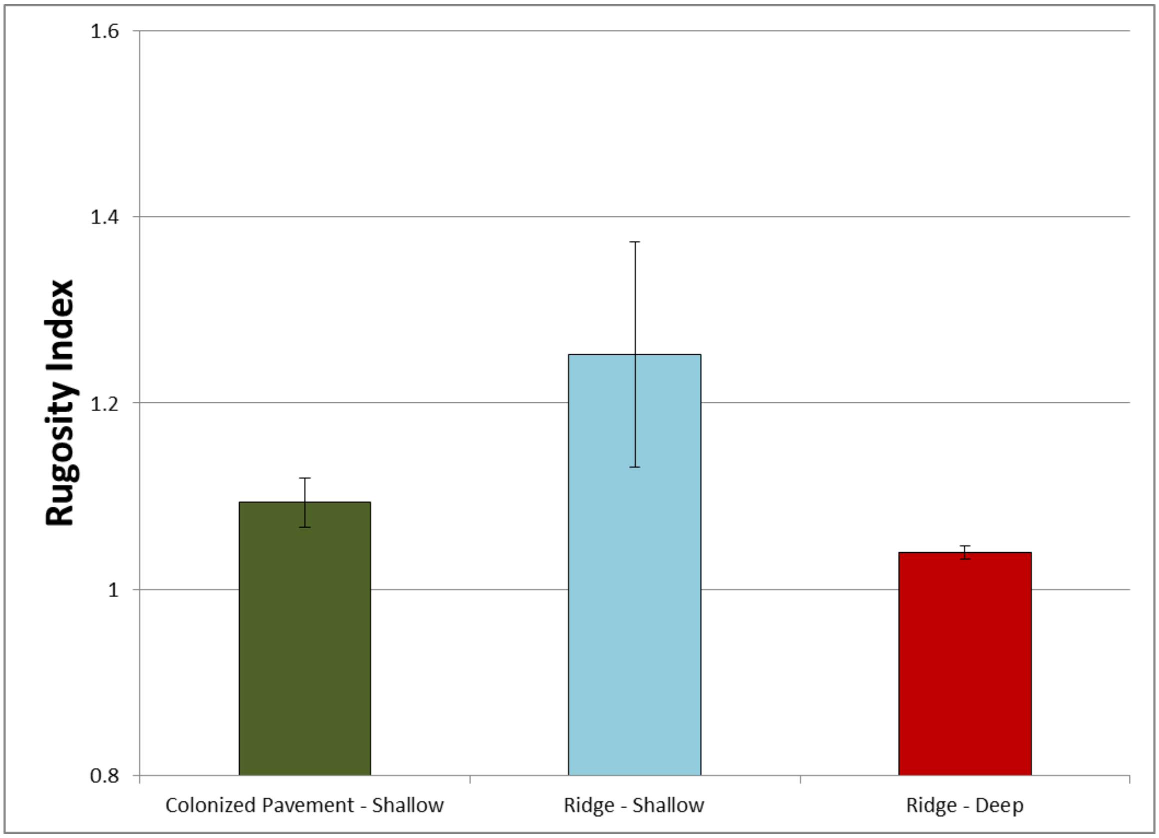


Figure 43. Summary of rugosity indices at each site by habitat type. Error bars indicate one standard error of the mean.

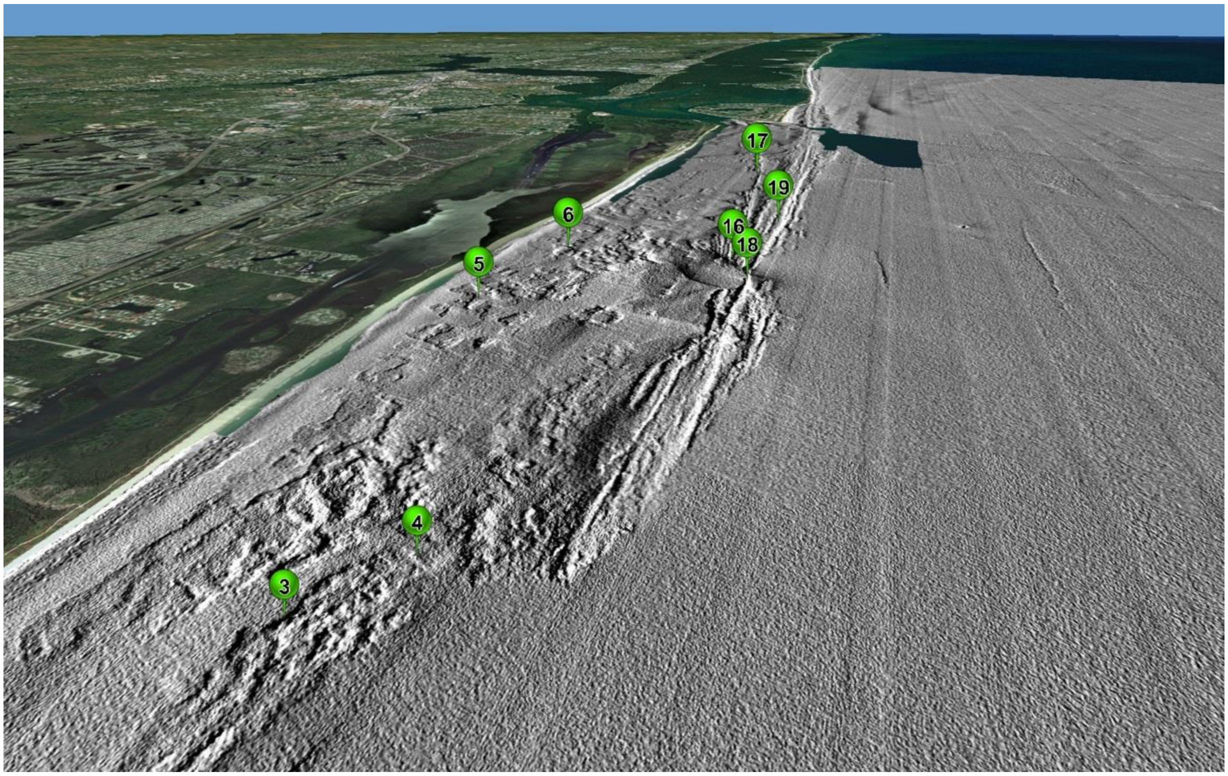


Figure 44. 3 dimensional image of the Nearshore Ridge Complex ((NRC) comprised of the habitats Ridge-Shallow and Colonized Pavement-Shallow) south of St. Lucie inlet with the quantitative ground truthing site locations.

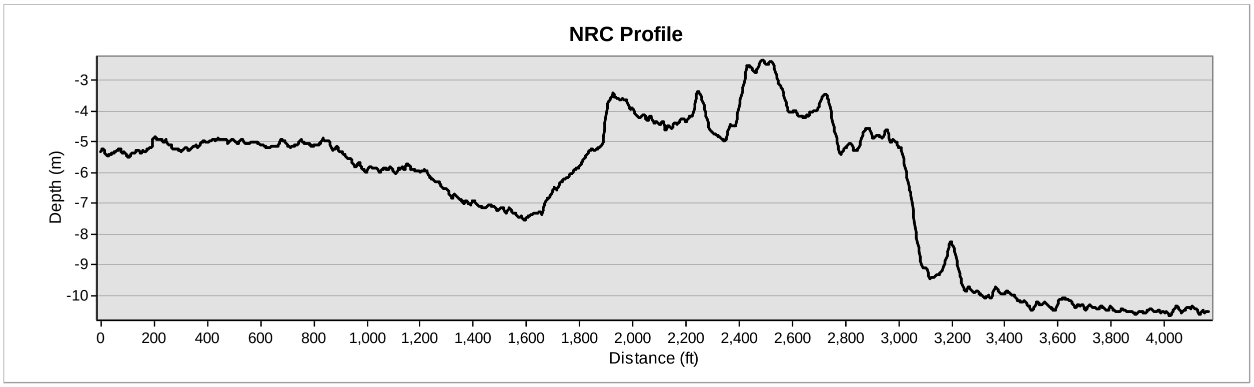


Figure 45. A depth profile of the NRC near Site 19 showing a cross-shelf surface contour of the flatter colonized pavement on the left (west), the ridge right of center, and the sand on the right (east). The ridge in this area exhibits a 7m drop in elevation over 800 ft in distance.

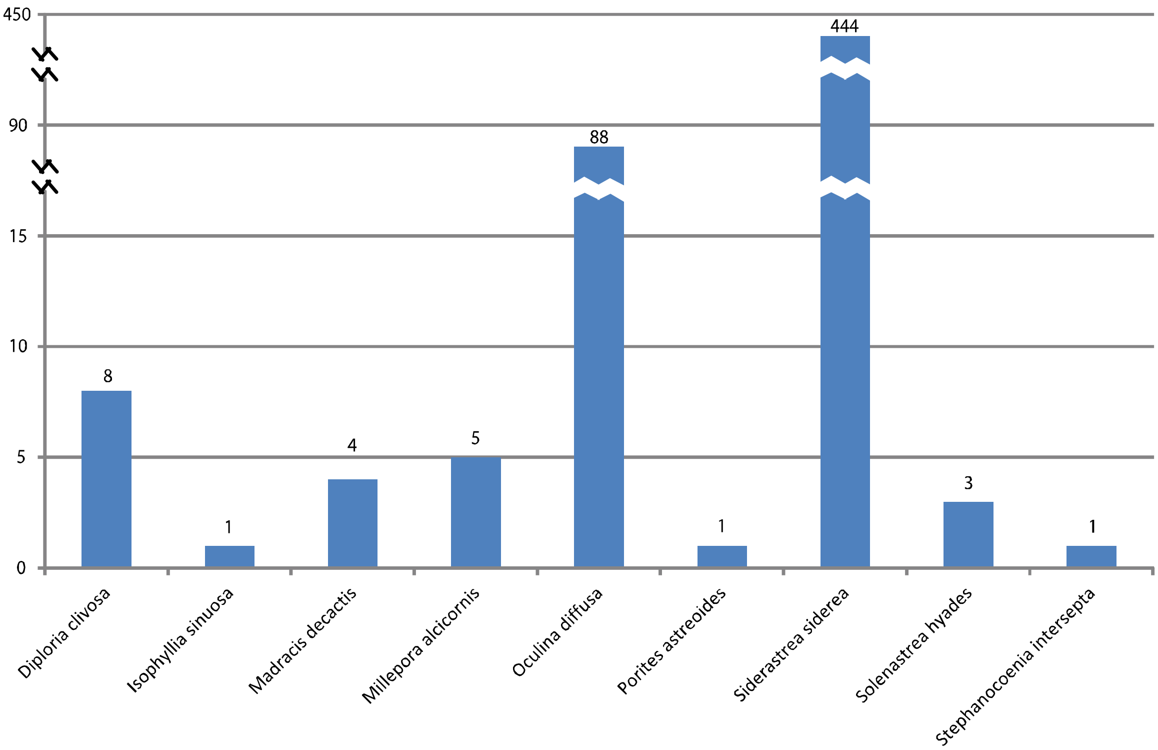


Figure 46. Total number of stony corals counted in all transects at all sites by species.

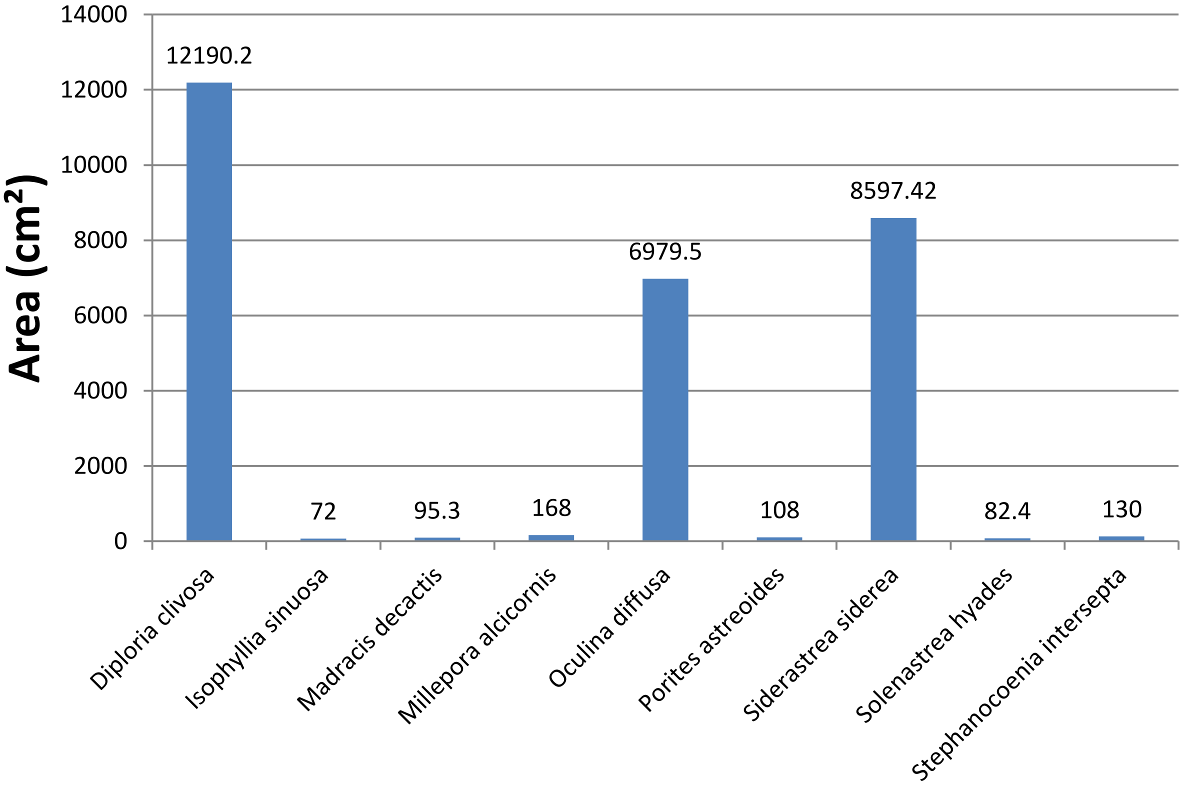


*Figure 47. Estimated total area (max length * max width – ((max length * max width) * percent total mortality)) of all stony corals counted in all transects at all sites by species. 1 cm² = 0.0001 m².*

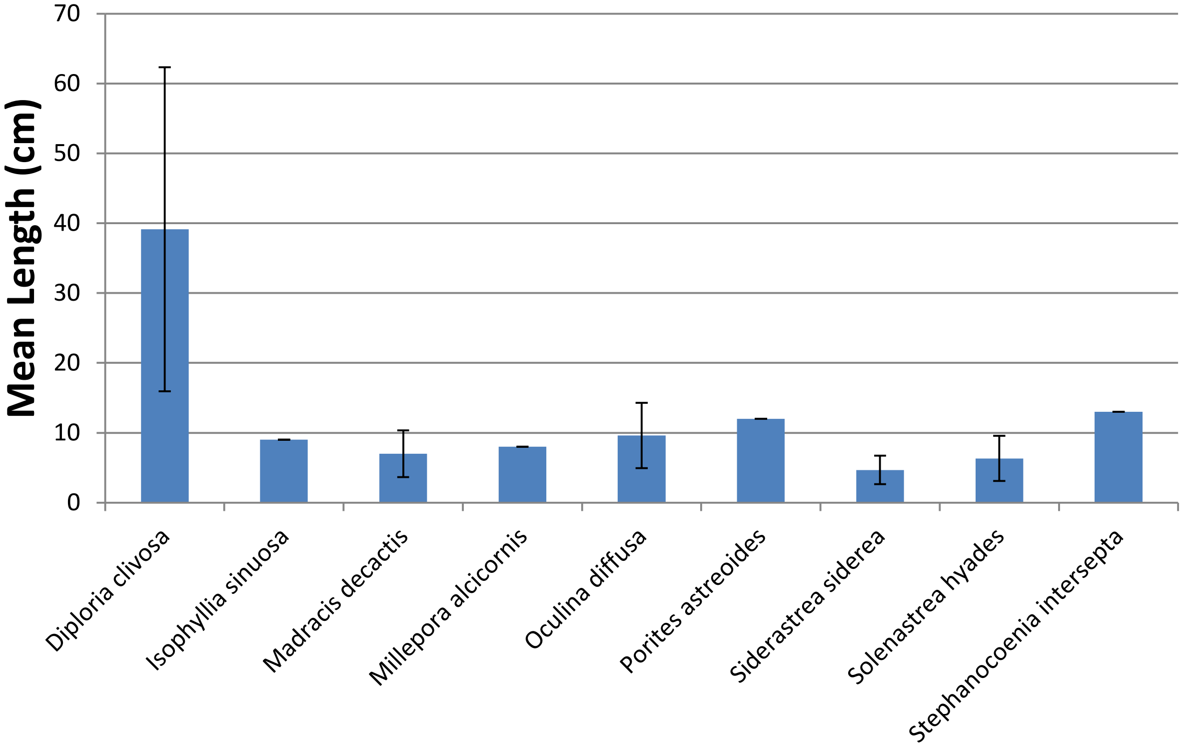


Figure 48. Mean length (cm) of stony corals counted in all transects at all sites by species.

Table 7. Number and density (m^{-2}) by habitat and by site of hard corals in the belt transects.

Habitat	Site	Coral Species	Number	Survey Area (m^2)	Density (m^{-2})
Ridge - Shallow	Site 14	*Siderastrea siderea*	5	120	0.04
	Site Total		**5**	**120**	**0.04**
	Site 16	*Madracis decactis*	4	120	0.03
		Oculina diffusa	16	120	0.13
		Siderastrea siderea	5	120	0.04
	Site Total		**25**	**120**	**0.21**
	Site 17	*Oculina diffusa*	2	105	0.02
		Siderastrea siderea	53	105	0.50
	Site Total		**55**	**105**	**0.52**
	Site 18	*Diploria clivosa*	8	102	0.08
		Millepora alcicornis	1	102	0.01
		Porites astreoides	1	102	0.01
		Siderastrea siderea	56	102	0.55
	Site Total		**66**	**102**	**0.65**
	19	*Siderastrea siderea*	1	120	0.01
	Site Total		**1**	**120**	**0.01**
Habitat Total			**152**	**567**	**$\bar{x}$ = 0.29**

Table 7. Continued.

Habitat	Site	Coral Species	Number	Survey Area (m^2)	Density (m^{-2})
Colonized Pavement - Shallow	Site 3	*Millepora alcicornis*	2	105	0.02
		Oculina diffusa	33	105	0.31
		Siderastrea siderea	9	105	0.09
		Solenastrea hyades	1	105	0.01
	Site Total		**45**	**105**	**0.43**
	Site 4	*Siderastrea siderea*	5	120	0.04
	Site Total		**5**	**120**	**0.04**
	Site 5	*Siderastrea siderea*	8	120	0.07
	Site Total		**8**	**120**	**0.07**
	Site 6	*Oculina diffusa*	2	120	0.02
		Siderastrea siderea	38	120	0.32
	Site Total		**40**	**120**	**0.33**
Habitat Total			**98**	**465**	**x̄ = 0.22**
Ridge - Deep	Site 8	*Oculina diffusa*	1	120	0.01
		Siderastrea siderea	1	120	0.01
	Site Total		**2**	**120**	**0.02**
	Site 9	*Oculina diffusa*	3	87	0.03
		Siderastrea siderea	46	87	0.53
	Site Total		**49**	**87**	**0.56**
	Site 10	*Oculina diffusa*	5	71	0.07
		Siderastrea siderea	64	71	0.90
	Site Total		**69**	**71**	**0.97**
	Site 11	*Siderastrea siderea*	58	94	0.62
	Site Total		**58**	**94**	**0.62**
	Site 12	*Isophyllia sinuosa*	1	93	0.01
		Oculina diffusa	6	93	0.06
		Siderastrea siderea	50	93	0.54
	Site Total		**57**	**93**	**0.61**
	Site 13	*Millepora alcicornis*	2	120	0.02
		Oculina diffusa	1	120	0.01
		Siderastrea siderea	38	120	0.32
		Solenastrea hyades	2	120	0.02
		Stephanocoenia intersepta	1	120	0.01
	Site Total		**44**	**120**	**0.37**
	Site 15	*Oculina diffusa*	17	120	0.14
		Siderastrea siderea	7	120	0.06
	Site Total		**24**	**120**	**0.20**
Habitat Total			**303**	**705**	**x̄ = 0.48**
Grand Total			**553**	**1737**	**x̄ = 0.32**

Coral density and live tissue area varied between species by habitat (Table 7 and Figure 49). The density by species at each site grouped by habitat is listed in Table 7. Although not significant due to high variation, Ridge – Deep habitats had the highest mean coral density (x̄ = 0.48 ± 0.31) followed by Ridge – Shallow (x̄ = 0.29 ± 0.29) and Colonized Pavement – Shallow (x̄ = 0.22 ± 0.19). *Siderastrea siderea* and *Oculina diffusa* were the densest corals in all habitats (Figure 49). Although not significant, *Siderastrea siderea* densities were highest in the deep ridge (x̄ = 0.43 ± 0.32), then shallow ridge (x̄ = 0.23 ± 0.27), and were lowest on the shallow colonized pavement (x̄ = 0.13 ± 0.13). This pattern was the same for *Siderastrea siderea* estimated live tissue area which was significantly higher on the deep ridge than the shallow ridge and colonized pavement. *Oculina diffusa* was significantly lowest on the shallow ridge, higher on the shallow colonized pavement and highest on the deep ridge. As previously discussed, *Diploria clivosa* had the highest estimated mean coral live tissue, but it was only found in the shallow ridge habitat.

Mean maximum coral length and height were low for most species and did not significantly differ between habitats (Figures 51 and 52). Mean max length for six species was less than 10 cm. There were one 12 cm *Porites astreoides* and one 13 cm *Stephanocoenia intersepta* also measured. *Diploria clivosa* was the only species of any size which had a mean max length of 39.1 (± 23.2) cm out of 8 colonies that ranged from 33 to 80 cm. Two of these colonies were also the tallest in of the corals encountered (25 cm). *Diplora clivosa* (11.6 ± 9.9) was the only species whose mean max height was above 10 cm (Figure 52). There were no significant differences of mean coral height between habitats.

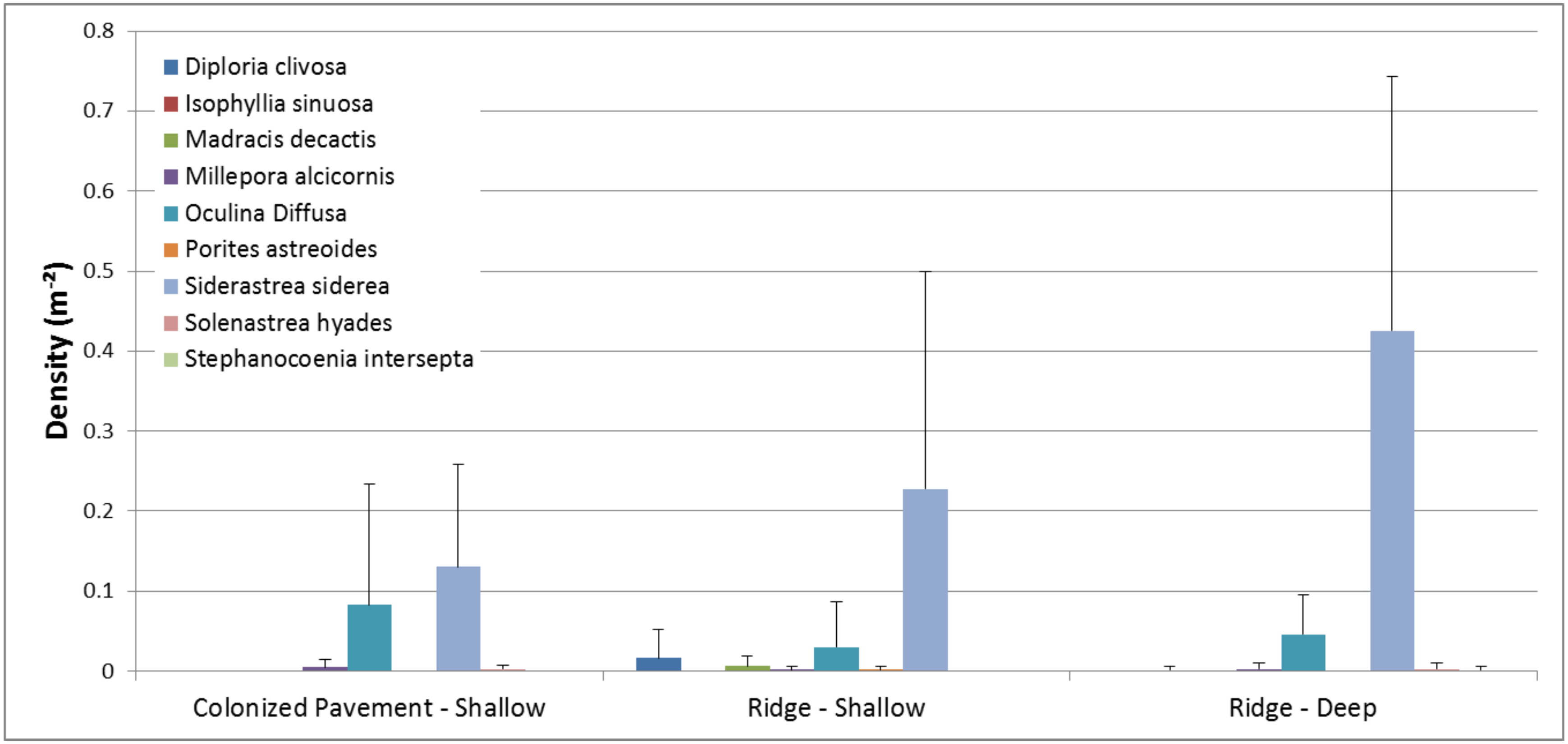


Figure 49. Mean coral density (m^{-2}) by species and by habitat. Error bars indicate ±1 standard deviation. The legend reflects all species encountered by both point intercept and belt transect surveys.

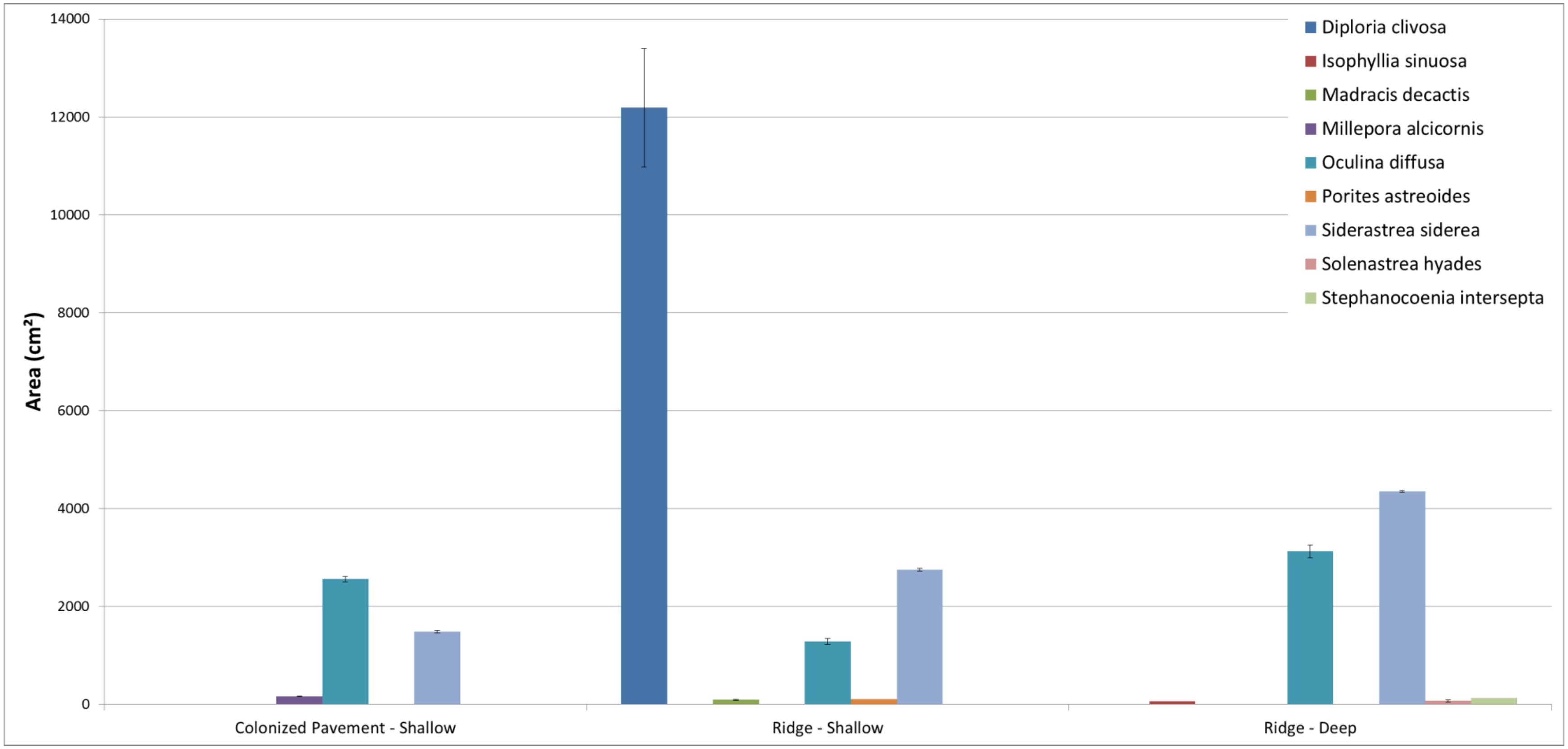


Figure 50. Mean coral live tissue area (cm²) by species and by habitat. Error bars indicate ±1 standard deviation. No error bars indicate a single colony. The legend reflects all species encountered by both point intercept and belt transect surveys.

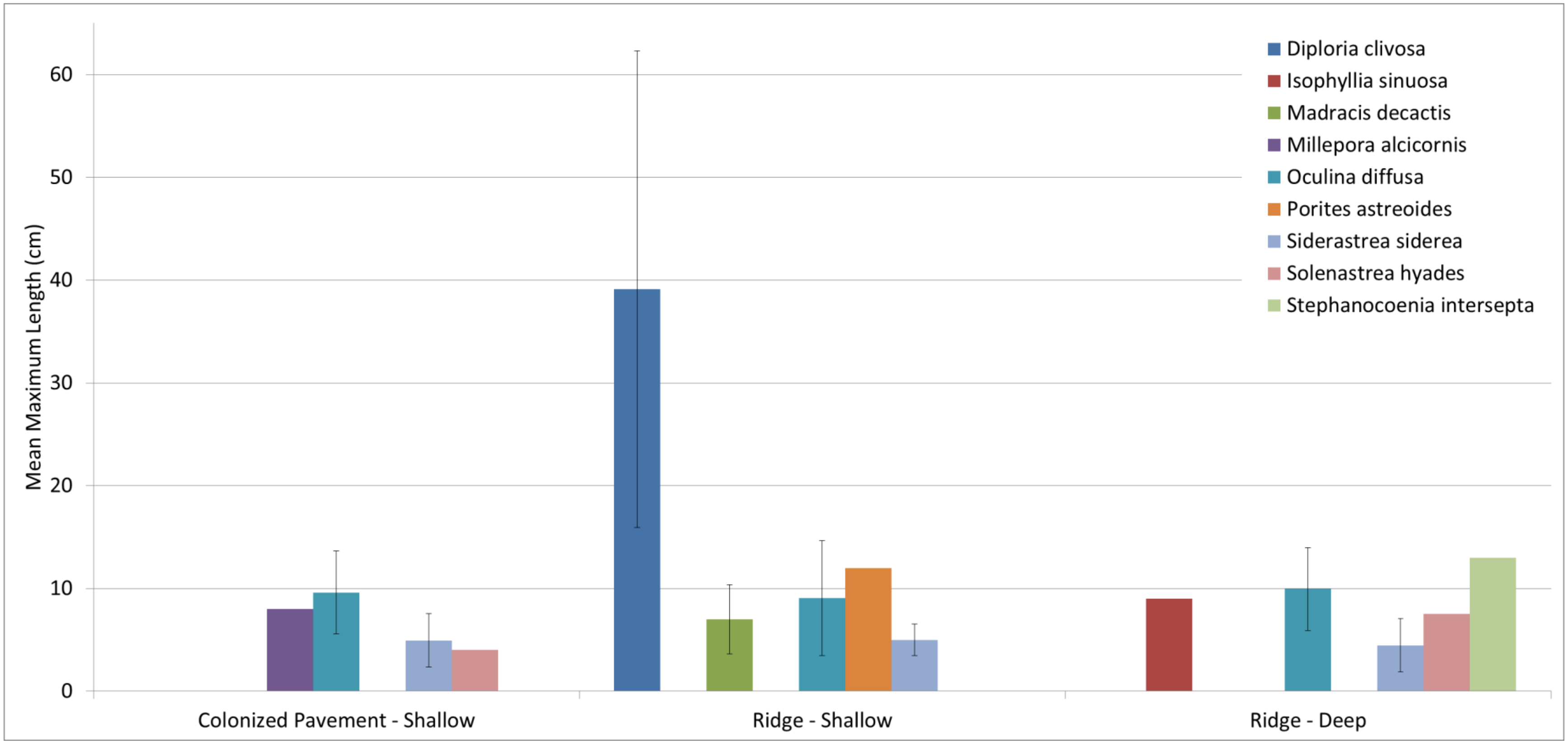


Figure 51. Mean maximum coral length (cm) by species and by habitat. Error bars indicate ±1 standard deviation. No error bars indicate a single colony. The legend reflects all species encountered by both point intercept and belt transect surveys.

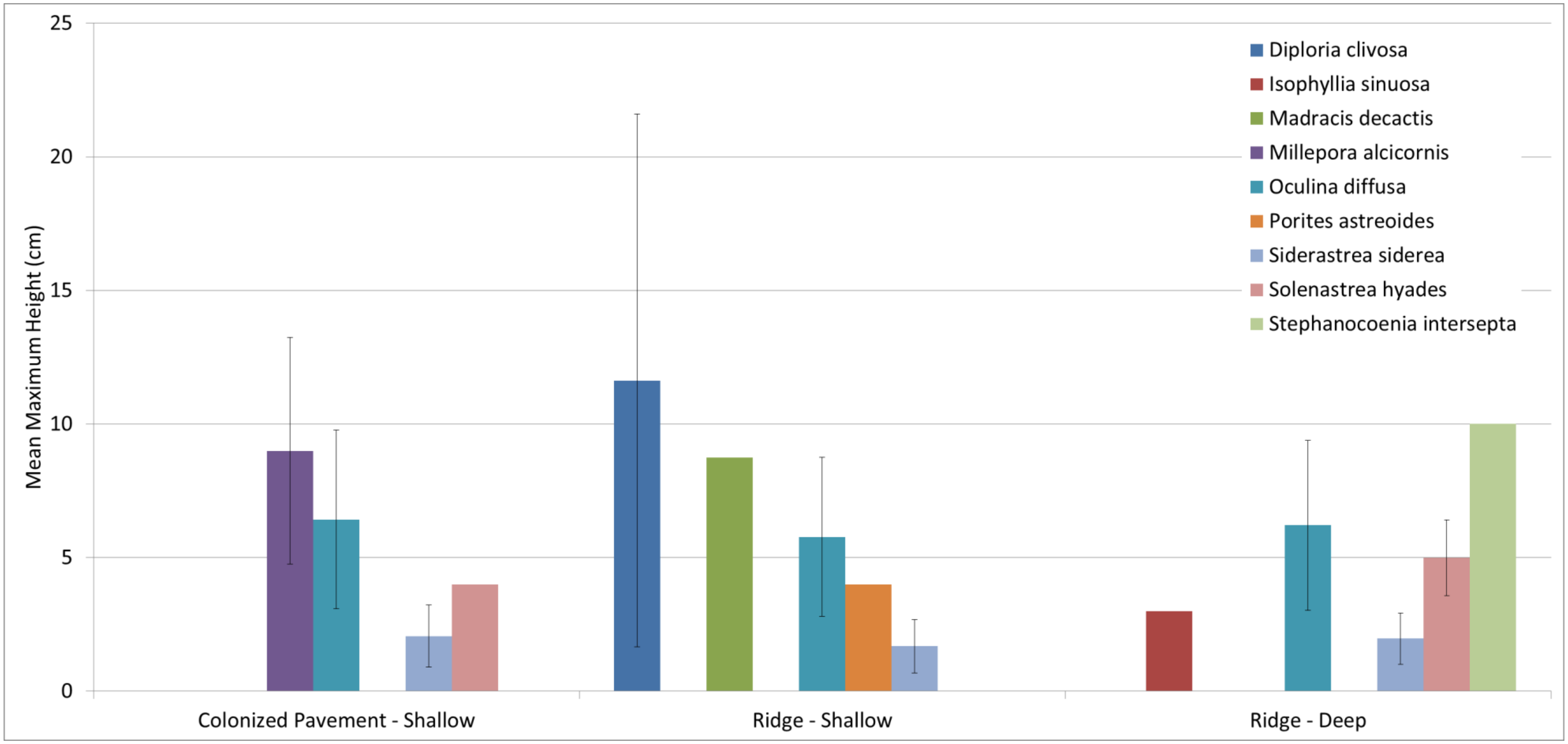


Figure 52. Mean maximum coral height (cm) by species and by habitat. Error bars indicate ±1 standard deviation. No error bars indicate a single colony. The legend reflects all species encountered by both point intercept and belt transect surveys.

Accuracy Assessment.—Of the total 199 ground validation targets, 196 sites were visited, of which 193 were used in this assessment. The identity and number of planned targets differed from that of the final targets as a result of several videos being unusable in identifying the seafloor. Three targets were omitted due to field logistical concerns.

Error matrices for Major Habitat are presented in Tables 8 and 9. The overall accuracy (P_o) was 85.6% at the Major Habitat level (Table 8). The Tau coefficient for equal probability of group membership (T_e) was 0.713 ± 0.102 (α=0.05), i.e. the rate of misclassifications at the Major Structure level was 71.3% less than would be expected from random assignment of polygons to categories. Table 9 is populated by the individual cell probabilities ($\hat{P}_{ij}$), which are the product of the original error matrix cell values and the known map marginal proportions, divided by the row marginal of the original error matrix. The overall accuracy (P_o), corrected for bias using the known map marginal proportions, was 94.9% ± 6.4 (α=0.05). The producer's accuracies, adjusted for known map marginal proportions, are shown for individual map categories. A 95% confidence interval was calculated for each value of producer's and user's accuracy.

The Major Habitat error matrix clearly demonstrated the effect of adjusting producer's accuracy to the known map marginal proportions. In the original error matrix (Table 8), 41 of 181 groundtruthed Soft-bottom (Unconsolidated Sediments) samples were correctly classified. The remaining 24 samples were incorrectly classified as Hard-bottom (Coral Reef and Colonized Pavement). The unadjusted producer's accuracy was therefore equal to 41/181 = 85.6%; however, the known map marginal proportions of the Soft habitats were 96.7%, versus 3.3% for Hard habitats (Table 9). Hence, the producer's confusion between these two habitats was exaggerated by a disproportionately high sampling of Hard habitats that had a disproportionately lower contribution to the total area. Discrimination between these two categories increased after the error matrix cell values were transformed from the original binomial observations to individual cell probabilities (24*0.033/138=0.0057 and 41*0.967/43=0.9220), increasing producer's accuracy from 63.1% to 99.4%.

Error matrices for Detailed Habitat are presented in Tables 10 and 11. The overall accuracy (P_o) was 85.0% at the Detailed Habitat level (Table 10). The Tau coefficient for equal probability of group membership (T_e) was 0.828 ± 0.058 (α=0.05), i.e. the rate of misclassifications at the Detailed Habitat level was 82.8% less than would be expected from random assignment of polygons to categories. T_e more closely approached P_o at the Detailed level (r = 9) than at the Major level (r = 2), reflecting the diminishing probability of random agreement with increasing map categories. Table 11 is populated by the individual cell probabilities ($\hat{P}_{ij}$), which are the product of the original error matrix cell values and the known map marginal proportions, divided by the row marginal of the original error matrix. The overall accuracy (P_o), corrected for bias using the known map marginal proportions, was 91.5% ± 7.5 (α=0.05). The producer's accuracies, adjusted for known map marginal proportions, are shown for individual map categories. A 95% confidence interval was calculated for each value of producer's and user's accuracy.

Table 8. Error matrix for Major Habitat. The overall accuracy (P_o) was 85.6%. The Tau coefficient for equal probability of group membership (T_e) was 0.713, with a 95% Confidence Interval of 0.611– 0.815.

		TRUE (j)			
	MAJOR HABITAT	**Hard**	**Soft**	n_{i-}	**USERS Accuracy (%)**
MAP (i)	**Hard**	**114**	24	138	**82.6**
	Soft	2	**41**	43	**95.3**
	n_{-j}	116	65	**181**	**<=** n
	PRODUCERS Accuracy (%)	**98.3**	**63.1**	P_o	**85.6%**

$T_e = 0.713 \pm 0.102$

Table 9. Error matrix for Major Habitat using individual cell probabilities (P_{ij}). The overall accuracy, corrected for bias using the known map marginal proportions (π_i), was 94.9% with a 95% Confidence Interval of 88.7% – 100%.

		TRUE (j)				
	MAJOR HABITAT	**Hard**	**Soft**	π_i	**USERS Accuracy (%)**	**USERS CI (± %)**
MAP (i)	**Hard**	**0.0273**	0.0057	0.033	**82.6**	**6.5**
	Soft	0.0450	**0.9220**	0.967	**95.3**	**6.4**
	n_{-j}	0.072	0.928	**1.000**	**<=** n	
	PRODUCERS Accuracy (%)	**37.8**	**99.4**	P_o	**94.9%**	
	PRODUCERS CI (± %)	**32.5**	**0.2**	**CI (±)**	**6.2%**	

Table 10. Error matrix for Detailed Habitat. The overall accuracy (P_o) was 85.0%. The Tau coefficient for equal probability of group membership (T_e) was 0.828, with a 95% Confidence Interval of 0.770 – 0.886. Blank cells indicate 0 occurrences.

TRUE (GROUND-TRUTHED) (j)

MAP DATA (i)

DETAILED HABITAT	**Colonized Pavement-Shallow**	**Ridge-Deep**	**Ridge-Shallow**	**Scattered Rock in Unconsolidated Sediment-Deep**	**Scattered Rock in Unconsolidated Sediment-Shallow**	**Sand-Deep**	**Sand-Shallow**	**Artificial**	**$n_{i\cdot}$**	**USERS Accuracy (%)**
CP - Shallow	**26**						1		27	**96.3**
Ridge-Deep		**40**				12	5		57	**70.2**
Ridge-Shallow			**46**				6		52	**88.5**
SCRUS - Deep				**1**					1	**100.0**
SCRUS - Shallow					**1**				1	**100.0**
Sand-Deep						**2**			2	**100.0**
Sand-Shallow		2					**39**	2	43	**90.7**
Artificial							1	**9**	10	**90.0**
$n_{\cdot j}$	26	42	46	1	1	14	52	11	**193**	**<= *n***
PRODUCERS Accuracy (%)	**100.0**	**95.2**	**100.0**	**100.0**	**100.0**	**14.3**	**75.0**	**81.8**	**P_o**	**85.0%**

T_e = 0.828 ± 0.058

Table 11. Error matrix for Detailed Habitat using individual cell probabilities (P_{ij}). The overall accuracy, corrected for bias using the known map marginal proportions (π_i), was 91.5% with a 95% Confidence Interval of 84.0% – 99.0%. Blank cells indicate 0 occurrences.

TRUE (GROUND-TRUTHED) (j)

MAP DATA (i)

DETAILED HABITAT	**Colonized Pavement-Shallow**	**Ridge-Deep**	**Ridge-Shallow**	**Scattered Rock in Unconsolidated Sediment-Deep**	**Scattered Rock in Unconsolidated Sediment-Shallow**	**Sand-Deep**	**Sand-Shallow**	**Artificial**	**π_i**	**USERS Accuracy (%)**	**USERS CI (± %)**
CP - Shallow	**0.00630**						0.00024		0.007	**96.3**	**7.3**
Ridge-Deep		**0.00972**				0.00292	0.00121		0.014	**70.2**	**12.1**
Ridge-Shallow			**0.01097**				0.00143		0.012	**88.5**	**8.9**
SCRUS - Deep				**0.00014**					0.000	**100.0**	**0.0**
SCRUS - Shallow					**0.00008**				0.000	**100.0**	**0.0**
Sand-Deep						**0.11537**			0.115	**100.0**	**0.0**
Sand-Shallow		0.03959					**0.77210**	0.03959	0.851	**90.7**	**8.9**
Artificial							0.00003	**0.00030**	0.000	**90.0**	**19.0**
$n_{\cdot j}$	0.006	0.049	0.011	0.000	0.000	0.118	0.775	0.040	**1.000**	**<= *n***	
PRODUCERS Accuracy (%)	**100.0**	**19.7**	**100.0**	**100.0**	**100.0**	**97.5**	**99.6**	**0.7**	**P_o**	**91.5%**	
PRODUCERS CI (± %)	**7.5**	**22.0**	**10.0**	**0.0**	**0.0**	**1.2**	**9.7**	**1.0**	**CI (±)**	**7.5%**	

The accuracy assessment of the Martin County major habitats yielded a high level of accuracy as indicated by the overall accuracy (85.6%), the overall accuracy adjusted for known map marginal proportions (adjusted accuracy) (94.9%), and the Tau coefficient (0.713), which adjusted for the number of map categories (Tables 8 and 9). Of the 26 classification errors (which excluded artificial sites), 24 were due to Unconsolidated Sediment being found in polygons classified as Coral Reef/Colonized Hardbottom. This yielded a low producer's accuracy (63.1%) for soft bottom, however correction to map marginal proportions yielded a much higher result (99.4%). The converse was also true where a high producer's accuracy for hardbottom (98.3%) was drastically reduced by map proportions (37.8%) due to its low spatial coverage.

The overall accuracy for major habitat was similar to other regional mapping efforts. Overall map accuracy in Martin was less than Broward (89.6%) (Walker et al. 2008), Palm Beach (89.2%) (Riegl et al. 2005), and Miami-Dade (93.0%) (Walker 2009), however it was higher than all of them after adjusting for map marginal proportions. The other mapping efforts did not account for this, but it is an important aspect in Martin County given the disparity between hard and soft bottom areas. Soft bottoms comprised 95.2% of the entire mapped area and hard bottoms only 4.13% (Table 5). This is much different than Palm Beach (63.9% soft, 35.02% hard), Broward (46.8% soft, 54.2% hard), and Miami-Dade (50.47% soft, 29.65% hard) and likely had a profound effect on the outcome. The map marginal proportion correction is a necessary adjustment in this case and likely better reflects the true map accuracy.

Although changes to the NOAA classification scheme precluded a direct comparison, results were consistent with other regional accuracy assessments. Kendall et al. (2001) reported a very similar overall accuracy of 93.6% for the NOAA Puerto Rico and Virgin Island maps. Walker and Foster (2010) reported an accuracy of 94% after map proportion correction for a two combined areas in the Florida Keys. The NOAA St. John effort reported 96% total map accuracy for Major Geomorphologic Structure (Zitello et al., 2009). They adopted the methods reported in Walker and Foster (2009) to adjust for map marginal proportions, which increased the overall accuracy to 96.7%.

The detailed Martin habitats were mapped at a similar level of accuracy, albeit slightly lower than major habitat, as indicated by the overall accuracy (85.0%), the overall adjusted accuracy (91.5%), and the Tau coefficient (0.828) (Tables 10 and 11). The overall accuracy was 5.5% less than that reported for Miami-Dade (Walker 2009), yet it was 1% higher after correcting for map marginal proportions. Twelve of the sixteen adjusted user's and producer's accuracies were greater than 90% and seven of those were 100%.

Ridge-Deep had the lowest adjusted user's accuracy (70.2%) of all classes. Seventeen of 57 sites mapped as Ridge-Deep were found to be Sand-Deep (12), and Sand-Shallow (5). Ridge-Deep also had the lowest adjusted producer's accuracy of the natural habitats (19.7%). Two of 42 sites ground-truthed as Ridge-Deep were mapped as Sand-shallow (Table 11), yielding an accuracy of 95.2%, but correcting for map proportions reduced it to 19.7% because it only comprised 1.36% of the entire mapped area. Misclassified points in proportionally small areas can dramatically reduce the accuracy of those habitats. The best example of this is in the artificial habitats where an accuracy of 81.8% was adjusted to 0.7%.

Sand had the most frequent and variable producer's errors in the map. Twenty-four sites ground-truthed as Sand-Shallow or Sand-Deep were mapped as one of four other classes; Colonized Pavement-Shallow (1), Ridge-Deep (17), Ridge-Shallow (6), and Artificial (1). This was a very similar outcome to the NOAA FL Keys map (Walker and Foster, 2009). Sand and Hardbottom can typically be distinguished with a high degree of success in shallow, clear water (Kendall et al. 2001, Zitello et al. 2009). Having lower than expected success in mapping Sand may have come from several sources. First, the errors could have arisen from a scaling mismatch between the mapping and the accuracy assessment. The minimum mapping unit (mmu) for the mapping was 0.4 hectares (4046 m^2). It was neither practical nor feasible to survey each accuracy assessment point at that scale, however to account for some of the difference, the vessel was allowed to drift at each location to get a better understanding of the general area instead of one particular point. Since the accuracy assessment point was not surveyed at the mmu, it is unknown whether the point was smaller than the mmu and should not be included as an error. All videos were assumed to represent the habitat at each location, therefore, if only Sand was seen throughout the video, it was considered a Sand site. Sand patches smaller than the mmu may have been large enough to be deemed a Sand habitat in the video, which would unfairly increase the producer's error for Sand.

The second possible source of error for Sand comes from the mapping protocol. The Lidar being used to map Martin County was acquired over a time series between 2008 and 2009. Lidar data processing and subsequent visual interpretation into a habitat map is a time consuming process that can take several years for a given portion of the map to be drawn, ground truthed and finalized, creating a lag time between data collection and map publication. For example, the Martin map was created in 2011 and assessed for accuracy in 2012, but the data upon which the maps are based are from 2008 and 2009. Thus the maps being released in 2012 are based on three to four-year-old data. This time lag can have significant impact on the accuracy of the maps. Low relief habitats can often be covered and uncovered by sand movement during large storm events (Walker and Foster 2010, Walker and Foster 2009, Walker 2009, Walker et al. 2008, Gilliam 2007) and the ephemeral nature of the system, especially in low relief pavement, likely contributed to some of the map errors. For example, the area in southern Miami-Dade is very dynamic and recent mapping showed large changes over a 3 year period, where large areas on the order of several thousand square meters that used to be dense seagrass were now sand (Walker 2009). Furthermore, Walker and Foster (2009) found large changes in satellite images between 2005 and 2006. Some large-scale changes were noted in the 2006 imagery that were not reflected in the map nor the AA, presumably due to extreme storm conditions during hurricanes Katrina and Wilma indicating that large-scale changes have occurred in the recent past within the mapped area. In Martin County, large sand dunes are evident that appear to sweep across the seafloor including hardbottom habitats (Figures 32 and 33). These types of changes throughout the region affect the benthic habitat map accuracy and may degrade it over time. The longer the time lag between data collection and map creation, the more probability there is for errors to be introduced into the map based on temporal changes in habitat through time and not actual mapping methodological errors. Nonetheless, they are errors in the map and are considered so in the accuracy assessment.

A lack of feature relief was another contributing factor for these producer's errors. Seventeen of the 24 Sand errors occurred in Ridge-Deep habitat where interpretation was limited to the Lidar bathymetry. Lidar bathymetry was very useful in detecting the edges of features with relief; however low relief features such as Ridge-Deep were problematic.

The Ridge-Deep was the most difficult habitat to map and this was reflected in its relatively low user accuracy (70.2%). Although bathymetric relief was present in the Lidar images, much of the Ridge-Deep was covered by sand, making it difficult to distinguish Ridge-Deep from Sand-Deep in some areas. The high range of sand cover was evident benthic survey data (Figure 41). Sand cover at Site 12 was only 6% whereas Site 13 was 49.8%. Figures 53 and 54 illustrate this well.

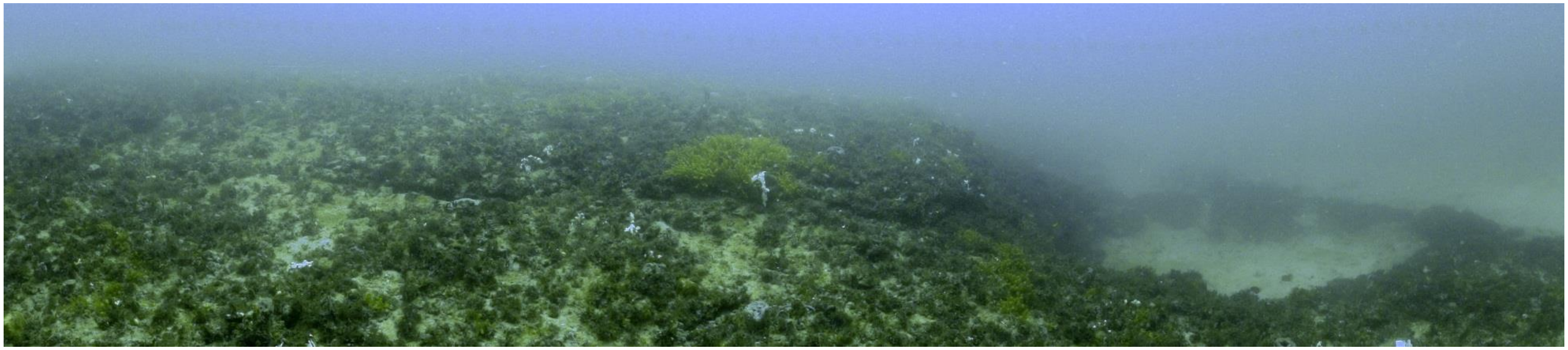


Figure 53. Site 12, the Ridge-Deep site with the lowest sand cover (6%).

Figure 54. Site 13, the Ridge-Deep site with the highest sand cover (49.8%).

There are no strict rules as to which ground validation sampling methodology works best. Assessments at point locations and areal assessments are equally valid (Stehman and Czaplewski, 1998), but ideally the reference data should be collected at the mmu's scale (Stadelmann, 1994). The Martin minimum mapping unit was 0.4 ha. It was neither practical nor economically feasible to assess the seafloor at this scale. However, assessment at a localized point wasn't ideal because it would not give a good representation of the area surrounding the sample point at the map scale. Localized point ground validation would have been problematic in mixed habitats like Scattered Coral Rock in Unconsolidated Sediment where patches may be spread out and might not be visible at all discrete locations in the polygon. For example, a random point may be placed in the polygon such that the video would contain only Unconsolidated Sediments. This would be considered an error in the map, yet the error was caused by the difference in scale between the map and the assessment method rather than a true map error. This could also cause problems in the assessment of Biological Cover which can vary significantly on small spatial scales. In order to address this issue, AA samples in this effort were taken near the random sample location while drifting. The drift allowed for more of the surrounding area to be visited and recorded, thus giving more insight and confidence in the Geomorphological Structure and Biological Cover at a scale closer to the map mmu. This also helped reduced the spatial errors associated with a precise GPS location.

The drifting assessment helped assess the transitions between habitats (i.e. the polygon borders) as well. A certain level of error is inherent in habitat transitions due to the scale of mapping (1:6000) and spatial errors in the imagery and GPS precision (Foody, 2002). Constraining sampling away from polygon boundaries to minimize spatial errors between the imagery and GPS is common practice (Dicks & Lo, 1990; Mickelson et al. 1998, Richards 1996, Wickham et al. 1997), however, this strategy, may optimistically bias the results by not assessing the habitat transitions (Congalton & Plourde, 2000; Foody, 2002; Hammond & Verbyla, 1996; Muller et al., 1998; Yang et al., 2000). Employing transect sampling and not constraining the samples from polygon edges allowed some component of the habitat transition errors to be captured. Although habitat transitions were not specifically targeted, assessed, or quantified, several occasions were encountered where the boat drifted from one habitat into another and the change was evident in the video. In these instances, the site location was considered the GPS coordinate from the point in the video where the targeted habitat was encountered.

The true error of non-sampled portions of the map is ultimately unknown and further sampling in these areas of the map would allow for a better understanding of the entire map accuracy, however, the accuracy assessments ensured that a well-distributed, representative set of monitoring locations were surveyed that closely represented the entire mapped region. For this reason it is thought to be a good measure of the map accuracies for the broader area. Many of the Biological Cover habitats were very small relative to the overall percentage of the entire mapped area; therefore the total map accuracy adjusted for marginal map proportions was likely a better gauge of the overall map accuracy than P_0. This, however, should not diminish the use of Tau as a metric to gauge map accuracy. Adjusting for marginal map proportions does not account for the probabilities of error due to increased number of classes, thus both metrics should be used as a gauge of the overall accuracy of the map products.

Spatial Analyses.— Recent analyses of the spatial distributions of habitats along the southeast Florida coast identified five coral reef ecosystem regions and potential biogeographic boundaries (Walker, 2012). The northern extent of the analysis was in southern Martin County just north of the Deep Ridge Complex where the maps ended at the time. The types and extent of shallow-water (< 30 m) coral reef habitats in the northern Florida Reef Tract are now known and can be included in the spatial assessment for coral reef ecosystem regions.

Using benthic habitat mapping data, this work statistically analyzed the amount and type of habitats along the coast to derive regions where the number of habitats and their morphology were most similar. The northern extent of the analysis was in southern Martin County just north of the Deep Ridge Complex where the maps ended at the time. The addition of the Martin County maps to these analyses allowed for further differentiation in the system. Spatial autocorrelation tests on the benthic habitat polygon areas using Moran's Index did not show a pattern significantly different from random (Moran's I 0.002; z-score 0.08; p-value 0.94). Cluster analysis of the cross-shelf transects yielded 13 clusters at the 60% similarity level and the two dimensional MDS plot showed a medium stress (0.15) (Figure 55). The Biscayne, Broward-Miami, and South Palm Beach region MDS clusters showed spatial groupings similar to the previous study. The Deerfield region, which was the weakest result in the previous study, was not evident in this analysis. The North Palm Beach transects clustered into one group that was also spatially clustered (Cluster A in Figure 56). The transects in Martin were members of five MDS clusters, however all but Cluster B were exclusive to the Martin area. This indicates that the seafloor habitat morphology in Martin is distinctly different from that further south and warrants identification as a separate region.

The analysis of similarity (ANOSIM) performed to statistically determine the similarity of the six final regions based on the cross-shelf transect data showed strong differences (R statistic > 0.849) between categories in 11 of the 15 pairwise tests (Table 12). The weakest grouping was between Deerfield and South Palm Beach regions (R = 0.115). Although not the strongest grouping, North Palm Beach and Martin groups were significantly strong (R = 0.621) and justified the split. Visual inspection of the transects in GIS revealed that weaknesses in the clusters were likely due to the absence of certain habitats in specific transects that were present at the larger scale, but were not captured along the transect.

The addition of the Martin County maps to these analyses justified the creation of a sixth region north of the North Palm Beach region based on habitat types and configurations. In contrast to reef regions further south where coral reef habitats ranged from 13.93% (South Palm Beach) to 52.6% (Broward-Miami) (Walker, 2012), the Martin area contained 4.1% coral reef habitat, most of which was spread throughout the county in a few thin deep and shallow ridges.

Differences in benthic cover indicate that the Martin region has a unique biological composition from other areas of the FRT. Previous research shows distinct differences in the macroalgal communities in southeast Florida (Lapointe, 2007). In 2007, a two-year detailed regional study on macroalgal communities showed that Martin County had the highest macroalgal cover in SE FL and the dominant species in these communities can shift over relatively short time frames. Blooms of Caulerpa brachypus and Phaeophytes (likely Dictyota sp.) were documented at fixed monitoring stations where cover changed by over 50% in a few months at some sites. Several unexplored spatial patterns are also present in these data. Differences were evident in algal populations along a latitudinal gradient between the deep and shallow reefs that are not seen solely by summing up the data for each county. In Martin, Lapointe (2007) surveyed 5 sites; 3 on shallow ridge and two on deep ridge. The 3 shallow ridge sites had a large component of Phaeophyta cover (> 50% during certain times) that was not present in the deep habitats, where Chlorophyta was dominant. This was further exemplified by the five sites on the deep ridge complex in north Palm Beach that were dominated by Chlorophyta and Rhodophyta and had very little Phaeophyta if any. Further investigations into the spatial relationships in these data are underway.

Comparisons of the coral communities also show regional differences. Monitoring data of reefs in similar depths approximately 75 km south (Broward County) found 2.8 times more stony coral species (Gilliam et al., 2010). Gilliam et al. (2010) reported 25 species of coral present in 750 m^2 of survey area, compared to nine found in Martin in 1737 m^2 of survey area. Similarly the Southeast Florida Coral Reef Evaluation and Monitoring Project (SECREMP), a regional coral reef monitoring program in place since 2003, found 9 species present in Martin compared to 25 species further south (Gilliam, 2010). They reported Martin had the lowest number of species per station (5.8). Coral density was found much lower in Martin than reefs further south. In Broward, coral density of 25 monitoring sites was 2.6 m^{-2}; 8.1 times greater than our density estimates in Martin (0.32 m^{-2}) (Gilliam et al., 2010). And finally, Diadema were more abundant in the Martin County sites (24 of the 46 urchins) than the sites in the other three counties (Gilliam and Walker, 2011).

This study and previous research shows that the northern FRT is quite different from other parts of the FRT. The extent of hardbottom is relatively sparse and the communities it harbors are distinct in both the types and amounts of biological constituents, supporting the reasoning that this area should be considered a separate biogeographic region.

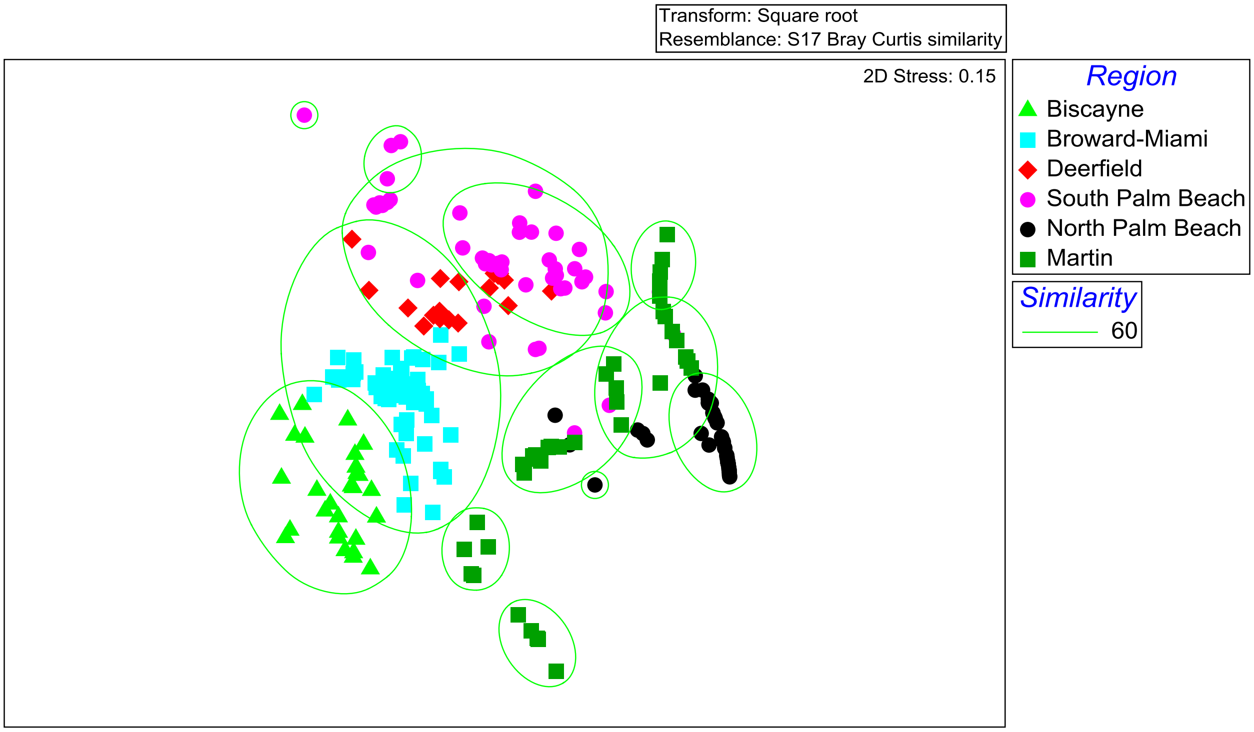


Figure 55. Multidimensional scaling (MDS) plot of Bray-Curtis similarity matrix of 248 regional cross-shelf transects displayed using the six final regional categories. The outlines represent 60% similarity from the cluster analysis.

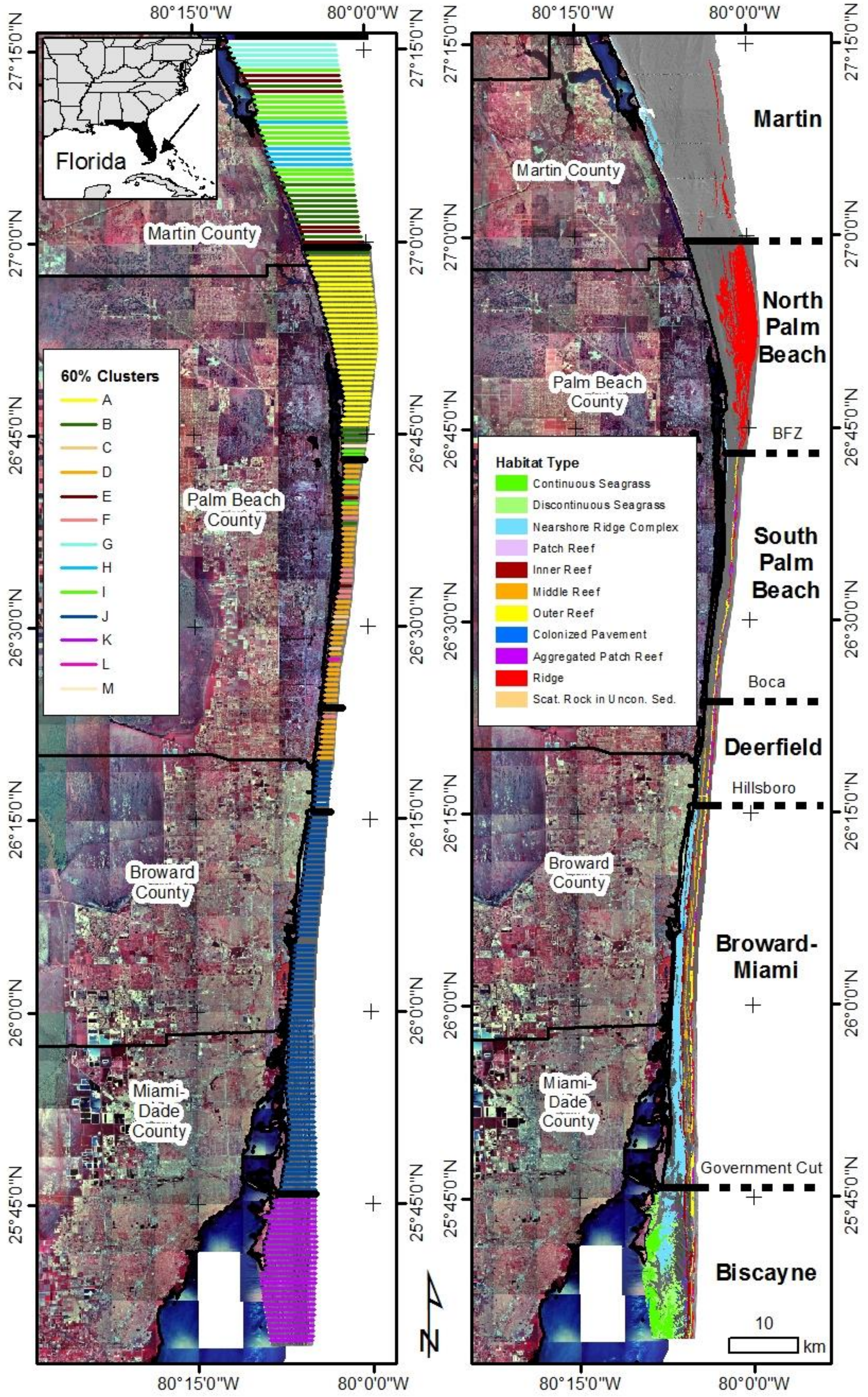


Figure 56. Overview maps showing the cross-shelf transects symbolized by the 60% similarity MDS clusters (left) and the six identified regions (right). BFZ = Bahamas Fault Zone.

Table 12. A summary of the analysis of similarity (ANOSIM) pairwise test between the six identified biogeographic regions.

ANOSIM Pairwise Tests	**R**	**Significance**
Groups	**Statistic**	**Level %**
Biscayne, Broward-Miami	0.941	0.1
Biscayne, Deerfield	0.993	0.1
Biscayne, South Palm Beach	0.873	0.1
Biscayne, North Palm Beach	1	0.1
Biscayne, Martin	0.806	0.1
Broward-Miami, Deerfield	0.895	0.1
Broward-Miami, South Palm Beach	0.883	0.1
Broward-Miami, North Palm Beach	0.998	0.1
Broward-Miami, Martin	0.88	0.1
Deerfield, South Palm Beach	0.115	3.2
Deerfield, North Palm Beach	0.996	0.1
Deerfield, Martin	0.671	0.1
South Palm Beach, North Palm Beach	0.849	0.1
South Palm Beach, Martin	0.531	0.1
North Palm Beach, Martin	0.621	0.1

Broward County

Phase 1.— Broward County's Environmental Protection and Growth Management Department subcontracted Coastal Planning and Engineering, Inc. (CP&E) to conduct the LIDAR bathymetric survey for Broward County. The final bathymetric dataset was collected by Tenix LADS Inc. between July and August 2008, for Baxley Ocean Visions, Inc., under contract to CP&E, for Broward County, Florida. Information regarding this survey can be obtained by contacting Ken Banks at Broward County's Environmental Protection and Growth Management Department, Biological Resources Division. Final survey reports, LADS Relative Reflectance data and Quester Tangent Optical Diversity results are available. Below is a map of the processed 2008 Broward County LIDAR data (Figure 56).

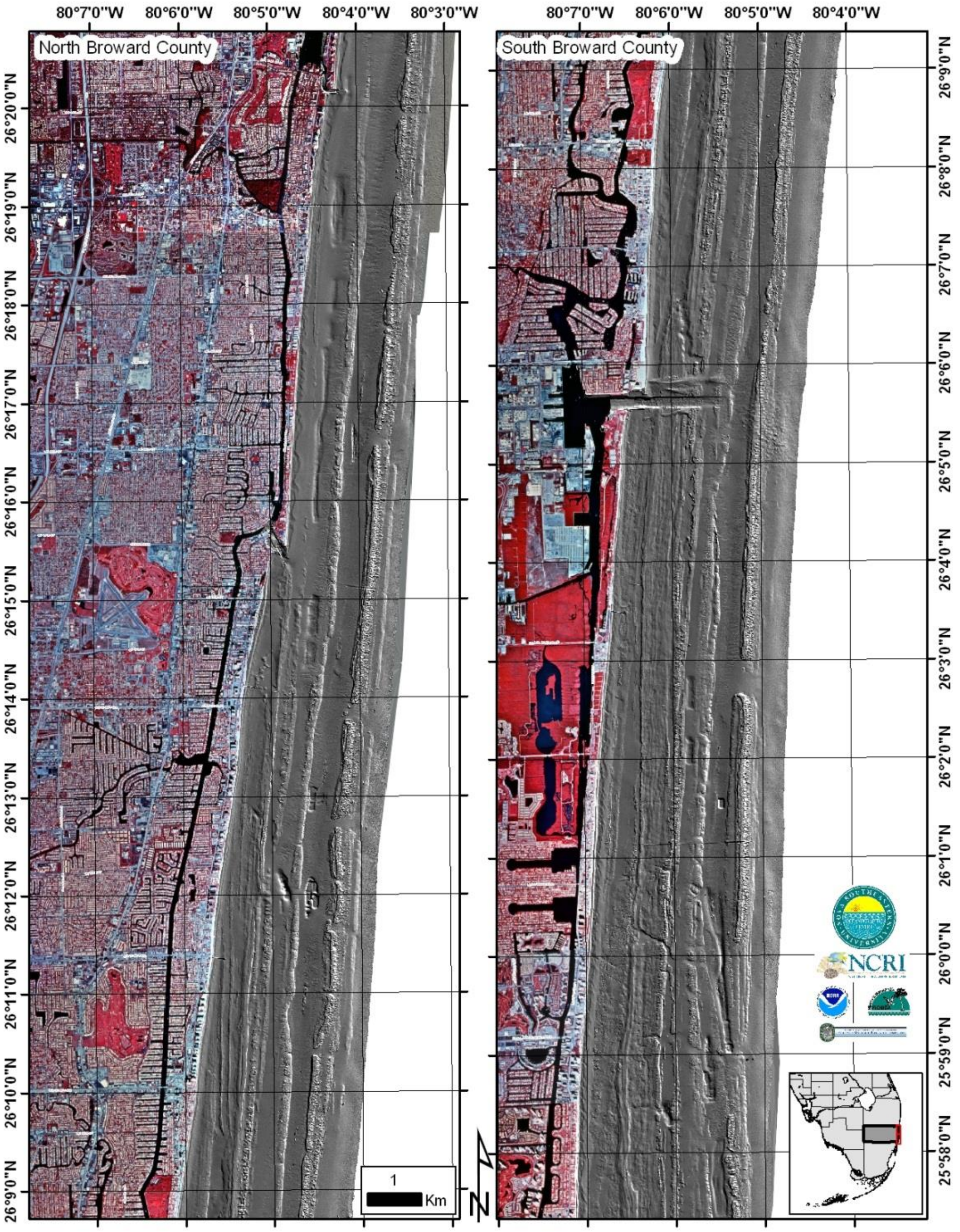


Figure 56. Broward County hill-shaded 2008 LIDAR bathymetry.

LITERATURE CITED

AGRRA. (2000). Atlantic and Gulf Rapid Reef Assessment (AGRRA). The AGRRA rapid assessment protocol. http://www.coral.noaa.gov/agra/method/methodhome.htm

Almada-Villela, P. C., P. F. Sale, G. Gold-Bouchot and B. Kjerfve. (2003) Manual of methods for the MBRS synoptic monitoring program: Selected methods for monitoring physical and biological parameters for use in the Mesoamerican region. April, 2003. 146 pp.

Banks K, Riegl B, Shinn E, Piller W, Dodge R (2007) Geomorphology of the southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA). Coral Reefs 26:617-633

Card, D.H. (1982) Using known map categorical marginal frequencies to improve estimates of thematic map accuracy. *Photogrammetric Engineering and Remote Sensing*, 48: 431-439.

Cohen, J. (1960) A coefficient of agreement for nominal scale. *Educational and Psychological Measurement*, 20: 37-46.

Congalton, R. (1991) A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37: 35-46.

Congalton, R. G., & Plourde, L. C. (2000). Sampling methodology, sample placement, and other important factors in assessing the accuracy of remotely sensed forest maps. In: G. B. M. Heuvelink, M. J. P. M. Lemmens (Eds.), Proceedings of the 4th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences (pp. 117– 124). Delft: Delft University Press.

Dicks, S. E., & Lo, T. H. C. (1990). Evaluation of thematic map accuracy in a land-use and land-cover mapping program. Photogrammetric Engineering and Remote Sensing, 56, 1247–1252.

Engle, V. D. & Summers, J. K. (1999) Latitudinal gradients in benthic community composition in Western Atlantic estuaries. Journal of Biogeography, 26, 1007-1023.

FMRI (2000) Benthic habitats of the Florida Keys. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute and National Oceanic and Atmospheric Administration.

Foody, G.M. (2002) Status of land cover classification accuracy assessment. Remote Sensing of Environment 80 185-201

Gilliam, D.S. (2007) Southeast Florida Coral Reef Evaluation and Monitoring Project 2007 Year 5 Final Report. Prepared for: Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, Florida Department of Environmental Protection. 36 pp. http://www.floridadep.org/coastal/programs/coral/reports/.

Gilliam, D. S., R. E. Dodge, R. E. Spieler, L. K. B. Jordan, and E. A. Goergen. (2008) Marine Biological Monitoring in Broward County, Florida: Year 8 (2007) Annual Report. Technical Report 08-01. Prepared for the Broward County Board of County Commissioners, Environmental Protection and Growth Management Department, Biological Resources Division. 66 pp.

Green, E.P., Mumby, P.J., Edwards, A.J., and Clark, C.D. (Ed. A.J. Edwards) (2000) Remote management. Coastal Management Sourcebooks 3, UNESCO, Paris. 316 p.

Hammond, T. O., & Verbyla, D. L. (1996) Optimistic bias in classification accuracy assessment. International Journal of Remote Sensing, 17, 1261– 1266.

Hay, A.M. (1979) Sampling designs to test land use map accuracy. *Photogrammetric Engineering and Remote Sensing*, 45: 529-533.

Hudson, W.D. and Ramm, C.W. (1987) Correct formation of the kappa coefficient of agreement. *Photogrammetric Engineering and Remote Sensing,* 53: 421-422.

Kendall MS, Christensen JD, Hillis-Starr Z (2003) Multi-scale Data Used to Analyze the Spatial Distribution of French Grunts, Haemulon Flavolineatum, Relative to Hard and Soft Bottom in a Benthic Landscape. Environmental Biology of Fishes 66:19-26

Kendall MS, Kruer CR, Buja KR, Christensen JD, Finkbeiner M, Warner RA, Monaco ME (2002) Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA, NOS, NCCOS, Silver Spring, MD 45

Lapointe B (2007) Comparative Ecology of Harmful Macroalgal Blooms in South Florida’s Coastal Waters (CEHAB). Harbor Branch Oceanographic Institution, Ft. Pierce, FL 64

Lugo, A. E., Brown, S. L., Dodson, R., Smith, T. S. & Shugart, H. H. 1999. Special paper: The Holdridge Life Zones of the conterminous United States in relation to ecosystem mapping. Journal of Biogeography, 26, 1025-1038.

Ma, Z. and Redmond, R.L. (1995) Tau coefficients for accuracy assessment of classification of remote sensing data. *Photogrammetric Engineering and Remote Sensing,* 61: 435-439.

Mickelson, J. G., Civco, D. L., & Silander, J. A. (1998). Delineating forest canopy species in the Northeastern United States using multi-temporal TM imagery. Photogrammetric Engineering and Remote Sensing, 64, 891– 904.

Muller, S. V., Walker, D. A., Nelson, F. E., Auerach, N. A., Bockheim, J. G., Guyer, S., & Sherba, D. (1998). Accuracy assessment of a land-cover map of the Kuparuk river basin, Alaska: considerations for remote regions. Photogrammetric Engineering and Remote Sensing, 64, 619– 628.

Richards, J. A. (1996). Classifier performance and map accuracy. Remote Sensing of Environment, 57, 161–166.

Riegl, B., Walker, B., Foster, G., and Foster, K. (2005) Development of GIS maps for southeast Florida coral reefs. Florida Department of Environmental Protection. DEP agreement no. G0098; NOAA Award NA03NOS4190209.

Smith SG, Ault JS, Bohnsack JA, Harper DE, Luo J, McClellan DB (2011) Multispecies survey design for assessing reef-fish stocks, spatially explicit management performance, and ecosystem condition. Fish Res 109:25-41

Stadelmann M, Curtis A, Vaughan R, Bailey M, Convis C, Goodchild M, Davis F, Li X, Goodin K, Grossman D (1994) Accuracy Assessment Procedures, NBS/NPS Vegetation Mapping Program. United States Department of Interior, National Biological Survey and National Park Service, Redlands, California (99)

Steel, G.D. and Torrie, J.H. (1960) *Principles and Procedures of Statistics*. McGraw-Hill Book Company, Inc., New York. 481 p.

Stehman SV, Czaplewski RL (1998) Design and analysis for thematic map accuracy assessment: Fundamental principles. Remote Sensing of Environment 64: 331-344

Story, M. and Congalton, R. (1986) Accuracy assessment: A user’s perspective. *Photogrammetric Engineering and Remote Sensing,* 52: 397-399.

van Genderen, J.L. and Lock, B.F. (1977) Testing land use map accuracy. *Photogrammetric Engineering and Remote Sensing,* 43: 1135-1137.

van Genderen, J.L., Lock, B.F., and Vass, P.A. (1978) Remote sensing: statistical testing of thematic map accuracy. *Remote Sensing of Environment,* 7: 3-14.

Walker B.K. (2012) Spatial Analyses of Benthic Habitats to Define Coral Reef Ecosystem Regions and Potential Biogeographic Boundaries along a Latitudinal Gradient. PLoS ONE 7:e30466

Walker BK (2010) A Study to Minimize or Eliminate Hard Bottom and Reef Impacts from Anchoring Activities in Designated Anchorages at the Ports of Miami and Palm Beach. Florida DEP report #RM083, Miami Beach, FL 59 Walker B.K., Foster G (2010) Accuracy Assessment and Monitoring for NOAA Florida Keys mapping ROI 2 (Key West). Prepared for the Office of National Marine Sanctuaries NOS/NOAA, Silver Spring, MD 43

Walker, B.K. (2009) Benthic Habitat Mapping of Miami-Dade County: Visual Interpretation of LADS Bathymetry. Interim Report 5 (January - March 2009). Florida Department of Environmental Protection. DEP agreement no. RM069; NOAA Award NA06NOS4190100.

Walker BK, Gilliam DS, Dodge RE, Walczak J (2012) Dredging and shipping impacts on southeast Florida coral reefs. Proceedings of the 12th International Coral Reef Symposium, 19A Human impacts on coral reefs: general session, Cairns, Australia, 9-13 July 2012

Walker B.K., Foster G. (2009) Accuracy Assessment and Monitoring for NOAA Florida Keys mapping AA ROI-1 (Hawk Channel near American Shoal). Prepared for the Office of National Marine Sanctuaries NOS/NOAA, Silver Spring, MD 32.

Walker, B.K., Riegl, B., and Dodge, R.E. (2008) Mapping coral reef habitats in southeast Florida using a combined technique approach. *Journal of Coastal Research*, 24: 1138-1150.

Wickham, J. D., O’Neill, R. V., Ritters, K. H., Wade, T. G., & Jones, K. B. (1997). Sensitivity of selected landscape pattern metrics to land-cover misclassification and differences inland-cover composition. Photogrammetric Engineering and Remote Sensing, 63, 397–402.

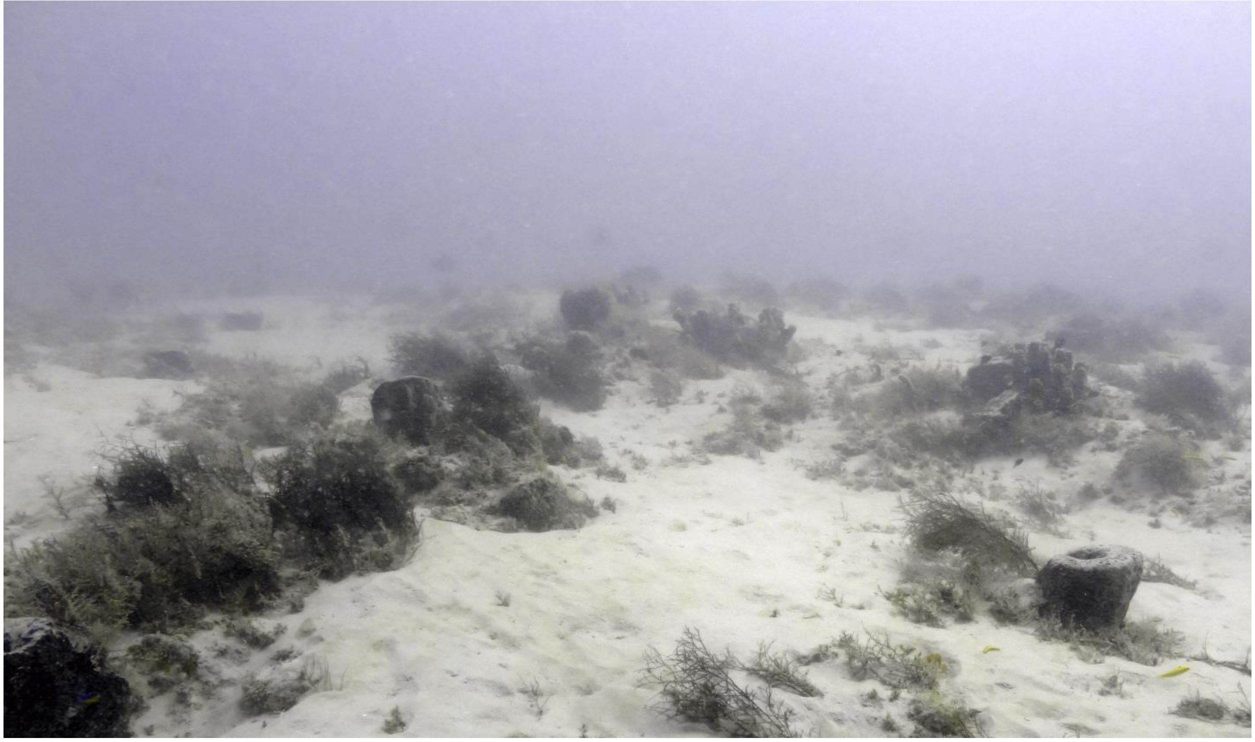
Yamano, H., Sugihara, K. & Nomura, K. (2011) Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. Geophys. Res. Lett., 38, L04601.

Yang, L., Stehman, S. V., Wickham, J., Jonathan, S., & VanDriel, N. J. (2000). Thematic validation of land cover data of the eastern United States using aerial photography: feasibility and challenges. In: G. B. M. Heuvelink, M. J. P. M. Lemmens (Eds.), Proceedings of the 4th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences (pp. 747–754). Delft: Delft University Press.

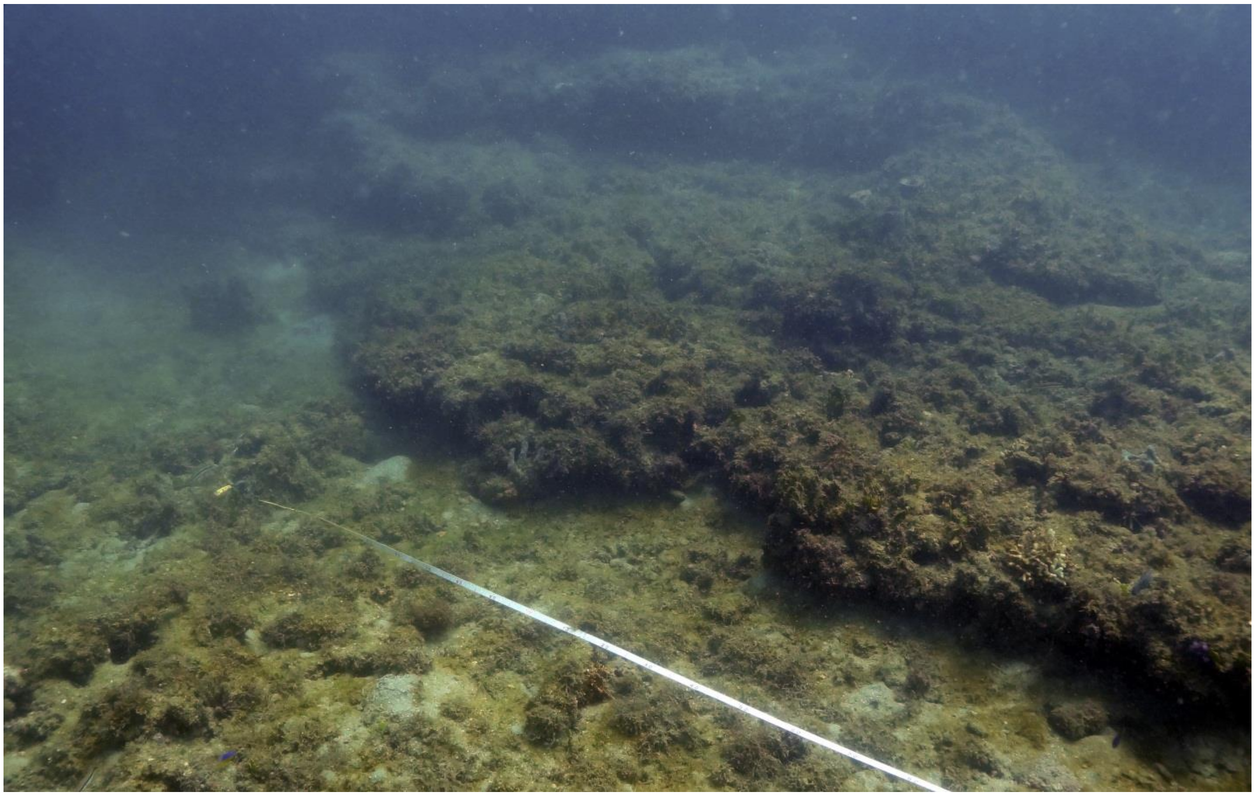
Zitello AG, Bauer LJ, Battista TA, Mueller PW, Kendall MS, Monaco ME (2009) Benthic Habitats of St. John, U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS 96, Silver Spring, MD 53

APPENDIX 1

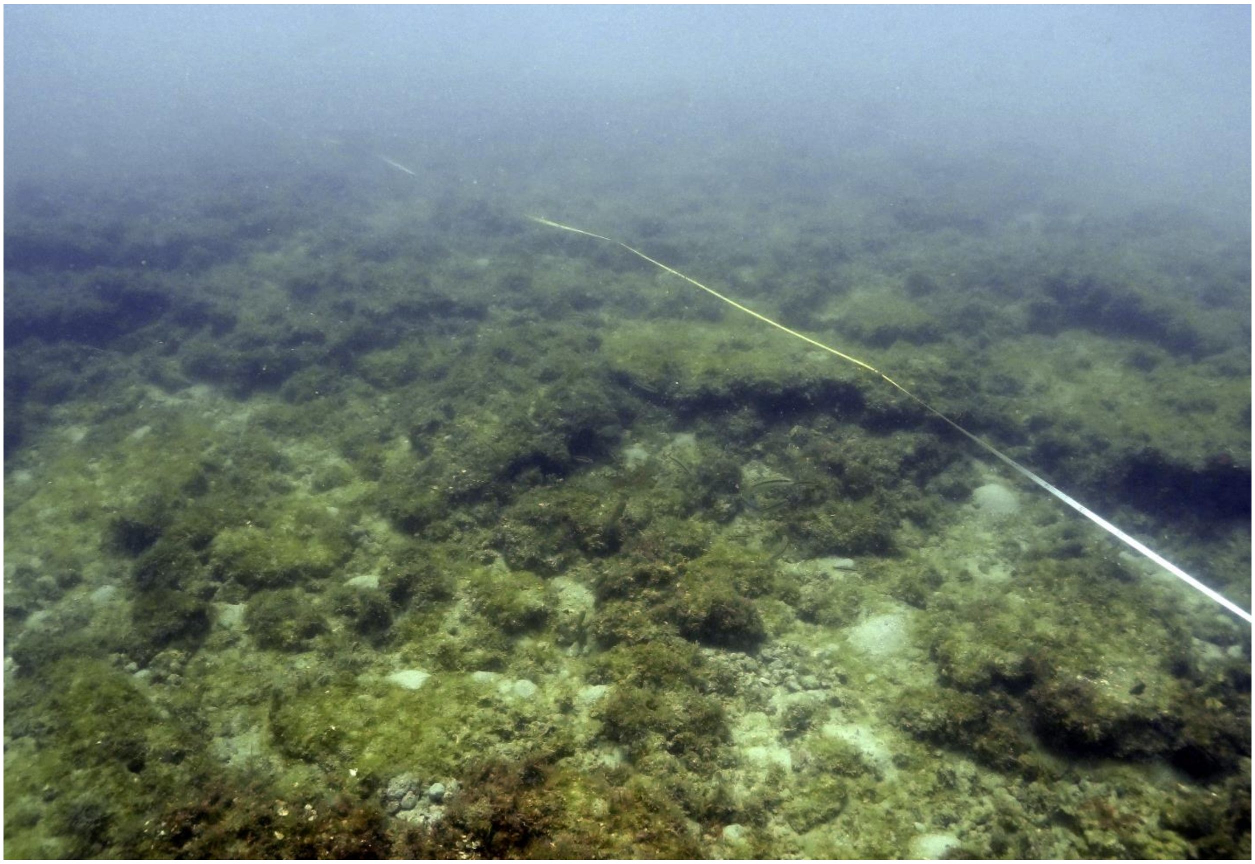
Site 2. Ridge-Deep. This dive was aborted due to strong current.



Site 3. Colonized Pavement-Shallow.

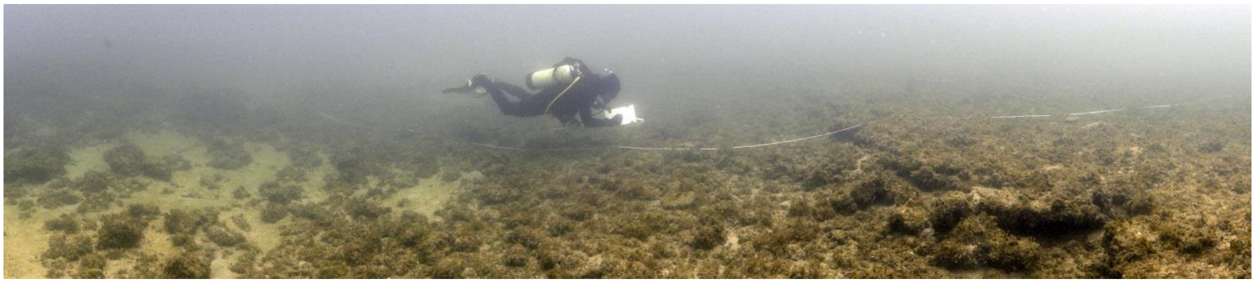


Site 4. Colonized Pavement-Shallow.

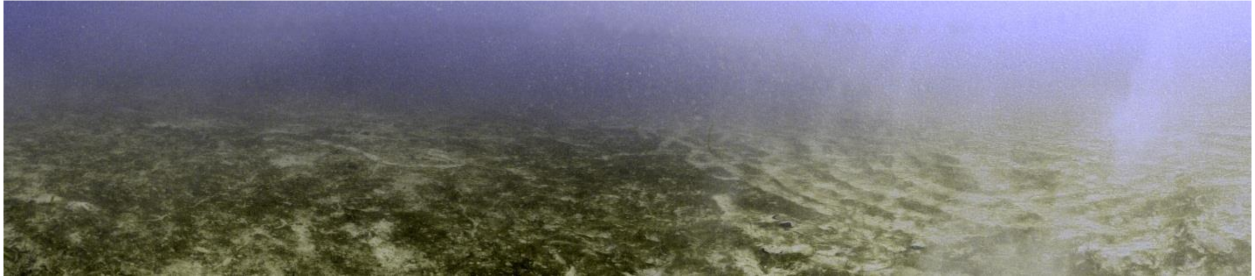


Site 5. Colonized Pavement-Shallow.

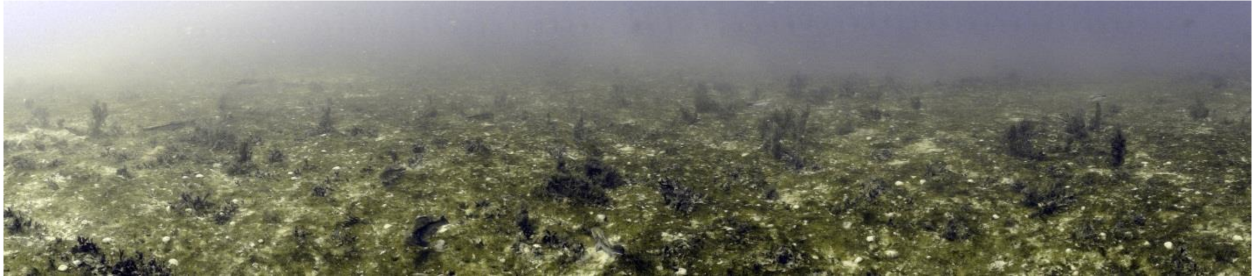
Site 6. Colonized Pavement-Shallow.



Site 7. Ridge-Deep. No data was collected at this site due to strong current.

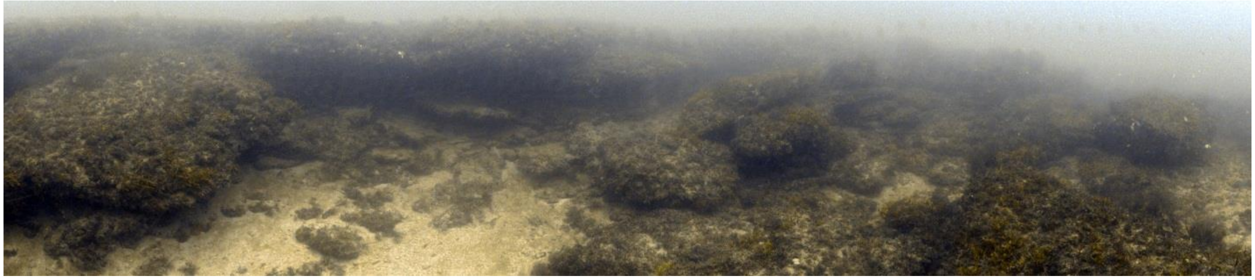


Site 8. Ridge-Deep (mostly sand covered by a layer of cyanobacteria).

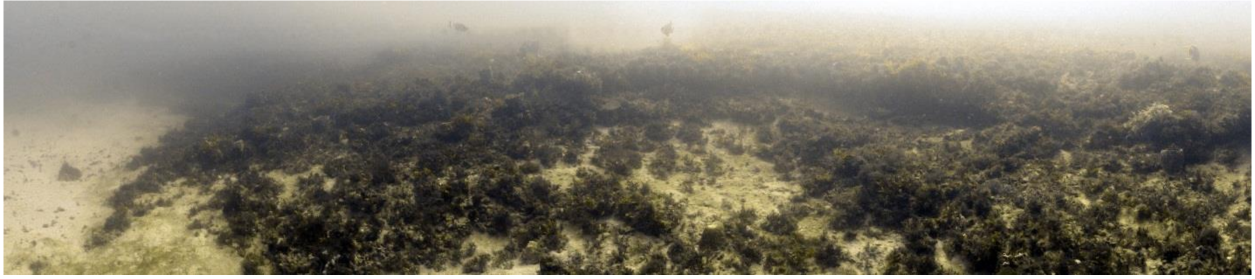


Site 9. Ridge-Deep with large (~3m) nurse shark.

Site 10. Ridge-Deep.



Site 11. Ridge-Deep.

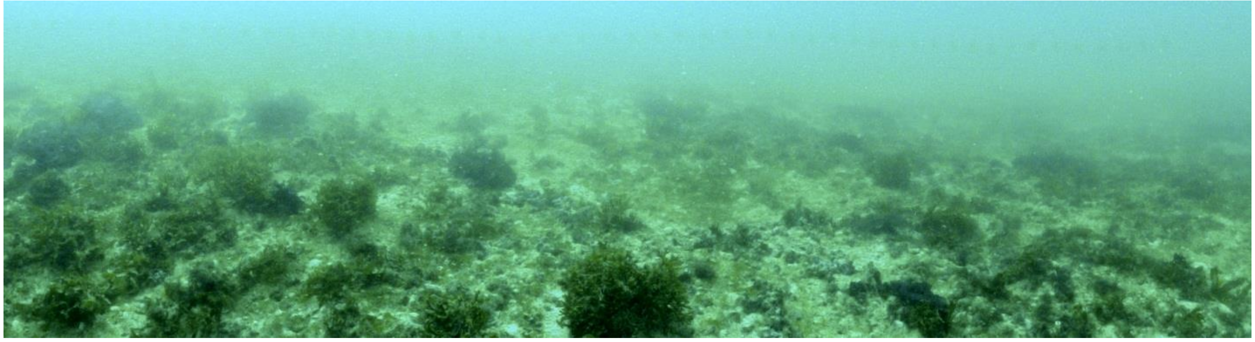


Site 12. Ridge-Deep.

Site 13. Ridge-Deep.

Site 14. Ridge-Shallow.

Site 15. Ridge-Deep.



Site 16. Ridge-Shallow.

Site 17. Ridge-Shallow.

Site 18. Ridge-Shallow with ~1.5m goliath grouper.

Site 19. Ridge-Shallow.