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Spatial dynamics of the quantity and diversity of natural and artificial hard bottom habitats in the eastern Gulf of Mexico

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ABSTRACT

The eastern Gulf of Mexico continental shelf (approximately 144,000 km^2), while dominated by unconsolidated sediments, contains diverse hard bottom habitats critical to economically important reef fishes. Although high-resolution mapping exists for several well-known hard bottom features (e.g. Florida Middle Grounds, The Sticky Grounds), the majority of the shelf remains unmapped. Through mapping efforts conducted in support of fisheries independent resource surveys, hard bottom habitats were identified and classified from 4208 randomly distributed, small-scale (2 km^2) side-scan sonar surveys conducted between 2010 and 2018. Thirty-three natural and artificial hard bottom habitat types were identified, with Flat Hard Bottom comprising both the greatest area coverage (131.7 km^2) and number of individual features classified (n = 42,829). Classification and regression tree analyses were conducted to identify spatial patterns of hard bottom habitat composition based on both area coverage and number of individual hard bottom features. These maps identified distinct spatial variability in the availability of several habitat types, such as increased number of Pothole habitats in deep shelf waters off the Florida Peninsula and increased coverage by artificial reef habitats within the Florida Panhandle. Extrapolating results from this representative, broad scale approach to habitat mapping indicated that approximately 3854 km^2 (2.6%) of the shelf is comprised of natural hard bottom habitat. The value of comprehensive habitat data is highlighted within recent efforts toward generating absolute abundances of reef fish species as well as continuing efforts toward ecosystem-based approaches to fisheries management.

1. Introduction

The geologic framework of the eastern Gulf of Mexico continental shelf is spatially dynamic, with siliciclastic sediments dominating the Florida Panhandle region while the Florida Peninsula consists predominately of carbonate sediments (Hine and Locker 2011). While much of the broad shelf is covered by sediments of varying thickness, localized areas of exposed hard bottom resulted from accretion of sediments during periods of stability between multiple sea-level changes occurring during the Neogene–Quaternary (Locker et al., 2003; Obrochta et al., 2003; Hine and Locker 2011). Sediment-rich environments of the nearshore shelf are important for some fish species as well as serving as sedimentary sources for beach renourishment (Balsillie and Clark 2001), while the hard bottom habitats support rich epibenthic communities, diverse demersal fishes, and, in turn, extensive recreational and commercial hard bottom fisheries (Caddy 2007).

Although several detailed mapping and habitat characterization studies have been conducted in the eastern Gulf, most were focused on localized areas (km's) containing geologically unique, high-relief features. For example, the Florida Middle Grounds, located approximately 160 km NW of Tampa Bay, has been mapped with a variety of instruments through multiple projects because of its extensive ridge features with attached epifauna (Brooks and Doyle, 1991; Mallinson et al., 2014). Pulley Ridge, positioned 90 km west of the Dry Tortugas, was mapped with high-resolution multibeam bathymetry indicating the hard bottom/ridge system contained structural similarities to drowned (and current) barrier islands (Jarrett et al., 2005). Pulley Ridge hard bottom habitats support mesophotic corals (60–100 m depth) and cover approximately 600 km^2 (Jarrett et al., 2005; Allee et al., 2012). Focused studies of potholes, or excavated hard bottom habitats created primarily by Red Grouper (*Epinephelus morio*), have identified potholes in great numbers in several regions of the West Florida Shelf (Coleman et al.,

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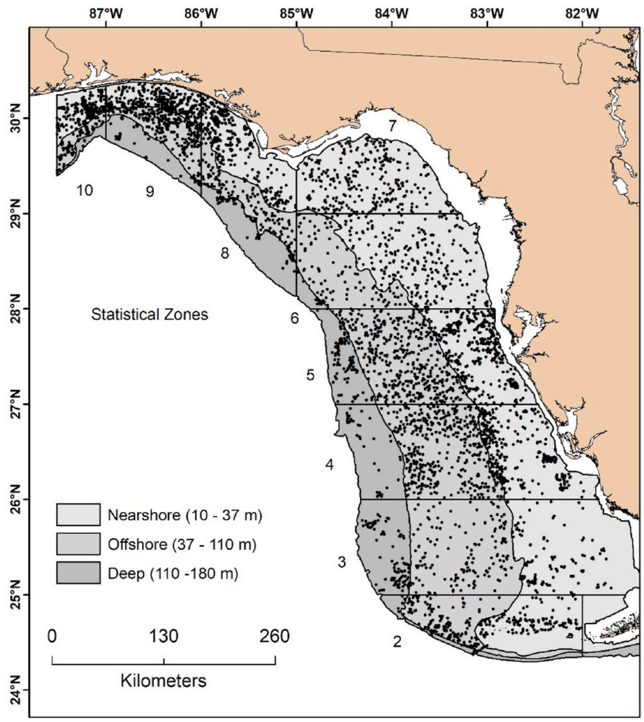

Fig. 1. Map showing the distribution of 4208 side-scan surveys conducted between 2010 and 2018. Surveys were randomly selected and allocated among National Marine Fisheries Service statistical zones and depth strata.

2010; Wall et al., 2011; Harter et al., 2017; Grasty et al., 2019). Other geologic and mapping studies have been conducted within nearshore areas along the coastline of western Florida and identified small scale areas of hard bottom habitat (Phillips et al., 1990; Locker et al., 2003; Obrochta et al., 2003; Hine and Locker 2011; Allee et al., 2012; Walker et al., 2020).

In addition to diverse natural hard bottom habitats, artificial reefs, and other man-made habitats (hereafter "artificial habitats") are also locally important in some areas of the eastern Gulf of Mexico. Distribution of natural hard bottom habitat is driven by regional geology, while artificial habitat placement is driven principally by needs of local end users. The intended purpose of the artificial habitats often dictates the materials used and spatial distribution of siting; increased fishing opportunities are provided through large-scale deployments of construction materials or materials of opportunity while the deployment of prefabricated modules or sunken vessels provides diverse diving or ecotourism opportunities (Bohnsack 1989; Lindberg 1997; Dupont 2008). In Florida, the majority of artificial habitats are deployed within Reef Permit Zones with known placement coordinates; however, unpublished, private reefs, often comprised of un-approved, reduced-longevity materials (e.g. metal chicken transport cages, fiberglass boat hulls) have been located outside these zones (Keenan et al., 2018). Artificial habitats are recognized to provide increased productivity and structure for fish communities within coastal areas generally lacking natural reefs (Bohnsack 1989; Lindberg 1997; Caddy 2007), however trade-offs exist between these benefits and increased exploitation rates from anglers (Simard et al., 2016; Karnauskas et al., 2017). Through standardized, long-term monitoring of paired natural and artificial habitat systems, a more comprehensive understanding can be gained of effects of habitat augmentation (Lindberg 1997; Patterson et al., 2013).

Although the eastern Gulf contains a diverse array of natural and artificial reef habitats, a comprehensive, standardized effort to quantify hard bottom habitat throughout the region has yet to be conducted. Understanding broad scale patterns of the quantity, quality, and distribution of natural and artificial reef habitats would improve fishery-independent surveys (Campbell et al., 2015; Switzer et al., 2020, Stunz et al., 2021), enhance the assessment and management of economically important fisheries (Karnauskas et al., 2017), and facilitate ecosystem-based approaches to fisheries management and marine planning (Peters et al., 2018). Improved understanding of spatial dynamics of hard bottom habitats would also aid decision making related to habitat restoration activities, including artificial reef deployment and dredging associated with beach renourishment, among others. Accordingly, we examined 10 years of randomly distributed habitat mapping data to quantify spatial dynamics of distribution and composition of benthic habitats throughout the eastern Gulf of Mexico. The mapping approach developed for this study was effective in generating habitat data suitable for both fine scale and broad scale applications, and therefore has broad applicability for other seascapes where conducting system-wide habitat mapping surveys is cost prohibitive.

2. Methods

2.1. Study area

Habitat mapping by the Florida Fish and Wildlife Research Institute began in 2010 to support reef fish survey efforts and initially was restricted to waters 10–110 m between 26° and 28° N latitude corresponding to the National Marine Fisheries Service Statistical Reporting Zones (statistical zones) 4 and 5 (Fig. 1). In 2014, the reef fish survey area was expanded to 180 m depth and incorporated the western Florida Panhandle (from 86° to approximately 87° 30′ W; encompassing statistical zones 9 and 10). Beginning in 2016, sampling was further expanded into all statistical zones along the Florida coastline (statistical zones 2–10), from the Florida Keys and Dry Tortugas (terminates at 24° 35.0′ N when east of 83° W) to the Florida-Alabama border 87° 30' W (Fig. 1). Thus, the total area that could be surveyed (i.e. potential survey area) was approximately 144,403 km^2 and mapping data collected from

Table 1
Summary of number of side-scan sonar surveys conducted and the total percentage of area mapped within each NMFS statistical zone and depth strata. Total area represents the area of the statistical zone within each depth bound.

Statistical Zone	Depth Range (m)	Total Area (km^2)	Surveys Completed	Percentage Mapped (%)
2	10–37	4252.69	122	5.5
	37. –110	4680.04	143	5.8
	110.1–180	904.11	12	2.7
3	10–37	11,558.60	121	2.7
	37.1–110	12,358.20	149	2.0
	110.1–180	5553.79	92	2.3
4	10–37	9020.47	308	3.0
	37.1–110	10,598.08	389	6.2
	110.1–180	5489.74	40	6.9
5	10–37	7393.14	335	1.4
	37.1–110	10,278.89	417	8.2
	110.1–180	3506.14	97	7.7
6	10–37	13,373.89	236	4.9
	37.1–110	7040.88	91	3.3
	110.1–180	627.38	14	2.5
7	10–37	11,300.08	273	3.5
8	10–37	5800.98	279	4.4
	37.1–110	3804.80	118	7.9
	110.1–180	4176.92	62	5.7
9	10–37	2965.37	278	2.6
	37.1–110	3316.42	260	15.0
	110.1–180	2759.29	51	13.8
10	10–37	2118.26	240	3.0
	37.1–110	1072.58	72	16.4
	110.1–180	452.54	9	12.5
Total		144,403.27	4208	5.2

Table 2
Habitats occurring with the study area as identified through interpretation of side scan sonar imagery.

Origin	Habitat Class	Definition
Geologic	Flat Hard Bottom	Flat or nearly flat areas (≤0.1 m of relief) of hard bottom generally colonized by benthic biota
Geologic	Fragmented Hard Bottom	Areas dominated by exposed rock or coral that may be separated by narrow channels of sediment that have been eroded leaving the rock elevated above the seafloor with relief > 0.1 m
Geologic	Mixed Hard Bottom	Mainly flat areas of hard bottom containing some features that have relief of >0.1 m
Geologic	Pavement	Generally flat and unbroken hard bottom substrate formed by deposition and consolidation of material and overlying a deeper bedrock substrate
Geologic	Boulder/Boulder Field	Area containing pieces of rock > 0.5 m in diameter
Geologic	Ledges	A linear change in elevation of the seafloor that is associated with a rocky outcrop or underwater ridge of rocks. Ledges are defined spatially as the area within 5-m of the identified ledge
Geologic	Escarpment	Relatively straight, cliff-like face or slope of considerable linear extent (generally >100m), which breaks up the general continuity of the seafloor by separating surfaces lying at different depths (>3 m)
Geologic	Potholes	Small (2–10 m diameter) indentations or depressions lower than the surrounding surface usually surrounded by unconsolidated sediments. This feature could be naturally made such as a pothole excavated by Serranids or created by subsidence of an artificial structure and subsequent current scour
Geologic	Pinnacle	Steep-sided peak or series of peaks of >2 m relief that can occur at depth or reach close to the surface
Geologic	Rubble Field	Area containing a loose mass of rock fragments (<0.5-m in diameter) deposited on the seafloor by natural processes
Geologic	Unknown Natural Hard Bottom	Natural habitat >2 m in diameter that either cannot be identified or does not fit into one of the other Natural categories
Geologic	Fracture	Crack or split formed in a rock or bedrock as a result of local erosion or rock stress
Geologic	Spring Sink	Natural depression on the seafloor surface (>2 m in diameter) that may connect to a subterranean passage, generally occurring in limestone regions and formed by solution or by collapse of a cavern roof
Biogenic	Reef Rubble	Low relief areas of coral, either actively developing or deposited
Biogenic	Aggregate Coral Reef	Continuous coral formations >50 m wide that occur in various shapes and lack sand channels
Biogenic	Aggregate Patch Reef	Patch reefs separated by sand or hard bottom channels that are <5 m wide
Biogenic	Spur & Groove	Areas of alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief and are separated from each other by 1–5 m of sand or bare hardbottom (grooves)
Biogenic	Individual Patch Reef	Coral formations with circular or oblong shapes that are <50 m wide at their widest point and isolated from other coral formations by a distance of ≥5 m
Anthropogenic	Construction Materials	Any material deposited on the seafloor that was originally intended for construction purposes
Anthropogenic	Pipeline Area	Corridor through which one or more pipelines have been placed on the seafloor
Anthropogenic	Unidentified Artificial Reef	Any artificial material >2 m in diameter that cannot be identified
Anthropogenic	Reef Modules	Pre-fabricated structures that have been constructed for the purpose of being deployed as reef-fish habitat (e.g., reef balls, pyramids, etc.)
Anthropogenic	Large Vessels/Barge	Vessel or barge > 10-m in length that was either intentionally or unintentionally sunk
Anthropogenic	Dredge Deposit	Accumulation of material (rocks, shells, etc.) on the seafloor not associated with a designated reef site where spoil material from a dredging operation or other development related project is placed
Anthropogenic	Rock Piles	Deposit of rocks placed on the seafloor intentionally and not as a part of natural geologic processes
Anthropogenic	Chicken Transport Units	A steel and wire cage used for transporting poultry
Anthropogenic	Oil Platform Material	Large structures built to support wells or facilities used for the extraction of petroleum or other natural resources
Anthropogenic	Tires	Reef type can include a single tire or series of tires fastened together
Anthropogenic	Military Tanks	Decommissioned tanks that were deposited as a part of an artificial reef
Anthropogenic	Small Vessels	Vessel ≤10-m in length that was either intentionally or unintentionally sunk
Anthropogenic	Marine Wreckage	Materials associated with a wreck that are scattered around the wreck site (includes vessels, aircraft, tanks, vehicles) at a distance > 5-m from the superstructure
Anthropogenic	Vehicles Other	Vehicle deposited on the seafloor to act as an artificial reef (cars, train cars, etc.)
Anthropogenic	Cable	Structures that serve as linear conduits for electricity or as supporting lines for other in-water infrastructure

2010 to 2018 were included in subsequent analyses (Table 1).

2.2. Selection of survey sites and habitat classification

Each survey location was randomly selected from a gridded universe within the potential survey area using ArcGIS and the Geospatial Modeling Environment add-on for R (http://www.spatialecology.com/gme/). Randomized habitat-mapping surveys (each covering an area of approximately 2.0 km^2) were conducted to identify and delineate hard bottom habitats using a side-scan sonar (L3-Klein 3900) operating at 445 kHz. Annual survey efforts were allocated among predetermined depth strata (10–37 m; 37.1–110 m; and 110.1–180 m) within each statistical zone with a goal of 100 surveys per statistical zone per year, except for statistical zone 7, which contained only the nearshore depth stratum. Although the total area scanned was standardized for all surveys, the survey footprint varied based on location and presumed target habitat type. For natural hard bottom surveys, survey lines ran perpendicular to the shore, covering survey areas approximately 0.5 km N–S and 4 km E–W along the peninsula (statistical zones 2–6) or 0.5 km E–W and 4 km N–S along the panhandle (statistical zones 7–10). For artificial reef surveys (initiated in 2014), surveys covered 1.3 km E–W and 1.6 km N–S, with the randomly selected, presumed artificial reef centered within the surveyed area to provide both mapping data on the artificial reef (locations presumably known) and the proximate natural habitats. This design allowed for 10% overlap between mapping swaths to correct for potential positional errors.

Surveys were processed to correct for time-varied gain and navigational errors using Chesapeake Technologies SonarWiz software to produce a geotiff with 0.25-m resolution. Geotiffs were imported into ArcGIS in which habitats were identified and manually delineated using a polygon-drawing tool and the Habitat Digitizer extension (https://coastalscience.noaa.gov/project/habitat-digitizer-extension/). The habitat classification scheme established for this study was a derivative of the geoform and surface geological component of the Coastal and Marine Ecological Classification Standard developed by the National Oceanic and Atmospheric Administration's Office for Coastal Management (www.fgdc.gov/standards/projects/cmecs-folder) and consisted of a series of distinct geologic, biogenic (i.e. presumed reef building) and anthropogenic (i.e. man-made or artificial) hard bottom benthic habitats (Table 2; Keenan et al., 2018). As several people were involved in the habitat classification, we implemented a rigorous quality assurance process whereby the polygons that were drawn and classified by each reader were reviewed by a second reader. All of the discrepancies were then reviewed to formulate a consensus (Switzer et al., 2020). For a subset of identified polygons, habitat classification was verified through comparison with corresponding habitat imagery obtained from underwater video surveys (Keenan et al., 2018; Switzer et al., 2020). The minimum mapping unit for geologic and biogenic habitats was 4 m diameter and for anthropogenic habitats was 2 m in diameter.

2.3. Analysis

Habitat data were summarized by both total area coverage (m^2) and total number of distinct features (polygons) for each habitat type within each side-scan sonar survey. Survey effort was summarized by statistical zone and depth strata, whereas habitat composition and area coverage were summarized across the entire region. The total natural hard bottom area within each spatial stratum, as well as the entire study area, was estimated by extrapolating the proportion of natural hard bottom habitat (geologic and biogenic habitat only) identified within mapped areas and applying that ratio to the remaining unmapped area for that stratum. Side-scan surveys of artificial habitats were selected from a universe of known reefs and wrecks; therefore, extrapolation analyses for artificial habitats were not conducted.

Spatial patterns in the quantity and composition of hard bottom habitats were identified through classification and regression tree (CART) analyses using PRIMER 7 software. Parallel analyses were conducted using survey X habitat matrices (areas of non-hard bottom habitats were excluded) of total hard bottom area and number of hard bottom features, respectively. For analyses of total hard bottom area, values were log transformed prior to analyses, while for analyses of the number of hard bottom features, values were 4th root transformed prior to analyses to reduce the influence of especially abundant habitat types. For each analysis, a Bray-Curtis similarity matrix was constructed representing similarity in habitat composition between each pair of surveys. CART analyses were conducted via LINKTREE, with latitude, longitude, and depth as potential explanatory variables, a minimum group size of $N = 420$ (10% of the data), and 9999 iterations. SIMPROF analyses were conducted to test for statistical significance ($\alpha = 0.05$) between identified habitat groups.

3. Results

In total, 4208 side-scan surveys were conducted and digitized between 2010 and 2018; of these, 2507 (59.6%) were found to contain natural hard bottom habitat. In total, the surveys encompassed an area of 7558.3 km^2 or 5.2% of the potential survey area although proportion mapped varied by statistical zone (Table 1). In some regions (e.g. statistical zone 10), approximately 10% of the area was mapped, while for others (e.g. statistical zone 3), less than 3% was mapped. Spatial variability in mapping effort was attributable to both the total area to be mapped as well as the number of years for which mapping efforts were conducted.

A total of 33 unique hard bottom habitat types were identified, including 13 of geologic origin, five of biogenic origin, and 15 of anthropogenic origin (Table 3). There were 107,600 individual polygons delineated; the vast majority were of geologic habitats ($n = 99,986$), with far fewer biogenic ($n = 455$) and anthropogenic polygons ($n = 7159$) delineated. Among geologic habitats, Flat Hard Bottom ($n = 42,829$), Potholes ($n = 27,747$), and Boulders/Boulder Field ($n = 8226$) were numerically dominant (Table 3). Most biogenic hard bottom polygons were classified as Reef Rubble ($n = 355$). Among anthropogenic habitats Unknown Artificial Reefs ($n = 2572$), Construction Materials ($n = 1911$), and Artificial Reef Modules ($n = 1641$) comprised the top three most abundant habitat types.

While non-hard bottom habitat (hereafter referred to as unconsolidated sediments) comprised the vast majority (96.9%) of the area scanned, we identified a total of 226.2 km^2 of natural hard bottom habitat (geologic and biogenic combined; Table 3). For geologic habitats, Flat Hard Bottom (131.7 km^2 or 62.8% of geologic hard bottom identified), Fragmented Hard Bottom (32.3 km^2; 15.4%) and Mixed Hard Bottom (18.9 km^2; 9.0%) had the greatest areal coverage. Among biogenic reef habitats, Reef Rubble (14.9 km^2 or 88.4% of all biogenic reef identified) and Aggregate Coral Reefs (1.6 km^2; 9.5%) covered the greatest area. Habitats of anthropogenic origin covered approximately 2.2 km^2 and were predominantly comprised of Construction Materials (0.73 km^2 or 42.5% of anthropogenic reef habitat identified), Pipeline-associated habitats (0.57 km^2; 32.9%) and Unknown Artificial Reefs (0.20 km^2; 11.5%). Mean area was greatest for biogenic reef and least for anthropogenic habitats; however, large variability existed within the origin categories (Table 3).

Results from CART analyses of habitat area coverage identified seven spatial groups that differed statistically with respect to hard bottom habitat composition (Fig. 2). Along the West Florida Shelf, the composition of hard bottom habitats differed significantly with depth. Shallow habitats (10–21 m; group A) consisted primarily of Flat Hard Bottom, Fragmented Hard Bottom, Mixed Hard Bottom and Pavement. Mid-shelf habitats (21–66 m) differed regionally. To the south (group C), habitats were dominated by Reef Rubble, Fragmented Hard Bottom, and to a lesser extent, Flat Hard Bottom, whereas to the north, higher proportions of both Mixed Hard Bottom and Boulder/Boulder Field habitats were detected; the central region was comprised almost exclusively of Flat Hard Bottom. Deeper habitats within the eastern Gulf of Mexico (66–180 m; group E) were a diverse mixture of Potholes, Boulders, and Escarpment in addition to Flat, Mixed, and Fragmented Hard Bottom. Unique habitats were also detected in the Florida Panhandle; the eastern panhandle (group G) was comprised primarily of Flat Hard Bottom and Pavement, whereas the diverse habitats of the western panhandle (group F) contained Pinnacles, Construction Materials, Escarpment, and Boulder/Boulder Field in addition to Flat and Fragmented Hard Bottom. Although artificial habitats were commonly present, they were not represented within the top 12 (selected as it accounted for >95% composition) by area except for Construction Materials.

The CART analyses of number of habitat polygons identified eight spatial groups with habitat groups distributed in depth gradients along the West Florida Shelf (Fig. 3). Similar to analysis by habitat area, shallow habitats (10–21 m; group A) were comprised of Flat, Fragmented, and Mixed Hard Bottom as well as Ledge polygons. Groups B (21–35 m), C (36–45 m) and D (46–55 m) consisted of a majority of Flat Hard Bottom polygons with decreasing number of Ledge and Mixed Hard Bottom polygons and increasing numbers of Pothole polygons. Group E (56– 70 m) contained a near equal proportion of Flat Hard Bottom and Pothole polygons while deeper surveys (>71 m; group F) were comprised almost entirely of Pothole and Boulder/Boulder Field polygons. Nearly identical to analysis by area, the Florida panhandle was separated into two unique hard bottom habitat groups with the western panhandle (group G) containing a wide diversity of natural and anthropogenic habitats, including a large number of Unknown Artificial Reefs, Reef Modules, and Chicken Transport Cages. The eastern panhandle (group H) contained more natural habitat than the western panhandle, with more Flat Hard Bottom and Pavement polygons.

Because of the randomly distributed format of the mapping design, proportion of natural hard bottom habitats from geologic and biogenic origin within mapped areas were extrapolated to unmapped areas to provide regional and overall habitat estimates (Table 4). Proportion of habitats varied greatly across the spatial strata, with the highest positive proportion (12.7% hard bottom habitat) in nearshore statistical zone 2. Many spatial strata contained less than 1% hard bottom habitat with deep statistical zone 9 having the lowest (<0.1%) corresponding with lowest projected hard bottom habitat of 0.74 km^2. The nearshore depth strata within statistical zone 7 (738.25 km^2), 6 (730.22 km^2), 5 (621.21 km^2), and 2 (540.6 km^2) had the greatest projected amount of natural hard bottom habitat. The projected sum of the natural hard bottom habitat was 3854.16 km^2 (Table 4) and was comprised predominantly of

Table 3
Summary of 33 habitats classified from side-scan data in the eastern Gulf of Mexico between 2010 and 2018. Habitats were summarized by total area coverage in square meters and the number of individual polygons delineated. Data were summarized at the individual polygon level rather than pooled within individual side-scan surveys.

Habitat Class	Total Area (m^2)	Mean Area (m^2)	Std Error	Minimum Area (m^2)	Maximum Area (m^2)	Number of Polygons
Flat Hard Bottom	1.31 e+08	3075.6	119.8	4.0	1.71 e+06	42,829
Fragmented Hard Bottom	3.23 e+07	5331.9	913.3	4.1	2.75 e+06	6069
Mixed Hard Bottom	1.89 e+07	4199.9	417.5	4.0	1.46 e+06	4504
Pavement	1.34 e+07	5952.9	1058.2	7.5	1.56 e+06	2254
Boulder/Boulder Field	4.00 e+06	486.3	86.7	4.0	4.64 e+05	8226
Ledge	2.81 e+06	1175.9	87.1	5.0	1.03 e+05	2388
Escarpment	2.52 e+06	61,419.8	13,883.4	143.5	4.07 e+05	41
Pothole	2.38 e+06	85.6	0.5	4.0	9.96 e+02	27,747
Pinnacle	7.98 e+05	368.0	54.8	4.1	1.03 e+05	2168
Rubble Field	4.56 e+05	340.8	58.9	4.4	4.29 e+04	1338
Unknown Natural Hard Bottom	2.24 e+05	147.2	13.0	5.0	1.44 e+04	1522
Fracture	1.05 e+05	126.5	8.8	4.0	4.48 e+03	830
Spring Sink	1.65 e+04	235.5	47.5	10.7	3.02 e+03	70
Total	2.10 e+08					99,986
Reef Rubble	1.50 e+07	42,171.0	9301.5	4.5	1.67 e+06	355
Aggregate Coral Reef	1.61 e+06	53,603.6	31,316.2	192.5	9.39 e+05	30
Aggregate Patch Reef	1.83 e+05	16,658.4	5557.0	16.6	5.31 e+04	11
Spur & Groove	1.55 e+05	154,704.4	.	154,704.4	1.55 e+05	1
Individual Patch Reef	2.57 e+04	442.4	193.7	4.6	1.11 e+04	58
Total	1.70 e+07					455
Construction Materials	7.36 e+05	385.0	64.0	4.0	6.98 e+04	1911
Pipeline Area	5.70 e+05	15,820.3	2264.7	1162.4	5.65 e+04	36
Unknown Artificial Reefs	1.98 e+05	77.1	12.0	4.0	2.82 e+04	2572
Artificial Reef Modules	6.58 e+04	40.1	1.9	4.0	2.09 e+03	1641
Large Vessel/Barge	6.51 e+04	757.4	86.6	37.1	5.47 e+03	86
Dredge Deposit	2.71 e+04	3871.0	2889.3	351.5	2.12 e+04	7
Rock Piles	2.65 e+04	26,493.4	.	26,493.4	2.65 e+04	1
Chicken Transport Cages	2.62 e+04	37.5	1.6	5.1	7.09 e+02	700
Oil Platform Material	4.41 e+03	1468.6	282.7	943.4	1.91 e+03	3
Tires	3.34 e+03	41.8	23.8	4.1	1.87 e+03	80
Military Tanks	2.98 e+03	71.0	10.2	16.9	4.08 e+02	42
Small Vessel	1.96 e+03	56.1	9.3	9.0	2.14 e+02	35
Marine Wreckage	1.91 e+03	50.1	10.5	4.6	2.83 e+02	38
Vehicles Other	3.85 e+02	64.2	7.0	42.1	8.52 e+01	6
Cable	1.90 e+01	19.0	.	19.0	1.90 e+01	1
Total	1.73 e+06					7159
Unconsolidated sediment	7.33 e+09	88,598.38	32.63	.	9.36 e+04	.

Flat Hard Bottom.

4. Discussion

Implementation of a randomized, broad scale habitat mapping survey revealed insights into the composition and distribution of natural and artificial reef habitats at a scale not previously achieved in the eastern Gulf of Mexico. Thirteen geologic, five biogenic, and 15 artificial reef habitat classes, delineated and quantified from over four thousand 2-km^2 side-scan sonar surveys, provided input to quantify and visualize habitat distribution related to area coverage and number of individual hard bottom polygons identified. Originally intended as input for fisheries-independent monitoring efforts (Keenan et al., 2018; Switzer et al., 2020), a decade of these small-scale, high-resolution surveys yielded results that were scalable to a basin-level context (Lecours et al., 2015), in contrast to other mapping surveys that focused on localized areas of interest (Obrochta et al., 2003; Mallinson et al., 2014) or broad scale surveys which characterized landscape-level geological features, unlikely to produce habitat data relevant to fish distribution (Sowers et al., 2020). Overall, the approach used in this study utilized a standardized methodology, cost-effective gear and provided a template for broad scale mapping efforts applicable in all continental shelf regions.

To our knowledge, this is one of the first studies to utilize randomly distributed, small-scale habitat surveys to quantify habitat dynamics across broad expanses of the ocean seafloor. Globally, the generation of broad scale benthic habitat maps is critical for a variety of applications, including the establishment of MPAs (Baker and Harris 2020), siting offshore energy facilities (U.S BOEM 2016), and the identification of human-induced disturbances. While novel approaches use environmental datasets as proxy for broad scale habitat (Andersen et al., 2018), the majority of habitat maps are generated through direct sampling (e.g. bathymetry and backscatter) (Brown et al., 2011; Lecours et al., 2015; Andersen et al., 2018). Although, comprehensive interpretation of the seafloor requires complete coverage of bathymetry, geology, and habitat (Johnson et al., 2017), characterizing these metrics requires costly and cumbersome technologies such as multibeam sonar and sub-bottom profilers. Side-scan sonar offers advantages that include the ability to generate high-resolution (cm-level) backscatter imagery using a cost-effective and portable system. Side-scan sonar imagery has been demonstrated to effectively differentiate habitat classes within mid-shelf hard bottom areas (Cochrane and Lafferty 2002; Prada et al., 2008; Kingon 2013; Switzer et al., 2020). Further, many habitats and features identified via side-scan sonar and sampled by underwater video (Switzer et al., 2020) likely would not be identified through techniques which generate lower-resolution (e.g., 10-m pixel) imagery (see habitat maps in Switzer et al., 2020 and Ilich et al., 2021).

While specific areas and habitats within the eastern Gulf have been well-studied (Hine and Locker 2011; Locker et al., 2016; Grasty et al.,

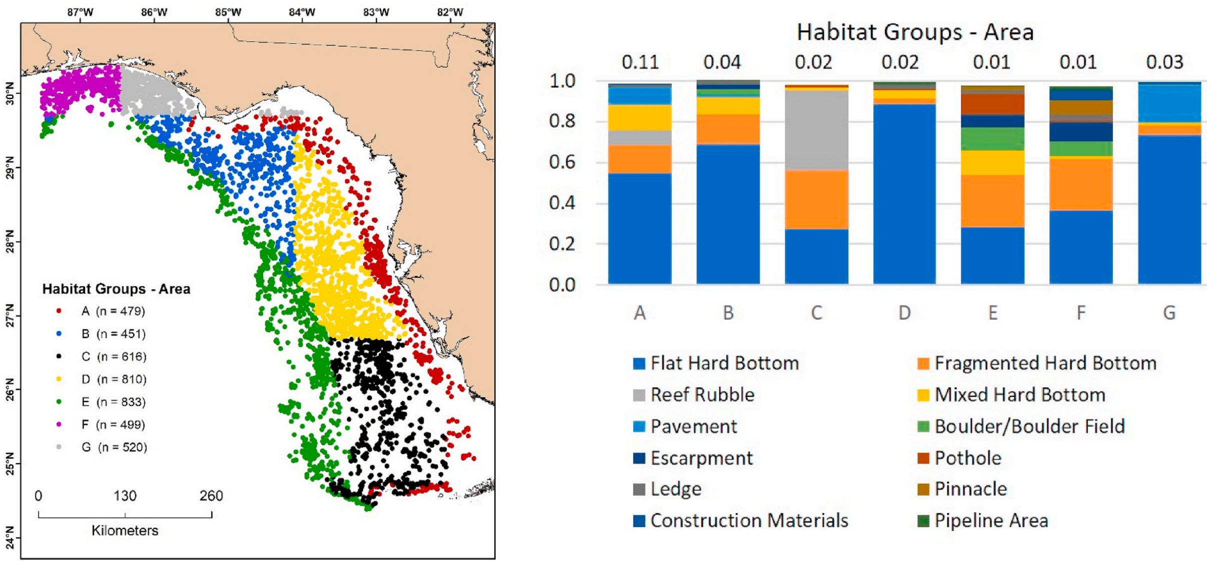

Fig. 2. Results of classification and regression tree (CART) analyses (left panel) to identify differences in hard bottom habitat composition (area coverage) in relation to spatial predictor variables. In the left panel, each point represents the center point of an individual side-scan sonar survey, and color groupings represent areas with statistically different hard bottom habitat composition. The right panel represents proportion composition of the 12 habitats with the highest total coverage within each region. Values above each bar represent the proportion of hard bottom habitat classified within the mapped area, with the remainder comprised of unconsolidated sediment. Color schemes between panels do not correspond. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

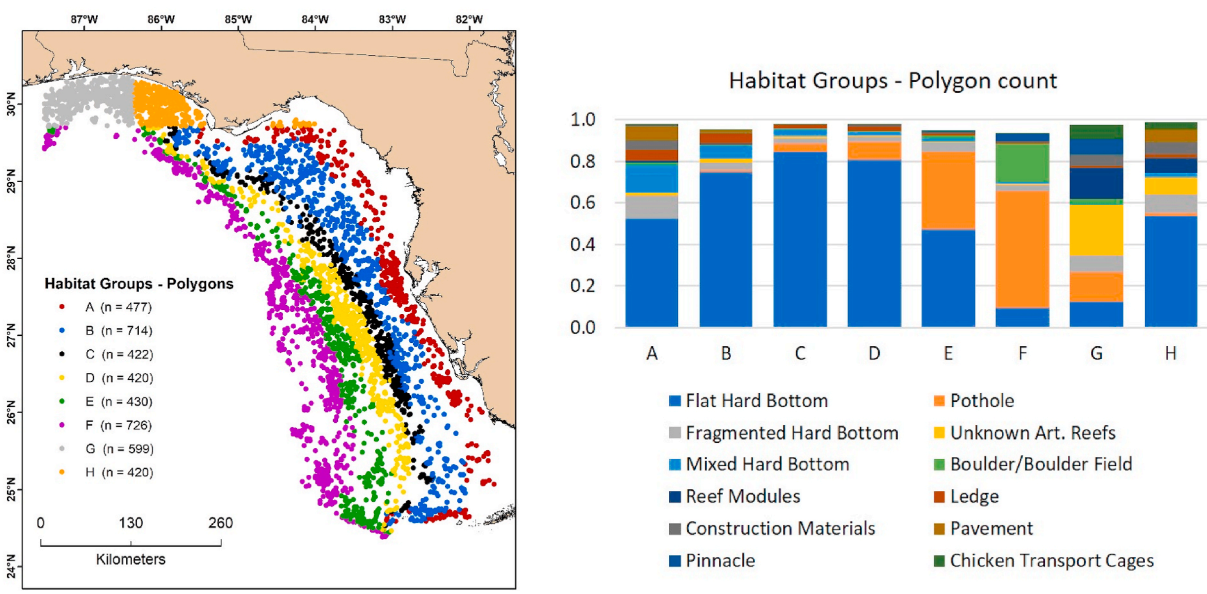

Fig. 3. Results of classification and regression tree (CART) analyses (left panel) to identify differences in hard bottom habitat composition (number of polygons) in relation to spatial predictor variables. In the left panel, each point represents the center point of an individual side-scan sonar survey, and color groupings represent areas with statistically different hard bottom habitat composition. The right panel represents proportion composition of the 12 habitats with the greatest number of classified polygons within each region. Color schemes between panels do not correspond. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2019), this study provided insight into the spatial dynamics and high diversity of hard bottom habitats through the novel application of multivariate analytical approaches. Flat (low-relief) Hard Bottom comprised both the greatest area and the greatest number of polygons across the study area. Through verification via video deployments, Flat Hard Bottom habitats often contain a diverse array of epibiotic organisms such as soft corals or sponges and supports diverse reef fish communities (authors unpublished data, Switzer et al., 2020). Mixed and Fragmented Hard Bottom, characterized by slightly higher relief patterns in the imagery (Switzer et al., 2020), were common across the study region. Other habitats with even greater relief (~1 m+) were less common, including Ledges, which were distributed across the region, while Boulder/Boulder Fields, Escarpments and Pinnacles were generally found in deeper areas and in the western Florida Panhandle. Pinnacles were also located in areas similar to the "Sticky Grounds" from Locker et al. (2016) which described these reef habitats located near the shelf-break (~125m depth) along the West Florida Shelf. Habitats of increasing complexity contribute to reef fish community structure (Hixon and Beets 1989; Caddy 2007; Walker et al., 2009), but distribution patterns of the habitats may also be useful for interpretation of

Table 4
Estimated quantity of natural reef habitat as determined by extrapolating data from mapped areas into unmapped areas. All natural reef habitat classes were combined for these estimates.

Statistical Zone	Depth Range (m)	Total Area (km^2)	Percentage Natural Reef Habitat (%)	Extrapolated Area – Natural Reef only (km^2)
2	10–37	4252.69	12.7	540.56
	37.1–110	4680.04	2.4	113.72
	110.1–180	904.11	1.1	9.65
3	10–37	11,558.60	0.2	28.72
	37.1–110	12,358.20	0.2	18.91
	110.1–180	5553.79	0.5	28.01
4	10–37	9020.47	1.5	131.84
	37.1–110	10,598.08	0.8	83.07
	110.1–180	5489.74	0.4	19.95
5	10–37	7393.14	8.4	621.21
	37.1–110	10,278.89	2.0	209.16
	110.1–180	3506.14	1.3	45.57
6	10–37	13,373.89	5.5	730.22
	37.1–110	7040.88	1.3	89.32
	110.1–180	627.38	0.2	1.18
7	10–37	11,300.08	6.5	738.25
8	10–37	5800.98	1.1	66.21
	37.1–110	3804.80	3.2	122.75
	110.1–180	4176.92	0.2	7.31
9	10–37	2965.37	2.4	69.94
	37.1–110	3316.42	1.2	40.25
	110.1–180	2759.29	<0.1	0.74
10	10–37	2118.26	0.1	1.34
	37.1–110	1072.58	12.4	133.15
	110.1–180	452.54	0.7	3.15
Total		144,403.27		3854.16

the regional geology (Brooks 2003; Hine and Locker 2011; Locker et al., 2016).

Potholes were the second most abundant hard bottom habitat identified. Since their size is generally small (~3–5 m diameter), potholes do not encompass a large total area; however, when viewed by frequency, they constitute a great proportion of hard bottom features in deeper (>55 m) waters in the eastern Gulf. Pothole habitats contain a rich fish species assemblage including many economically important reef species (Coleman et al., 2010; Harter et al., 2017; Grasty et al., 2019; Switzer et al., 2020). In addition, the invasive Lionfish (*Pterois* sp.) have become common occupants in these habitats (Harter et al., 2017; Grasty et al., 2019; Switzer et al., 2020) since first being recorded in the eastern Gulf in 2010 (Scyphers et al., 2014; Switzer et al., 2015). While pothole habitats may be temporally dynamic (Grasty et al., 2019), results from this study (based on extrapolative calculations) indicate there may be well over 725,000 individual potholes on the shelf.

Artificial habitats represented a small proportion of hard bottom habitats identified in the present study; however, improved understanding of the distribution and composition of these habitats is critical to both marine spatial planning and fisheries management (Baine 2001; Caddy 2007; Adams et al., 2011). Our artificial habitat surveys were randomly selected from published artificial reef and wreck locations and therefore we cannot explicitly extrapolate their composition to surrounding unmapped areas. Nevertheless, artificial habitats were more prevalent in the Florida Panhandle and were comprised mostly of materials of opportunity such as Construction Materials. Our surveys observed many Chicken Transport Cages outside of reef permit areas, indicating that private reef deployments are common (Keenan et al., 2018). Artificial habitats often support unique species assemblages (Patterson et al., 2013; Streich et al., 2017; Keenan et al., 2018), experience increased levels of fishing pressure (Simard et al., 2016; Karnauskas et al., 2017), and are commonly used as habitat restoration tools (NRDA funding: https://www.gulfspillrestoration.noaa.gov/restoration/early-restoration/phase-iii/). Therefore, it is critical to continue to incorporate these habitats within both habitat mapping and fisheries surveys.

While other studies have generated estimates for hard bottom habitat coverage within the eastern Gulf, our study incorporated a broad scale, comprehensive database of classified habitat features to generate impartial, representative approximations of hard bottom habitat availability. Parker et al. (1983) used data from 382 underwater television camera deployments conducted between Key West and Pensacola (18–91 m depths) to estimate that approximately 45,000 km^2 of hard bottom habitat existed within that area. Jaap (2015) utilized hard bottom estimates from Rohmanns et al. (2005) to estimate 13% of the eastern Gulf shelf (numbers based on 225,000 km^2 total area) or 29,250 km^2 consisted of hard bottom habitat. Our estimates of 3854 km^2 (2.7%) were generated from unbiased, randomized mapping surveys conducted throughout the eastern Gulf and covering a relatively large proportion (5.2%) of the total study area (144,403 km^2). Further studies in the eastern Gulf are justifiable to understand what benthic communities inhabit hard bottom areas (Jaap 2015; Walker et al., 2020), how habitats may change over time (Grasty et al., 2019), and how reef fish communities vary among habitat classes (Patterson et al., 2013; Keenan et al., 2018; Switzer et al., 2020). The integration of hard bottom habitat area estimates into reef fish population “counts” (Stunz et al., 2021) hinge on the quality and representability of the estimates, which we feel are represented here. Ultimately, pairing results of our study with multi-species, reef fish survey data represent a windfall for fisheries management efforts that utilize ecosystem-based approaches to enhance stock assessments for numerous economically important species.

The general lack of comprehensive benthic habitat maps of a sufficient spatial resolution to manage resources or protect sensitive habitats is not restricted to the Gulf of Mexico; rather it is a worldwide challenge (Brown et al., 2011; Lecours et al., 2015). In areas where comprehensive habitat data are available, studies have been conducted to evaluate fish-habitat population dynamics (Smith et al., 2011), ascertain effectiveness of protected areas (Battista et al., 2007), improve survey design (Johnson et al., 2017; Hanisko et al., 2018), and monitor changes due to environmental perturbations, human use or climatic variability (Caddy 2007; Galparsoro et al., 2015). Without adequate benthic habitat data, scientists and managers are often forced to utilize lower resolution or outdated sources which can add uncertainty towards resource management goals (Stunz et al., 2021). Other efforts have been made to utilize best-available or alternative datasets to generate broad scale maps (Andersen et al., 2018; Sowers et al., 2020). However, this study highlights a potentially-effective approach to provide an interim assessment of habitat dynamics at both broad and fine scales that can not only serve as proxy until comprehensive maps are available, but also provide insight that can direct focused mapping effort.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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