Final Report

Effects of mobile fishing gear on geological and biological structure: A Georges Bank closed versus open area comparison

2011 Atlantic Sea Scallop Research Set-Aside Program
Grant: NOAA/NMFS NA11NMF4540026
Award Date: 03/01/2011
Start Date: 03/01/2011
End Date: 02/28/2014
Final Report Due: 05/29/2014

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1. Introduction

1.1. The Problem

Mobile fishing gear may alter geological and biological structures on the seabed, potentially adversely effecting fish habitats. U.S. federal law requires the assessment of and minimization of fishing effects on habitat components used by marine biota for feeding, breeding, spawning and maturation. Scallop dredges and otter trawls likely reduce the amount of geological and biological structures in their paths, and because gravel seabed is rough and provides attachment substrates for vertical epifauna it is considered particularly vulnerable to these impacts (Grabowski et al. 2014). Gravel-dominated sediments cover 38% of the Georges Bank area and are patchily distributed in a ~13,000 km^2 swath stretching from Cape Cod to northeastern Georges Bank consistent with estimates of prehistoric glacial extent (Figure 1, Harris and Stokesbury 2010). Trawls and dredges have been used in the gravels of Georges Bank for nearly a century but the magnitude and duration of their effects on benthic structures on gravel substrates are poorly understood and recent studies give conflicting results (see Collie et al. 1997 and Stokesbury and Harris 2006).

In order to reduce fishing-related mortality on groundfish, large portions of Georges Bank were closed to fishing in 1994 (see Closed Area I and Closed Area II in Figure 1). Subsequently, managers designated areas within CAI and CAII as Essential Fish Habitat (EFH) Closures under provisions in the Magnuson Stevens Fisheries Conservation Management Act (CAI EFH and CAII EFH and HAPC in Figure 1). The 1994 closures prohibited the use of bottom-tending mobile fishing gears including otter trawls and dredges and therefore created a unique opportunity to study the effects of fishing on biological and geological structures by comparing adjacent sites in open and closed areas of Georges Bank.

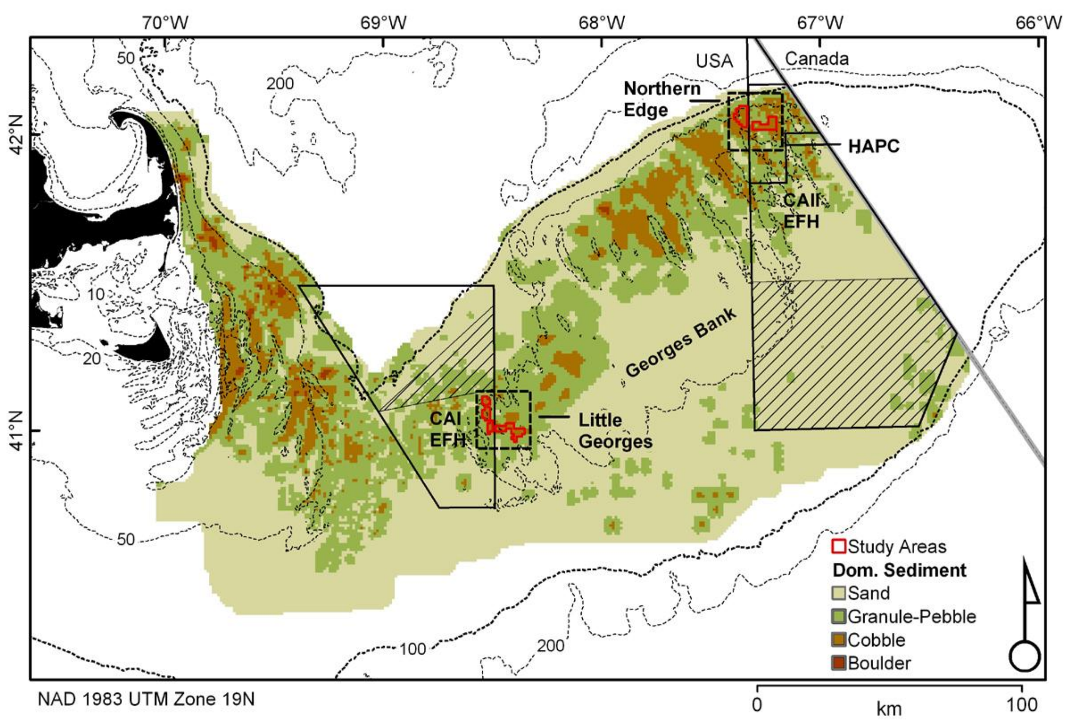


Figure 1. Map of dominant sediment types (S_d) demonstrating the distribution of Gravel (granule-pebble, cobble and boulder) on Georges Bank, the Great South Channel (GSC) and Nantucket Shoals (NS). The Little Georges and Northern Edge study areas are identified with dashed boxes and the gravel outcrops spanning the fishery closure boundaries are outlined in red (adapted from Harris and Stokesbury 2010). The fishery closures, Closed Area I (CAI) and Closed Area II (CAII), are outlined in black. The CAI EFH closures and Habitat Area of Particular Concern (HAPC) in CAII are identified. Hashed lines indicate scallop fishery access areas.

1.2. Conceptual Framework

The distribution of surficial benthic sediments on Georges Bank is patchy and is influenced by prehistoric glaciations, and modern deposition and erosion processes (Backus 1987, Butman 1987). During the late Wisconsinan Glaciation (95,000 - 20,000 years ago), the Laurentide Ice Sheet stretched across North America, extending beyond the eastern seaboard into the Atlantic Ocean (Dyke and Prest 1987). The ice edge crossed Nantucket Shoals, the Great South Channel and ran along Georges Bank, which was probably a peninsula or island at that time (Figure 1, Shepard et al. 1934, Pratt and Schlee 1969, Schlee and Pratt 1970, Bothner and Spiker 1980, Emery 1987, Uchupi and Austin 1987). The retreating ice left behind a mixture of coarse and fine sediments which were flooded as sea level rose. Reworking by strong tides, currents and storm events has resulted in the redistribution of finer particles to deeper waters along the edges of the Bank, with stationary coarse sediments buried or exposed, leaving a heterogeneous benthic landscape (Butman 1987, Twichell 1983, Uchupi et al.1996). Harris and Stokesbury (2010) provided the first quantitative assessment of surficial sediment spatial structure on Georges Bank (Figure 1). Using their map of *dominant sediment* we selected two large gravel outcrops, the Northern Edge (NE) site on northeastern Georges Bank and the Little Georges (LG) site on western Georges Bank (Figure 1, Harris and Stokesbury 2010) because both are bisected by Essential Fish Habitat (EFH) Closed Area boundaries (Figure 1), thereby providing an opportunity to isolate control and treatment sites in close proximity. Fishing with trawls and dredges has been prohibited in these closed areas since 1994 while adjacent fished areas have been open to continuous fishing (Figure 2, NEFMC 2010). The specific open "*Impact*" and closed "*Reserve*" areas (30 km^2 each) at each outcrop were chosen based on the locations of the EFH Closed Area boundaries, gravel outcrop shape, and NOAA observed otter trawl and scallop dredge tows from 2003 - 2009 (Figure 2).

We examined whether the biological and geological structures in the *Reserve* areas, closed to fishing for 17 years, exhibited patterns in density, presence/ absence, area coverage and vertical height consistent with recovery from damage due to fishing relative to the *Impact* areas. The success of this approach depends on establishing that the *Impact* and R*eserve* areas at each study site are true replicates and therefore support the inference that observed differences are due to the treatment (fishing) effects and not to other unobserved processes. Unfortunately, no data were available to directly assess the biological or geological structures or fishing intensity in the study sites prior to the 1994 closures. However, owing to their proximity the *Impact* and *Reserve* areas at both study sites are expected to have experienced very similar levels of historic fishing and natural disturbance. The Little Georges areas are separated by 1 km at their nearest and 21 km at their farthest points. The Northern Edge areas are separated by 2 km at their nearest and 18 km at their farthest points.

From 1999 - 2010 the University of Massachusetts - Dartmouth, School for Marine Science & Technology conducted extensive video surveys on Georges Bank and sampled 9 and 10 stations in the Little Georges closed and open study sites, respectively, and 103 stations and 69 stations in the Northern Edge closed and open study sites, respectively (Stokesbury et al. 2004, 2010). While there were too few locations sampled in any year to permit a balanced experimental comparison, these observations verified that the composition of surficial sediments (Harris and Stokesbury 2010), the water depths (Harris et al. 2012), and types of biological and geological features (Stokesbury and Harris 2006) in the open and closed sites were similar. Further, the study sites experience similarly high levels of natural disturbance. The M_2 (principal lunar semidiurnal) and S_2 (solar) tidal components account for about 80% of the kinetic energy on Georges Bank , and both the Northern Edge and Little Georges study areas generally experience high levels of tidal, current and wave energy (Butman 1987a, Butman and Beardsley 1987). Additionally both study areas are relatively shallow (∼50 m) and both are likely to experience similar levels of disturbance from the surface waves typical in winter storm events (≥ 10 sec. period, Butman 1987b).

The *Impact* and *Reserve* areas at both study sites were mostly likely heavily fished with bottom-tending fishing gears beginning the mid-1900s including intensive factory trawling by foreign fleets in the 1960s-70s (Borne 1987) until the closures in 1994. Unfortunately, no pre-closure fishing intensity data are available for these areas. The levels of mobile bottom-tending fishing activity in the *Impact* areas of both study sites continue to be high. Since 2003, the Northeast Fisheries Observer Program has monitored 435 tows (139 trawl and 296 dredge) in the Little Georges *Impact* area and 842 tows (477 trawl and 365 dredge) in the Northern Edge *Impact* area (Figure 2). This represents a minimum estimate of fishing intensity as observed tows represent only 5 - 20% of actual fishing activity (Table 1; pers. comm. C. Demarest, NOAA Fisheries - Northeast Fisheries Science Center). For detailed descriptions of the otter trawls and scallop dredges used on Georges Bank see NEFMC (2010).

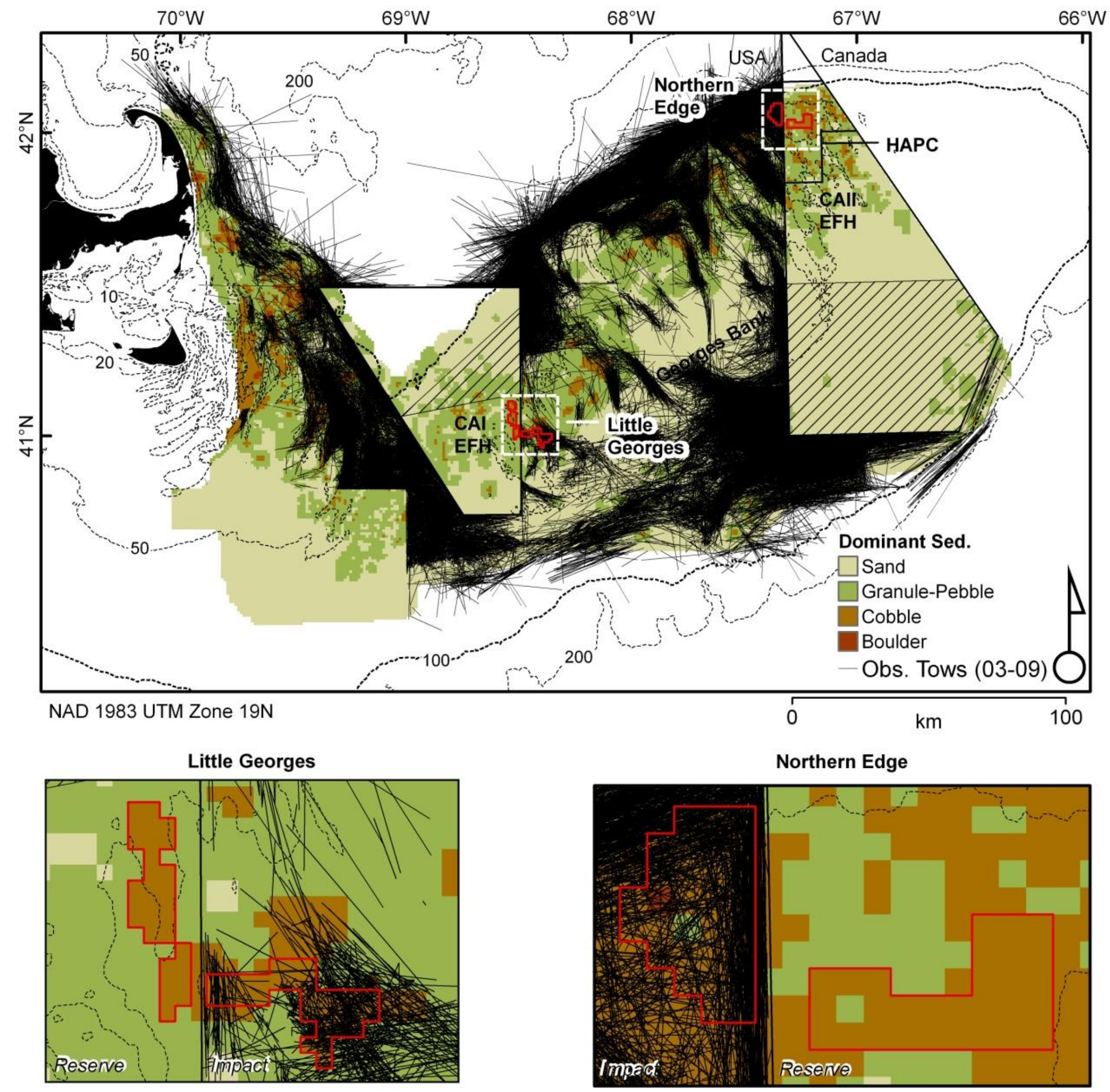


Figure 2. Map of Georges Bank showing dominant sediments and the observed trawl and dredge tows (lines reflect reported haul start and stop points) between 2003 and 2009. The lower maps show the Little Georges and Northern Edge study sites with the cobble-gravel outcrops, open and closed study sites, and trawl and dredge tows observed from 2003-2009.

Table 1. Table with Observed numbers of otter trawl and scallop dredge tows in the Little Georges (LG) and Northern Edge (NE) study site open areas. Observed tows represent between 5-20% of actual fishing.

Area	**LG**	Obs. Coverage	
	Observed	*20%*	*5%*
Trawl	139	695	2780
Dredge	296	1480	5920
	435	**2175**	**8700**

Area	**NE**	Obs. Coverage	
	Observed	*20%*	*5%*
Trawl	477	2385	9540
Dredge	365	1825	7300
	842	**4210**	**16840**

1.3. A priori Hypotheses and Fishing Effects Context

Empirical studies on the effects of mobile fishing gear on benthic communities of Georges Bank have been opportunistic and spatially localized; however, efforts have been made to use simulation modeling to examine long term effects of fishing on Georges Bank benthic habitats at a landscape scale. These modeling results provide insight into expected long term effects from fishing, and were used as a guide to formulate a priori hypotheses about differences in geological and biological structure between areas closed to fishing as compared against open areas. The Swept Area Seabed Impact model (SASI) developed by the New England Fisheries Management Council Habitat Plan Development Team is being used to 1) assess fishing impacts on Essential Fish Habitat (EFH) from Cape Hatteras to the USA-Canada border and 2) to develop new spatial fishery management measures (e.g. habitat closed areas). The SASI model translates literature-based information on geological and biological structure *susceptibility* to and *recovery* from fishing effects into quantitative modifiers of fishing gear swept area (Table 2; NEFMC 2010). The model combines area swept fishing effort data with the best available sediment data and benthic boundary water flow estimates in a geo-referenced, GIS-compatible environment (NEFMC 2010). The core information in the model derives from extensive substrate survey data, observed fishing vessel effort, and an exhaustive literature review (97 peer-reviewed papers) of the fishing impacts work relevant to Northeast USA fishing gears and seabed types (see Grabowski et al. 2014) to inform habitat feature susceptibility to fishing gear effects and recovery there from. The state of the science derived from the literature was distilled in a formal vulnerability assessment with quantitative susceptibility and recovery parameters for use in the spatial SASI model (see scallop dredge on cobble seabed example provided in Table 3; Grabowski et al. 2014). Consistent with language in the MSFMCA, the vulnerability assessment quantifies both the magnitude of the impacts that result from the physical interaction of fish habitats and fishing gears, and the duration of recovery following those interactions.

Table 2. Susceptibility and recovery codes and associated % of structure removed (S) and recovery time (R) values.

Code	*Quantitative definition of susceptibility (% of structure removed)*	*Quantitative definition of recovery (recovery time)*
0	0 – 10%	< 1 year
1	>10%-25%	1 – 2 years
2	25 - 50%	2 – 5 years
3	> 50%	> 5 years

Table 3. Susceptibility (S) values and recovery (R) scores for dredge effects on high energy cobble including feature-specific gear effects. S and R values are defined in Table 4 (NEFMC (2010). Shaded fields indicate structure most likely to be adversely effected.

Scallop Dredge / Cobble / High energy			
Feature name and class – G (Geological) or B (Biological)	**Gear effects**	**S**	**R**
Cobble, pavement (G)	burial, mixing, homogenization	1	0
Cobble, piled (G)	smoothing, displacement	3	3
Cobble, scattered in sand (G)	burial, mixing, displacement	1	0
Anemones, actinarian (B)	breaking, crushing, dislodging, displacing	2	2
Ascidians (B)	breaking, crushing, dislodging, displacing	2	1
Brachiopods (B)	breaking, crushing, dislodging, displacing	2	2
Bryozoans (B)	breaking, crushing, dislodging, displacing	1	1
Hydroids (B)	breaking, crushing, dislodging, displacing	1	1
Macroalgae (B)	breaking, dislodging	1	1
Mollusks, epifaunal bivalve, *Modiolus modiolus* (B)	breaking, crushing, dislodging, displacing	2	3
Mollusks, epifaunal bivalve, *Placopecten magellanicus* (B)	breaking, crushing	1	2
Polychaetes, *Filograna implexa* (B)	breaking, crushing, dislodging, displacing	2	2
Polychaetes, other tube-dwelling (B)	crushing, dislodging	2	1
Sponges (B)	breaking, dislodging, displacing	2	2

The SASI model predicts that in high-energy gravel dominated seabed on average each dredge or trawl tow will reduce the geological and biological structure by 25 - 50% in the area swept by the gear with the recovery of these features requiring 1-5 years (NEFMC 2010). If the literature-based susceptibility and recovery parameters used in the SASI model are correct, then the gravel dominated sediments in the 17-yr mobile gear closures on Georges Bank will contain significantly more geological and biological structure compared to those in continuously fished areas.

This work has substantial implications for present and future spatial prohibitions on dredge and trawl fisheries and is based on research recommendations of both the NEFMC Habitat Plan Development Team and the NEFMC Science and Statistical Committee. It specifically addresses two priorities identified by the 2011 Sea Scallop Research Set-Aside RFP (in *italics* below).

We *examine the habitat effects from scallop fishing* and test the fishing impacts parameters of the model being used to develop strategies to *minimize or mitigate those impacts* on EFH (Priority #7). Additionally, this work c*ompares areas where scallop fishing versus no scallop fishing have occurred* for the past 17 yrs *using video and/or photographic techniques;* it *provides information* *on the short and long term effects and recovery rates of scallop fishing on various habitats;* it *examines Essential Fish Habitat (EFH) and Habitat of Particular Concern (HAPC) closures and identifies factors that significantly influence efficacy of these closures to guide future closures* (Priority #8).

2. Methods

2.1. Sampling Design

The *Impact* and *Reserve* areas of each study site were surveyed during summer 2011 using video quadrats deployed in a two-stage sampling design. Sixty randomly selected stations (200 m minimum separation) were surveyed (stage 1) in the *Impact* and *Reserve* areas at both study sites and four quadrats were sampled at each station (stage 2, Figure 3; Krebs 1989). At each station the survey vessel stopped and a 700 kg steel pyramid (Figure 4) was lowered to the seabed for 15-30 seconds, raised until the seabed was beyond view and then dropped again. This process was repeated until four quadrat samples were taken at each station. Due to small movements in the survey vessel, repeat photo-pyramid deployments resulted in quadrats placed in close proximity to each other (on the order of 10s of meters apart), but quadrats did not overlap.

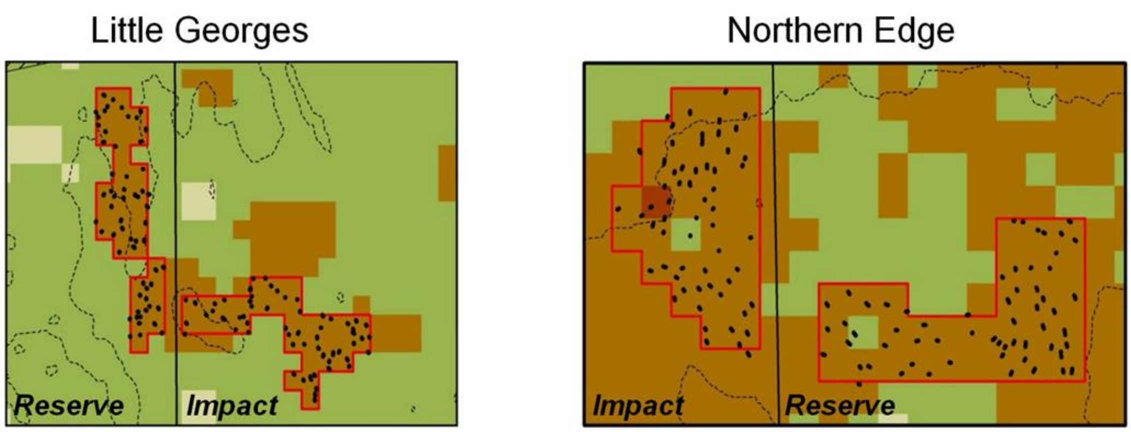


Figure 3. Maps showing the randomly selected stations (black dots) in the cobble-gravel outcrops (brown; from Figure 6 in Harris and Stokesbury 2010) in the impact and reserve areas of the Little Georges (Left) and Northern Edge (Right) study sites.

The pyramid houses three live-feed S-VHS underwater video cameras (Multi-SeaCam® 2050 or 2060, Deepsea Power & Light) and one high definition digital still camera (DSC) which simultaneously viewed each quadrat (Figure 4). Two cameras sample in plan-view (quadrats) and one in parallel-view. The plan-view cameras view 2.84 m^2 (Video 1), 0.59 m^2 (Video 2), and 1.04 m^2 (DSC) respectively, with the smaller quadrats nested within the larger to provide a higher resolution samples for identifying small sediments and organisms. The parallel-view camera (Side-View) provides a cross-quadrat view of the sampled area (Figure 4). Multi-SeaLights (100 - 250 watt, Deepsea Power and Light) illuminated the quadrat; and four to eight lights were used depending on water turbidity and seabed reflectivity. As the pyramid landed on the seabed the latitude and longitude of the vessel was used as the quadrat position. The drift of the vessel during sampling determined the distance and direction between the quadrats. The position, date, time and quadrat identification were overlaid on the video which was recorded simultaneously to S-VHS and DVD. For details including camera and light specifications and sampling pyramid configuration see Stokesbury et al. (2004), Stokesbury and Harris (2006), Stokesbury et al. (2010), Harris and Stokesbury (2010) and Carey and Stokesbury (2011). Video quadrats were subsequently processed at a later date by analysts trained to recognize physical and biological habitat features of interest (see sections 2.3 and 2.4 below).

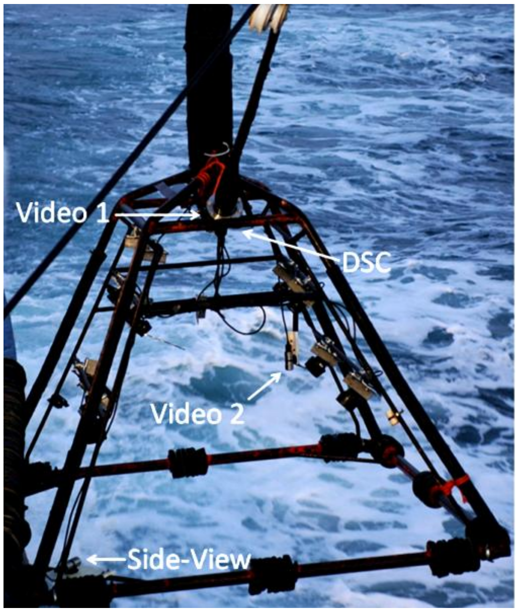


Figure 4. Sampling Pyramid with locations of the digital still camera (DSC), video cameras 1and 2 and the side-view camera.

2. 2. Sediment Sampling

The resolution of the video cameras supports visual identification of sediment to five broad Wentworth particle size categories: silt-mud, sand, granule-pebble, cobble, and boulder (Wentworth 1922). The video quadrats were calibrated in a 341,000 liter seawater tank at University of Massachusetts - Dartmouth SMAST using a grid template with 3 cm^2 cells and with sediment types ranging from sand to cobbles. Video quadrat analysts were trained to identify the five sediment types using a standard training-set of calibration quadrats. During surveys the presence or absence (detection/ non-detection) of each sediment type in each quadrat was recorded in real-time during sampling using all three video camera views. In the laboratory all the video was reviewed and the sediment identifications were verified.

2.3. Sampling Biological and Geological Structures

The density, presence/ absence, and percent coverage of the geological and biological structures listed below were assessed using the high resolution DSC image quadrats (1.04 m^2). Photos were imported to Image J (a public domain Java image processing and analysis program, Rasband 2014) and the "Unsharpen Mask Tool" was used to enhance photo clarity (Figure 5).

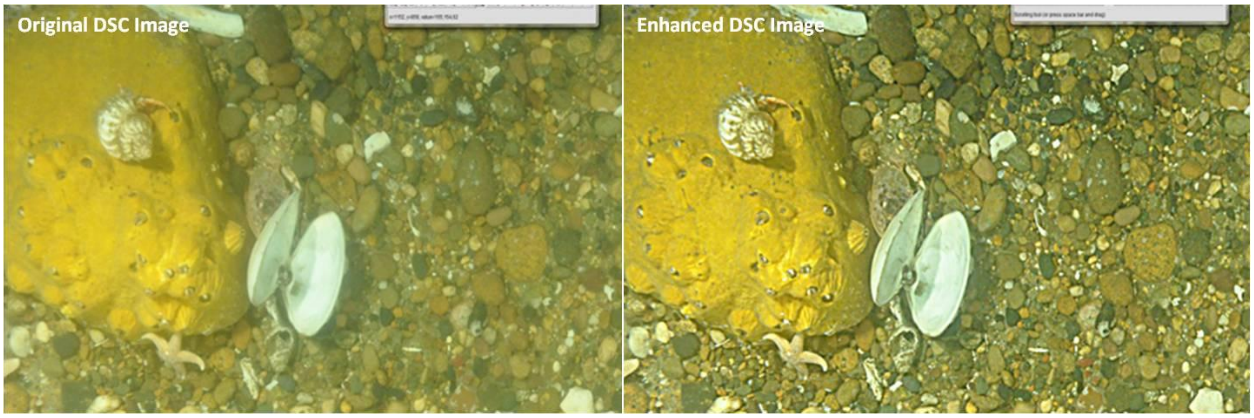


Figure 5. The results of the "Unsharpen Mask Tool" can be seen by comparing the original image (left) with the enhanced image (right).

Density (number of individuals per 1.04 m^2) was calculated for the taxa listed below. The taxa groups include the organisms are listed in parenthesis.

1. Sea scallops (*Placopecten magellanicus*)
2. Sea stars (including: *Asterias spp*., *Leptasterias spp*., *Luidia clathrata*, *Astropecten spp.*, and *Henricia spp.*)
3. Crabs (*Cancer irroratus* and *Cancer borealis*)
4. Hermit crabs (including: *Calcinus spp., Dardanus spp., Isocheles spp., Paruristes spp., Petrochirus spp., Aragicochirus spp., Cataguroides spp., Catapagurus spp., Discorpopagarus spp., Elassochirus spp., Enallopaguropsis spp,. Haigia spp., Iridopagurus spp., Labidochirus spp., Manucoplanus spp., Nematopaguroides spp., Ostraconotus spp., Orthopagurus spp., Parapagurodes spp., Philochirus spp., Pylopagurus spp., Rhodochirus spp., Solenopagurus spp.,* and *Tomopagurus spp.*)
5. Whelks (*Buccinum ondatum*)
6. Moonsnails (*Euspira heros* and *Neverita duplicata*).

Presence/ Absence was determined for the following taxa. The taxa groups include the organisms are listed in parenthesis.

1. Seed Scallops (juvenile *Placopecten magellanicus*)
2. Anemones (Orders Actiniaria, Ceriantharia, Family Cerianthidae)
3. Bryozoans and hydroids (*Aeverrillia spp., Alcyonidium spp., Amathia convoluta and vidovici, Anguinella palmata, Bugula turrita, Bugula simplex, Cabrera ellisi, Crisia eburnea and cribaria, Dendrobaenia murrayana, Eucratea loricata, Flustra foliacea, Idmonea atlantica, Tricellaria ternata, Abietinaria spp., Aglantha digitale, Bougainvillia carolinensis, Bougainvillia superciliaris, Bougainvillia rugosa, Capanularia spp., Clytia edwardsi, Corymorpha (Hybocodon) pendula, Diphasia spp., Eudendrium spp., Garveia spp., Gonothyraea loveni, Halecium spp., Hybocodon (Corymorpha) pendula, Lovenella spp., Obelia bicuspidata, Obelia commissuralis, Obelia longissima, Opercularella spp., Pennaria tiarella, Schizotricha tenella, Sertularella polyzonias, Sertularia cupressina, Sertularia argentea, Sertularia latiuscula, Sertularia pumila,* and *Tubularia spp.*)
4. Brittlestars (*Ophiopholis aculeata*)

5. Clam siphons (including: *Mercenaria mercenaria*, *Ensis directus*, and *Spisula solidissima*)
6. Corals (*Alcyonium digitatum* and *Pennatula aculeata*)
7. Ampelisca tubes (tubes of *Ampeliscidae*)
8. Tube worms (*Filograna implexa*)
9. Mussels (*Mytilus edulis and Modiolus modiolus*)
10. Sponges (*Suberites ficus*, *Haliclona oculata*, *Halichondria panicea*, *Cliona celata*, *Polymastia robusta*, *Isodictya palmata*, and *Microiona prolifera*)
11. Urchins (*Strongylocentrotus droebachiensis* and *Arbacia punctulata*)
12. Stalked tunicates (*Boltenia ovifera)*
13. Infaunal "holes" in the seabed surface
14. Shell debris

Areal coverage was assessed for the following taxa. The taxa groups include the organisms are listed in parenthesis.

1. Scallops (*Placopecten magellanicus*)
2. Mussels (*Mytilus edulis and Modiolus modiolus*)
3. Macroalgae (*Alaria spp., Agarum cribrosum, Laminaria digitata, Laminaria longicruris, Laminaria saccharina, Laminaria agardhii, Champia parvula, Chondria spp., Cystoclonium purpureum, Dasya spp., Gracilaria spp., Griffithsia globulifera, Grinnellia americana, Hypnea musciformis*, and *Lomentaria spp.*)
4. Brachiopods (*Terebratulina septentrionalis*)
5. Anemones (*actinarian*)
6. Anemones (*cerianthid*)
7. Ascidians (*Ascidia callosa, Ascdia prunum, Boltenia ovifera, Boltenia echinata, Ciona intestinalis, Halocynthia pyriformis, Molgula arenata*, and *Molgula manhattensis*)
8. Bryozoans (*Aeverrillia spp., Alcyonidium spp., Amathia convoluta* and *vidovici, Anguinella palmata, Bugula turrita, Bugula simplex, Cabrera ellisi, Crisia eburnea* and *cribaria, Dendrobaenia murrayana, Eucratea loricata, Flustra foliacea, Idmonea atlantica*, and *Tricellaria ternata*)
9. Hydroids (*Abietinaria spp., Aglantha digitale, Bougainvillia carolinensis, Bougainvillia superciliaris, Bougainvillia rugosa, Capanularia spp., Clytia edwardsi, Corymorpha (Hybocodon) pendula, Diphasia spp., Eudendrium spp., Garveia spp., Gonothyraea loveni, Halecium spp., Hybocodon (Corymorpha) pendula, Lovenella spp., Obelia bicuspidata, Obelia commissuralis, Obelia longissima, Opercularella spp., Pennaria tiarella, Schizotricha tenella, Sertularella polyzonias, Sertularia cupressina, Sertularia argentea, Sertularia latiuscula, Sertularia pumila*, and *Tubularia spp.*)
10. Sponges (*Suberites ficus*, *Haliclona oculata*, *Halichondria panicea*, *Cliona celata*, *Polymastia robusta*, *Isodictya palmata*, and *Microiona prolifera*),
11. Polychaetes (*Filograna implexa*)
12. Polychaetes (other).

Areal coverage of benthic features was estimated using a 5x5 grid (25 cells, 0.0416 m^2 each) overlain on the DSC images in ImageJ software (Figure 6). The amount of coverage for each taxa in each quadrat was tabulated as the number of presences and absences among the 25 grid cells.

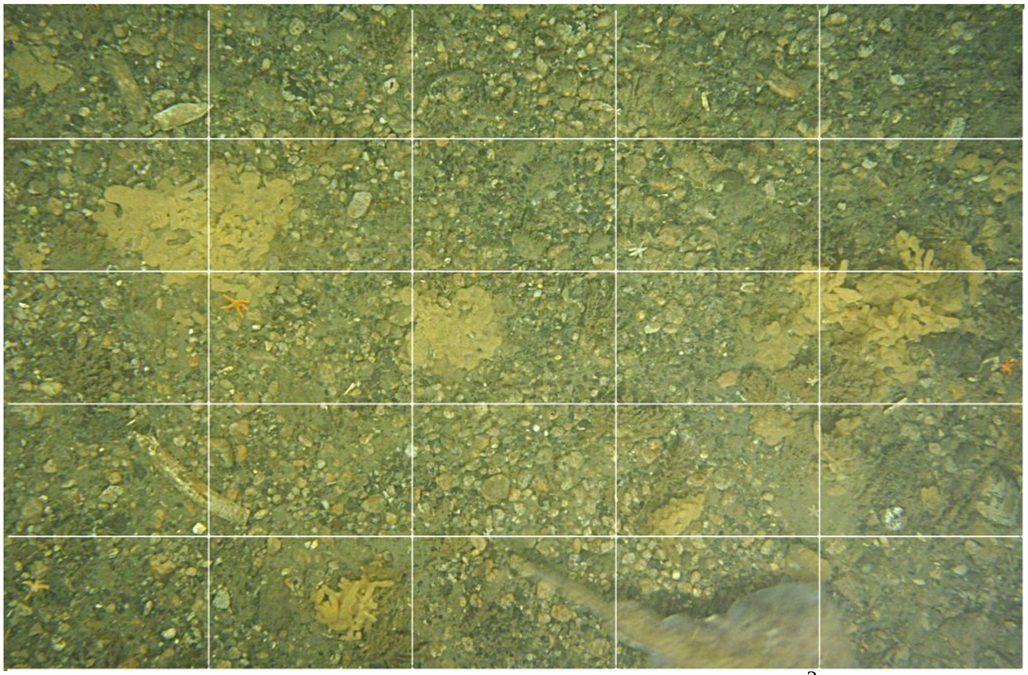


Figure 6. Image assessment grid (5x5) with 25 cells, 0.0416 m^2 each.

2.4. Impact and Reserve Area Environmental Comparison

To further explore the comparability of the *Impact* and *Reserve* areas at each study site, we assessed the distribution and spatial structure of substrates at the level of the *Impact* and *Reserve*, the station and the 1.04m^2 video quadrat. In addition, we compared water depths and benthic boundary shear stresses.

2.4.1. Sediment Mapping and Analysis of Spatial Structure

Following Harris and Stokesbury (2010), the most frequently occurring or "dominant" sediment type (S_d) at each station was calculated. In stations where sediment types were present with equal frequency (e.g. sand and granule-pebble in all four quadrats), the larger sediment type was considered "*dominant*" (Harris and Stokesbury 2010).

To map S_d , the mean latitude and longitude of the four quadrats were used as each station's location and plotted in ArcGIS® 10.2 software. The data were projected with the Universal Transverse Mercator Projection for Zone 19 North using the North American Datum 1983 horizontal control. The sediment characteristics were interpolated to a 500 m^2 raster grid using Sibson's Natural Neighbor method (Sibson 1981, Harris and Stokesbury 2010). The predicted value $\hat{K}$ of each interpolated map cell was calculated as

$$\hat{K}(x, y) = \sum_{i=1}^{n} w_i K(x_i, y_i),$$

where $\hat{K}(x, y)$ was the estimate at location *x, y,* and $K(x_i, y_i)$ was the survey data at locations x_i, y_i. The spatial weights w_i resulted from the areas of influence of the Voronoi polygons of x_i, y_i in each interpolated map cell (Sibson 1981, Isaaks and Srivastava 1989, Harris and Stokesbury 2010).

Following Harris and Stokesbury (2010), Moran scatterplots were constructed for the *Impact* and *Reserve* areas at each study site and used to explore the spatial structure of S_d values (GeoDa® software, Anselin et al. 2006). Moran's I is an index of linear association between a set of spatial observations z_i z_j, and a weighted average w_{ij} of their neighbors (Moran 1950):

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2},$$

where $z_i = x_i - \bar{X}$, x_i is the sediment value for station i, and $\bar{X}$ is the overall mean of each area's S_d values. Moran's $I > 0$ indicate the sediment characteristics are positively autocorrelated, while $I < 0$ indicates negative autocorrelation. When $I = 0$ the characteristics are spatially random.

The Moran scatterplot is a bivariate plot of w_i as a function of z_i, and the slope of a line fit to the scatterplot gives global Moran's I (Anselin 1996). The four quadrants of the scatterplot indicate an observation's value relative to its neighbors. Stations with higher than average values ($z_i > 0$) with neighboring high values ($w_i > 0$) are in the High-High quadrant and together with those in the Low-Low ($z_i < 0$, $w_i < 0$) quadrant indicate positive local spatial autocorrelation. The High-Low and Low-High quadrants indicate negative local spatial autocorrelation.

The null hypotheses that values of S_d were randomly distributed ($I = 0$) were tested by estimating p-values for I. The p-values were calculated using 1000 permutations of a spatially random reference distribution based on the survey data (GeoDa® software, Anselin et al. 2006). These p-values are one-sided *pseudo*-significance values: $p = (M + 1) / (R + 1)$ where R is the number of permutations and M is the number of instances where I or I_i are greater than or equal to the observed value for positive autocorrelation, or less than or equal to the observed value for negative autocorrelation.

To compare the spatial structure of dominant sediments (S_d) in *Impact* and *Reserve* sites, we examined the Moran's I scatterplots and used Chi squared tests to assess the equivalence of proportions of stations in the High-High, Low-Low, High-Low and Low-High quadrants in *Impact* and *Reserve* areas (Zar 1996).

2.4.2. Comparison of Sediment Distributions in Impact and Reserve areas.

The overall proportions of dominant sediment types present in the *Impact* and *Reserve* areas were calculated and the null hypothesis of no difference examined with χ^2 tests (Zar 1996).

2.4.3. Comparison of Sediment Area Coverage in Impact and Reserve areas.

The mean area covered by sand, gravel, cobble and boulder sediment at each station (based on the four 1.04 m^2 DSC quadrats) was estimated for the *Impact* and *Reserve* areas at each study site using equations for a two-stage nested sampling design with four quadrats sampled within each station (Cochran 1977). Since there was a constant number of quadrats at every station, the two-stage mean area covered for each sediment was calculated as:

$$\bar{\bar{x}}_s = \sum_{i=1}^{n} \left(\frac{\bar{x}_{si}}{n} \right)$$

where n = the number of stations, $\bar{x}_{s\,i}$ = the mean area covered by sediment type *s* in the four quadrats at station *i*. The standard error of this two-stage mean is calculated as:

$$\mathrm{SE}(\bar{\bar{x}}_s) = \sqrt{\frac{1}{n}(s^2)}$$

where: $s^2 = \sum(\bar{x}_s - \bar{\bar{x}}_s)^2/(n-1)$. According to Cochran (1977) and Krebs (1989) this simplified version of the two-stage variance is appropriate when the ratio of sample area to survey area (*n/N*) is small. In this case, hundreds of m^2 (*n*) are sampled compared with millions of m^2 (*N*) in the *Impact* and *Reserve* areas at each study site.

2.4.4. Comparison of Benthic Boundary Shear Stress in Impact and Reserve Areas

Shear stress (τ_{0s}) is the force per unit area exerted on the seabed by flowing water and is generally given in Newtons m^{-2}. It includes drag caused by and acting on sediment particles (skin friction), bed forms (form drag), and suspended sediments (transport drag, Soulsby 1997). Shear stress can be considered a proxy for natural disturbance levels as sediments become mobile when shears exceed their critical threshold levels (Harris et al. 2012) and moving sediments can bury or scour biological and geological structures. Estimates of shear stress in the impact and reserve areas of both study sites were derived from a regional tidal database application of the Finite Volume Community Ocean Model (FVCOM, Chen et al. 2011) following Harris et al. (2012). FVCOM is an open source Fortran90 software package for simulating ocean processes in coastal regions developed in the Marine Ecosystem Dynamics Modeling Laboratory at the University of Massachusetts Dartmouth, Department of Fisheries Oceanography (http://fvcom.smast.umassd.edu/FVCOM). The model computes a solution of the hydrostatic primitive equations on an unstructured triangular grid using a finite-volume flux formulation (for details see Chen et al. 2003, 2006, Cowles 2008a).

The FVCOM Gulf of Maine tidal model extends from the Scotian Shelf south to the New England shelf and encompasses all of Georges Bank including our two study sites (Chen et al. 2011). The model employs 45 vertical layers, and the horizontal resolution ranges from 0.5 - 10 km. On Georges Bank the horizontal resolution ranges from 1.0 - 2.0 km on the southern flank to 0.5 - 1.0 km on the northern flank (Figure 7). The model sea surface elevation is forced at the open boundary using eight regional tidal harmonics (M_2, N_2, S_2, K_1, K_2, O_2, P_1, Q_1) derived from the Egbert and Erofeeva (2002) 1/6° tidal database. The model was integrated for two months and the flow-field is archived at hourly intervals. Model-computed currents and sea level are decomposed into tidal constituents using a least squares harmonic method (Foreman, 1977). The FVCOM Gulf of Maine tidal model was validated through comparison with tidal current observations from 130 stations and tidal elevation measurements at 98 sites (Chen et al. 2011).

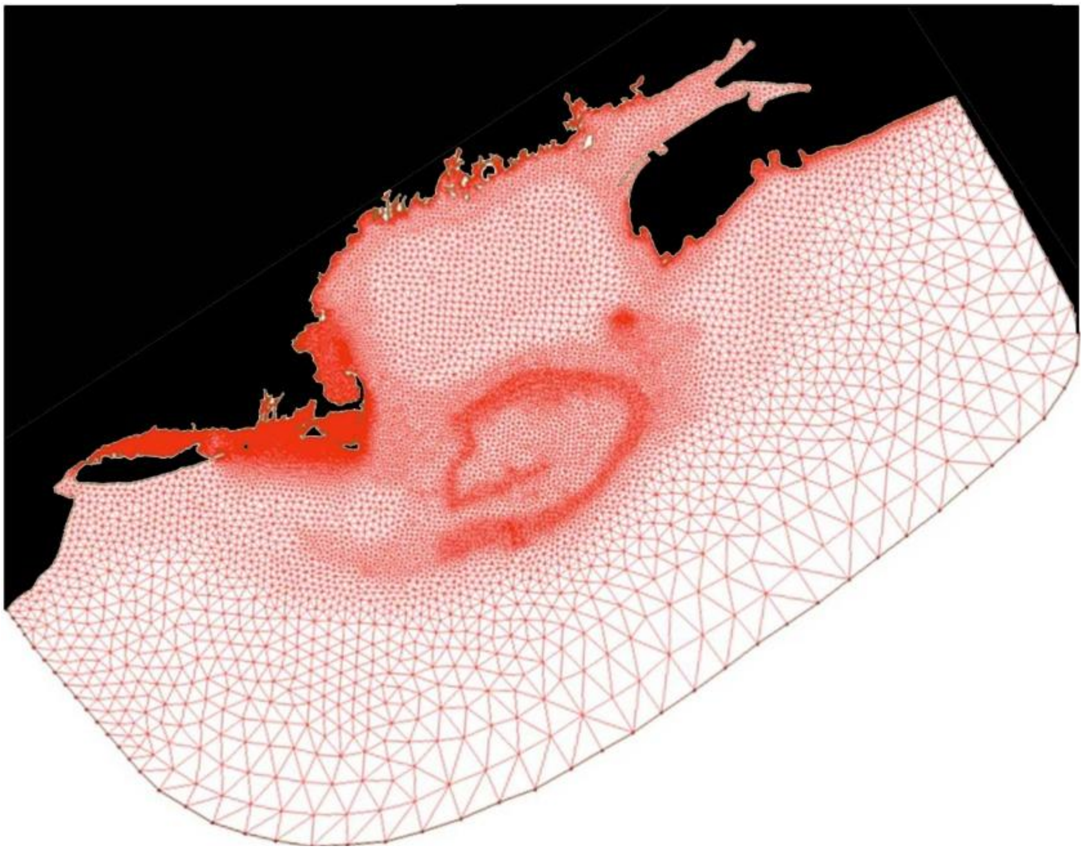


Figure 7. FVCOM-GOM model domain with unstructured triangular grid shown in red.

Mean maximum bi-weekly benthic boundary shear stresses were estimated using the sum of the M_2 and S_2 constituents of the tidal currents. The logarithmic law of the wall formulation with a depth dependent seabed roughness (Bradshaw and Huang 1995, for equations see Chen et al. 2003 and Cowles et al. 2008b) was used to derive the stress from the bottom tidal velocities. τ_{0s} values were interpolated to a 1-km raster grid using Sibson's Natural Neighbor method (Sibson 1981) following Harris et al. (2012) and mean τ_{0s} in the *Impact* and *Reserve* areas in both study sites were compared with t-tests (Zar 1996).

2.4.5. Comparison of Water Depths in Impact and Reserve Areas

Water depth was sampled at each station using the survey vessel's depth sounder. Preliminary analyses showed the depths in the *Impact* and *Reserve* areas at both study sites were not normally distributed and had un-equal variances so the median depths were compared with a non-parametric Mann-Whitney Rank Sum Test (Zar 1996).

2.5. Comparing Geological and Biological Features in Impact and Reserve Areas

Generalized linear mixed models (GLMM) implemented in a Bayesian framework were used to test the null hypothesis of no difference in density, presence/ absence, and areal coverage of the biological and geological structures in *Impact* and *Reserve* areas. Separate regressions were run for taxa or taxonomic groups, and for the coverage of all biological structures combined. Presence/ absence data and percent cover were modeled using Binomial GLMMs; density data were modeled using a Normal GLMM. Previous video survey work on Georges Bank showed strong local autocorrelation in habitat features (Harris and Stokesbury 2010) and species distributions (Adams et al. 2010). Generalized linear mixed models were appropriate given the hierarchical structure of the two-stage sampling design, controlling for potential pseudoreplication associated with replicate quadrats within stations. In all cases (except vertical height; see below) the models were fit with Reserve (*Impact* or *Reserve*), Site (LG or NE), and a Reserve x Site interaction as fixed effects, and Station (nesting quadrats) as a normally distributed random intercept.

GLMM models were fit using the 'MCMCglmm' package (Hadfield 2010) in the R statistical programming environment (RDCT 2013). Uninformative priors and hyperpriors were specified following the model defaults in MCMCglmm (see details in Hadfield 2010). MCMC model fits were implemented with a single chain run for 13000 iterations including a 3000 iteration burn-in period and a 10 iteration thin rate for a final retained sample of 1000 posterior parameter draws. Model convergence was verified by examining trace plots for fitted parameters and ensuring stable posterior MCMC sampling behavior.

2.6. Vertical Height

The vertical heights of attached epifaunal organisms were measured using the side-view video camera and the attachment substrates (Shell, Sand, Gravel, or None) for each measured organism were recorded (Figure 7). Height measurements made using the side-view camera required adjustments to account for the distance of the organism from the camera. These distance and vertical height corrections were made using video camera 1 quadrat (see Figure 8).

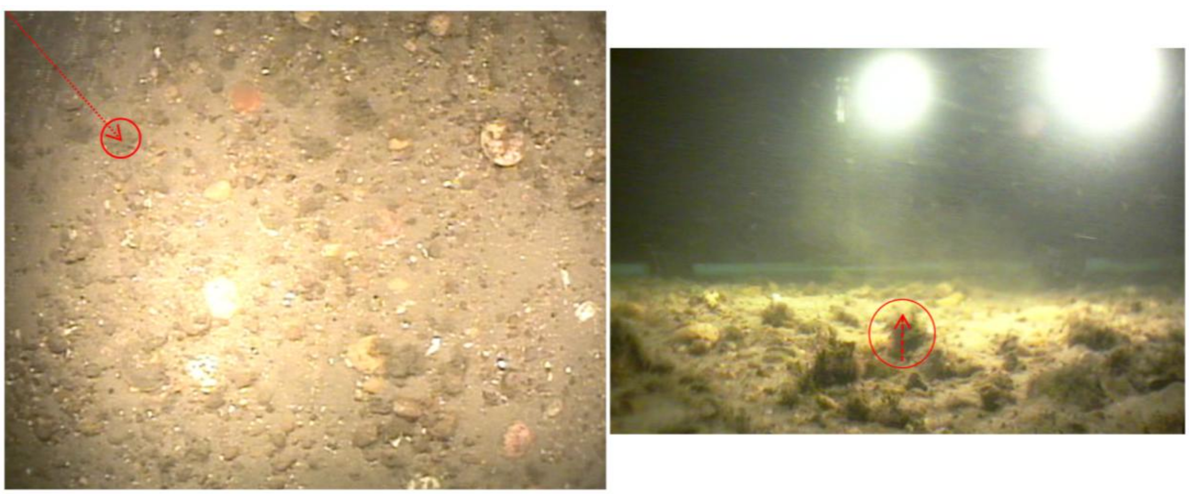


Figure 8. Corresponding video camera 1 quadrat (left) and Side Cam (right) images identifying a hydrozoa. Distance from the camera is measured in the Large camera and used to correct the vertical height measured in the side camera.

Vertical height measurements followed a different sampling design than plot-based density, presence-absence, and coverage, and were made on individual organisms at randomly selected quadrats. Measurements were made at a 44 randomly selected locations (quadrats) in the *Impact* (n = 21) and *Reserve* (n = 23) areas at the Little Georges study site (Figure 8). In the Northern Edge study site measurements were made at a 58 randomly selected locations (quadrats) in the

Impact (n = 37) and *Reserve* (n = 21) areas at the (Figure 9). Because the locations of sampled individuals were strictly random and did not follow a nested structure, no random effect was implemented to control for sampling location. A priori, we hypothesized that fishing impacts on biological structure may depend on attachment substrate type (e.g. shell, gravel, cobble), and thus differences in mean height in *Impact* and *Reserve* areas by study site and attachment substrate were assessed with 2-sample *t*-tests (Zar 1996).

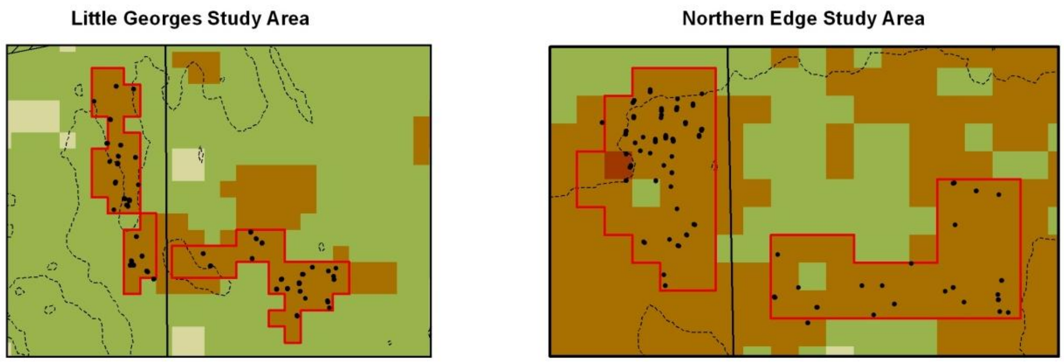


Figure 9. Maps showing the locations of randomly selected quadrats for vertical height measurements in the Little Georges (left) and Northern Edge (right) study areas.

Vertical heights were measured for Nipple Sponge (*Polymastia robusta*), Fig Sponge (*Suberites ficus*), Palmate Sponge (*Isodictya palmata*), Finger Sponge (*Haliclona oculata*), Hydrozoans, Anemones, and Stalked tunicates because these were common vertically erect sessile species in the study area.

2.7. Comparison of Community Structure and Taxonomic Richness in Impact and Reserve Areas
Richness (*S*=total number of types), diversity, evenness, similarity and fragmentation of the biological and geological structural communities in the *Impact* and *Reserve* areas of both study sites were compared with the Shannon Diversity Index (*H'*), Pielou's Evenness Index (*J'*), and Bray-Curtis Dissimilarity Index (*D*; Magurran 2004).

The Shannon Diversity Index (*H'*) is defined as:

$$H' = -\sum_{i=1}^{S}(p_i \times \ln p_i) = -\sum_{i=1}^{S}(\frac{n_i}{N} \times \ln \frac{n_i}{N})$$

where, *S* is the total number of biological taxa or geological feature types, *N* is the total number of observations, and n_i is the number of observations in the *i*-th biological taxa or geological feature types. $\frac{n_i}{N} = p_i$ is the probability of finding the *i*-th biological taxa or geological feature types. *H'* typically ranges between 1.5 and 3.5 and higher *H* values indicate greater diversity. (Shannon 1948; MacDonald, 2003).

Pielou's Evenness Index (*J'*) characterizes the distribution of the number of observations of given biological taxa or geological feature types over the number of types and is defined as:

$$J' = \frac{H'}{H'_{max}}$$

where $H'_{max} = \ln(S)$.

The Bray-Curtis dissimilarity measure, $D(i, j)$, quantifies the dissimilarity in the biological taxa or geological feature types between *Impact* (i) and *Reserve* (j), based on the abundances in each area, and is defined as:

$$D(i,j) = \frac{\sum_{k=1}^{n}|y_{i,k}-y_{j,k}|}{\sum_{k=1}^{n}(y_{i,k}-y_{j,k})},$$ (Legendre and Legendre 1998)

where $y_{i,k}$ and $y_{j,k}$ are the number of observations for the k^{th} biological taxa or geological feature type in i and j, respectively, and n is total number of biological taxa or geological feature types present in both samples. The measure $D(i, j)$ ranges between 0 and 1, where 0 means the *Impact* and *Reserve* areas share all the genera in similar abundances, and 1 means the two areas do not share any taxa at all.

3. Results

3.1. Sampling

The Northern Edge stations were surveyed with the F/V Diligence from 6-12 June 2011 and the Little Georges stations were surveyed with the F/V Westport from 24-29 June 2011. All sixty random stations were sampled in the *Reserve* and *Impact* areas of both study sites with video 1, video 2 and side-view cameras. All sixty stations in both the Northern Edge *Reserve* and *Impact* areas were sampled with the DSC camera, but due to equipment malfunction only 28 stations were sampled in the Little Georges site; 14 in the *Reserve* and 14 in the *Impact* area. Biological and geological structures were therefore assessed using the high resolution DSC quadrats at 56 locations in each of the Little Georges *Reserve* and *Impact* areas and 240 locations in each of the Northern Edge *Reserve* and *Impact* areas.

3.2. Impact and Reserve Area Environmental Comparison

3.2.1. Dominant Sediment the Impact and Reserve Areas

The *Reserve* and *Impact* areas at both study sites were dominated by gravel (granule-pebble and cobble) sediments (Table 4 and Figure 10). The proportions and spatial structure of the granule-pebble and cobble sediments (S_d) were similar in the *Reserve* and *Impact* areas at both study sites (Figures 10 and 11). Sediment proportions among *Reserve* and *Impact* stations within Little Georges were similar (χ^2 = 0.514, df = 1, p = 0.474), and in the Northern Edge areas sediment proportions were nearly identical (χ^2 = 0.0034, df = 1, p = 0.954).

Table 4. Percent of the *Reserve* and *Impact* areas at the Northern Edge and Little Georges study sites dominate by granule-pebble and cobble sediments.

	Northern Edge		Little Georges	
Dominant Sediment	*Reserve*	*Impact*	*Reserve*	*Impact*
Granule-Pebble	8.3%	7.1%	52.1%	46.6%
Cobble	91.7%	92.9%	47.9%	53.4%

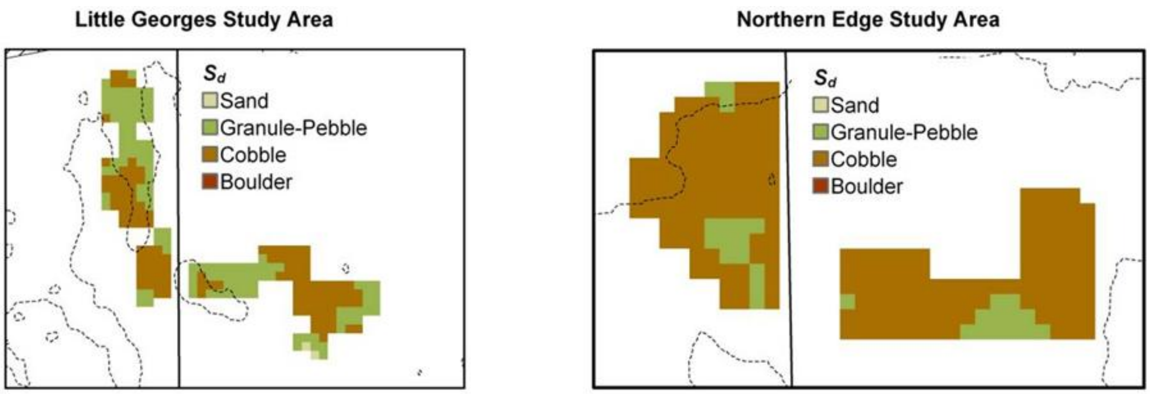


Figure 10. Map of Dominant Sediment (S_d) showing that both areas are dominated by Granule-pebble and Cobble sediments**.**

Dominant sediments demonstrated strong positive spatial autocorrelation ($I > 0$, $p \leq 0.001$) in the *Impact* and *Reserve* areas of both the Northern Edge and Little Georges study sites (Figure 11). The *I* values for the Northern Edge *Impact* ($I = 0.786$) and *Reserve* ($I = 0.765$) areas indicate that spatial clustering of sediments was very strong and the level of clustering was nearly identical between areas. The *I* values for the Little Georges *Impact* ($I = 0.805$) and *Reserve* ($I = 0.671$) indicate that spatial clustering of sediments was also very strong and the level of clustering was similar (differing by 13%). The High-High (H-H) quadrants indicate locations were large sediments (cobbles and boulders) occur together; the Low-Low (L-L) quadrants indicate where small sediments (sand and granule-pebble) occur together, both indicate positive local spatial autocorrelation. The High-Low (H-L) quadrants show locations were large sediments occurred in regions dominated by small sediments (e.g. outcrops of cobble in sand): the Low-High (L-H) quadrants indicate where small sediments occur in regions dominated by large sediments (e.g. (e.g. sand feature overlying a gravel pavement), both indicate negative local spatial autocorrelation. About 90% of all stations were in the H-H and L-L quadrats in all the areas; H-L and L-H stations were rare (4 to 6%, Table 5). Further, the proportion of stations in the H-H, L-L, H-L and L-H quadrants in the Northern Edge *Reserve* and *Impact* areas was similar ($\chi^2 = 3.12$, df = 3 $p = 0.362$, Table 5). The proportion of stations in the H-H, L-L, H-L and L-H quadrants in the Little Georges *Reserve* and *Impact* areas was nearly identical ($\chi^2 = 0.088$, df = 3, $p = 0.993$, Table 5). This indicates that the *Impact* and *Reserve* areas not only had similar levels of global autocorrelation (*I*-values above) but they shared nearly identical proportions of local sediment patchiness.

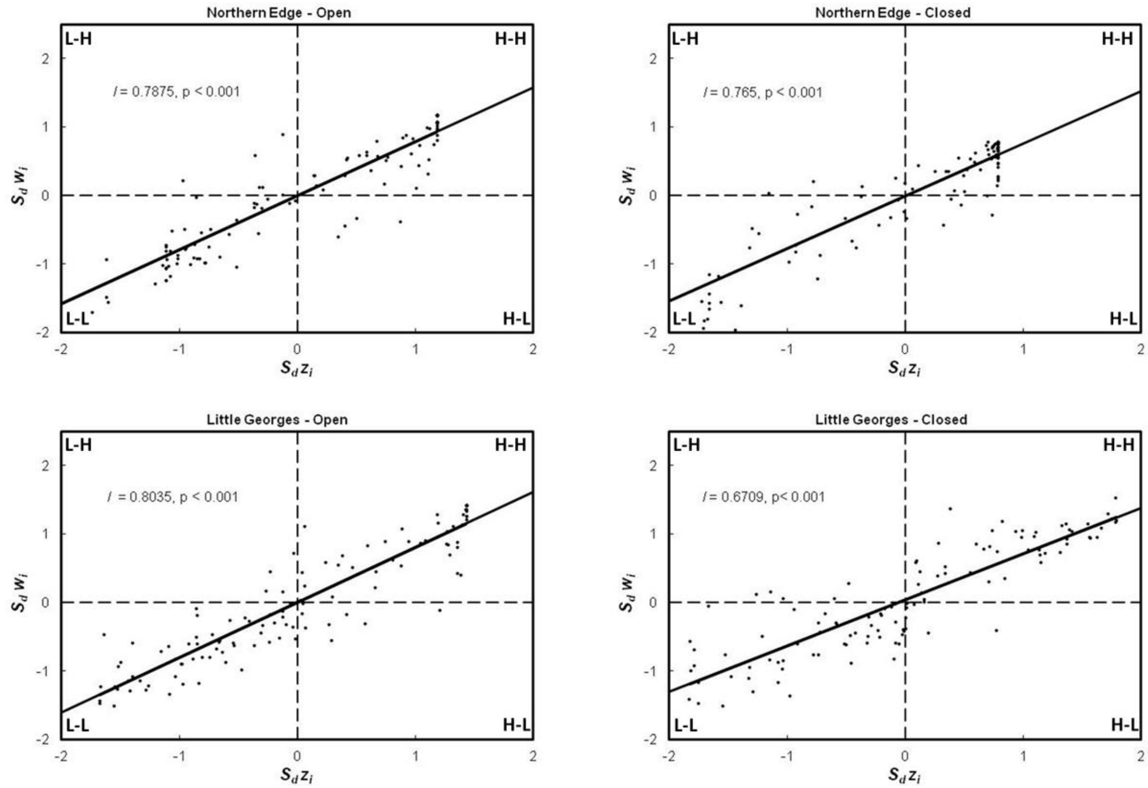


Figure 11. Moran scatterplot with High-High (H-H), Low-Low (L-L), High-Low (H-L) and Low-High (L-H) quadrants indicating that S_d values were globally autocorrelated ($I > 0$) in all areas and that the *Impact* and *Reserve* areas of both study sites were very similar.

Table 5. Percentage of stations in each Moran Scatterplot Quadrant in the *Reserve* and *Impact* areas of the Northern Edge and Little Georges study sites.

Moran Scatterplot Quadrant	**Northern Edge**		**Little Georges**	
	Reserve	*Impact*	*Reserve*	*Impact*
High-High	32%	43%	47%	47%
Low-Low	59%	48%	43%	42%
High-Low	5%	4%	5%	6%
Low-High	4%	5%	5%	5%

3.2.2. Sediment Types Present at the Stations

The proportions of sand, granule-pebble, cobble and / or boulder sediment types *present* at the randomly selected stations in the *Impact* and *Reserve* areas were similar at Little Georges (χ^2 = 4.21, df = 3, p = 0.239) and at the Northern Edge (χ^2 = 1.26, df = 3, p = 0.739, Figure 12).

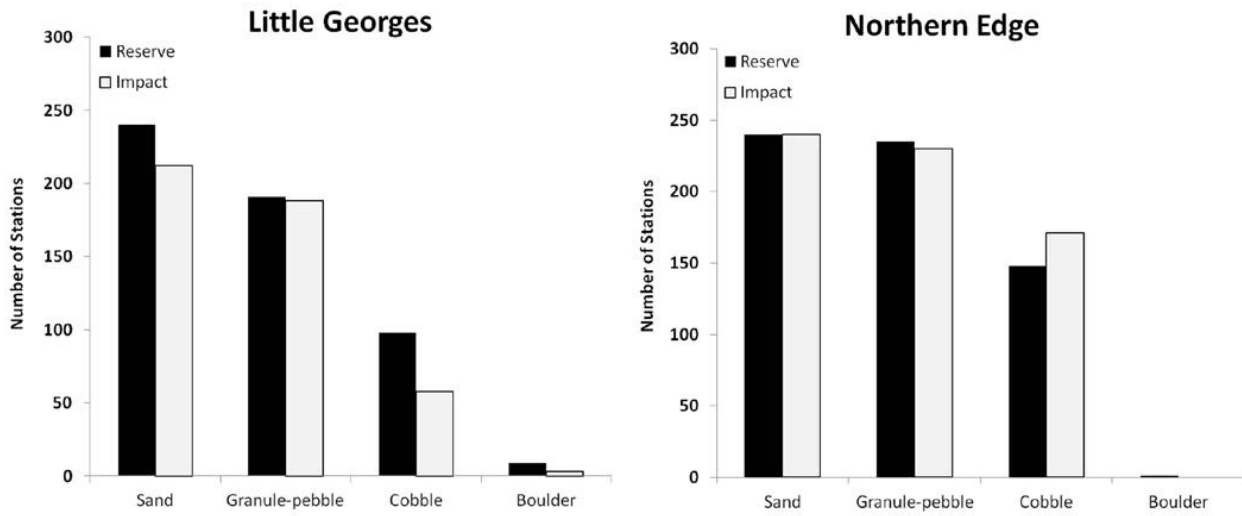


Figure 12. Number of stations with sand, granule-pebble, cobble and/ or boulder in the *Impact* and *Reserve* areas in the Little Georges and Northern Edge Study sites.

3.2.3. Sediment Area Coverage in the DSC Quadrats

The mean area covered by each dominant sediment type in the 1.04 m^2 DSC quadrats did not differ significantly among *Impact* and *Reserve* areas, although one substrate class (cobble at Little Georges and sand at Northern Edge) did differ amongst *Reserve* and *Impact* areas within both of the study sites (Figures 13 and 14).

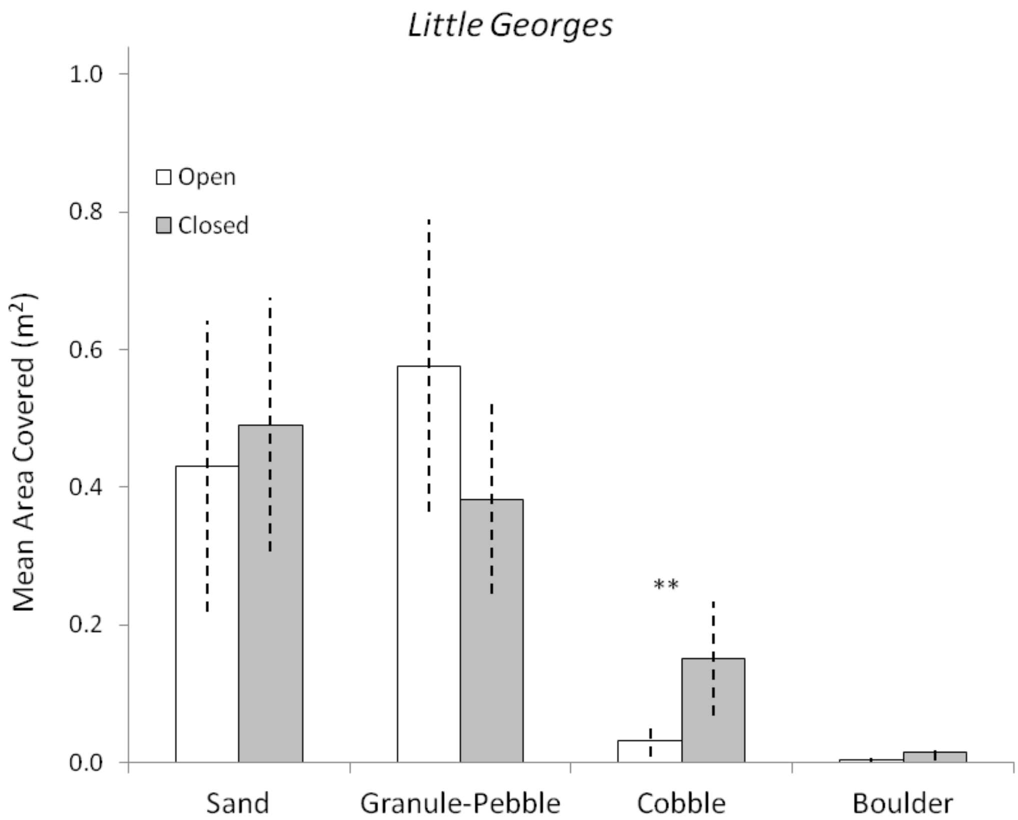


Figure 13. Mean sediment coverage area per quadrat (m^2) by sediment type for the Little Georges study site. Dashed lines indicate 95% confidence intervals. The differences in coverage were not statistically significant for any of the sediment types.

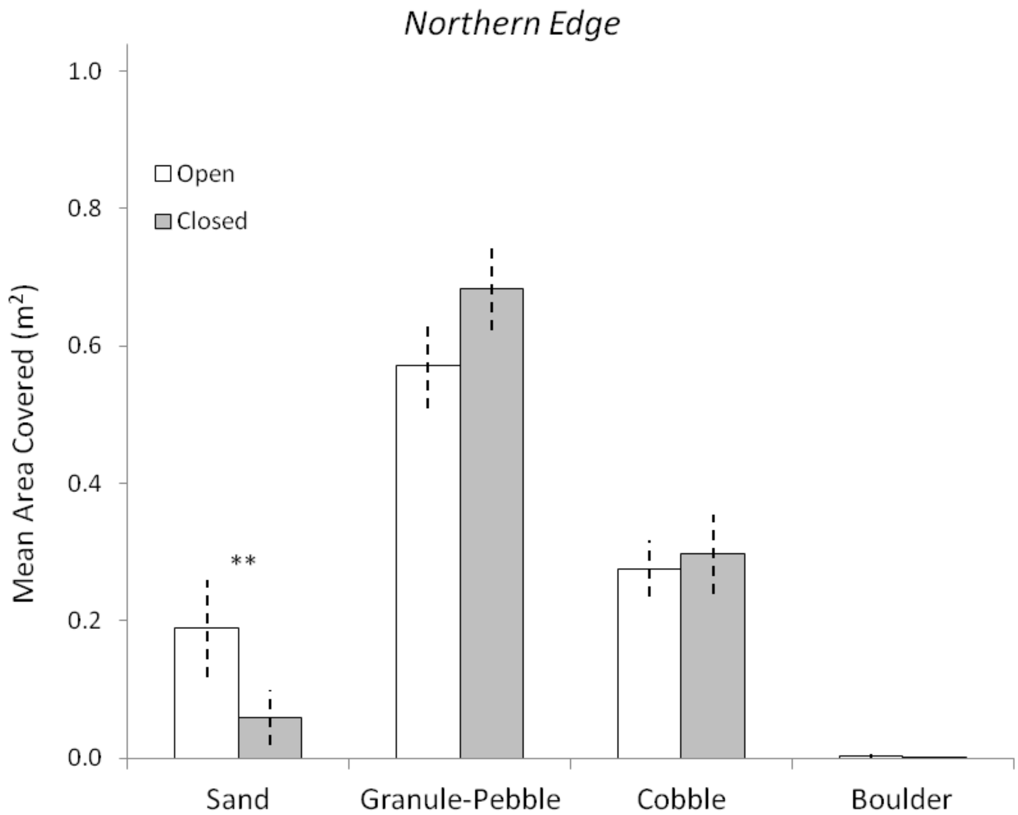


Figure 14. Mean sediment coverage area (m^2) by sediment type for the Northern Edge study site. Dashed lines indicate 95% confidence intervals and asterisks indicate where coverage differed between *Impact* and *Reserve* areas (* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

3.2.4. Benthic Boundary Shear Stress

The Little Georges and Northern Edge sites are within the high energy region on central and northeastern Georges Bank (Harris et al. 2012) and have estimated mean shear stresses = 1.31 N m^{-2} (SD 0.264), and 1.55 N m^{-2} (SD 0.276), respectively (Figure 15). Overall stresses at the Northern Edge site are significantly higher on average than at Little Georges (t = -26.66, df = 3598, p <0.001), but both are well above the critical thresholds required to initiate movement of Georges Bank sands (0.460 N m^{-2}; Harris et al. 2012), and the level adopted by the NEFMC to define "high" energy (0.194 N m^{-2}, NEFMC 2010).

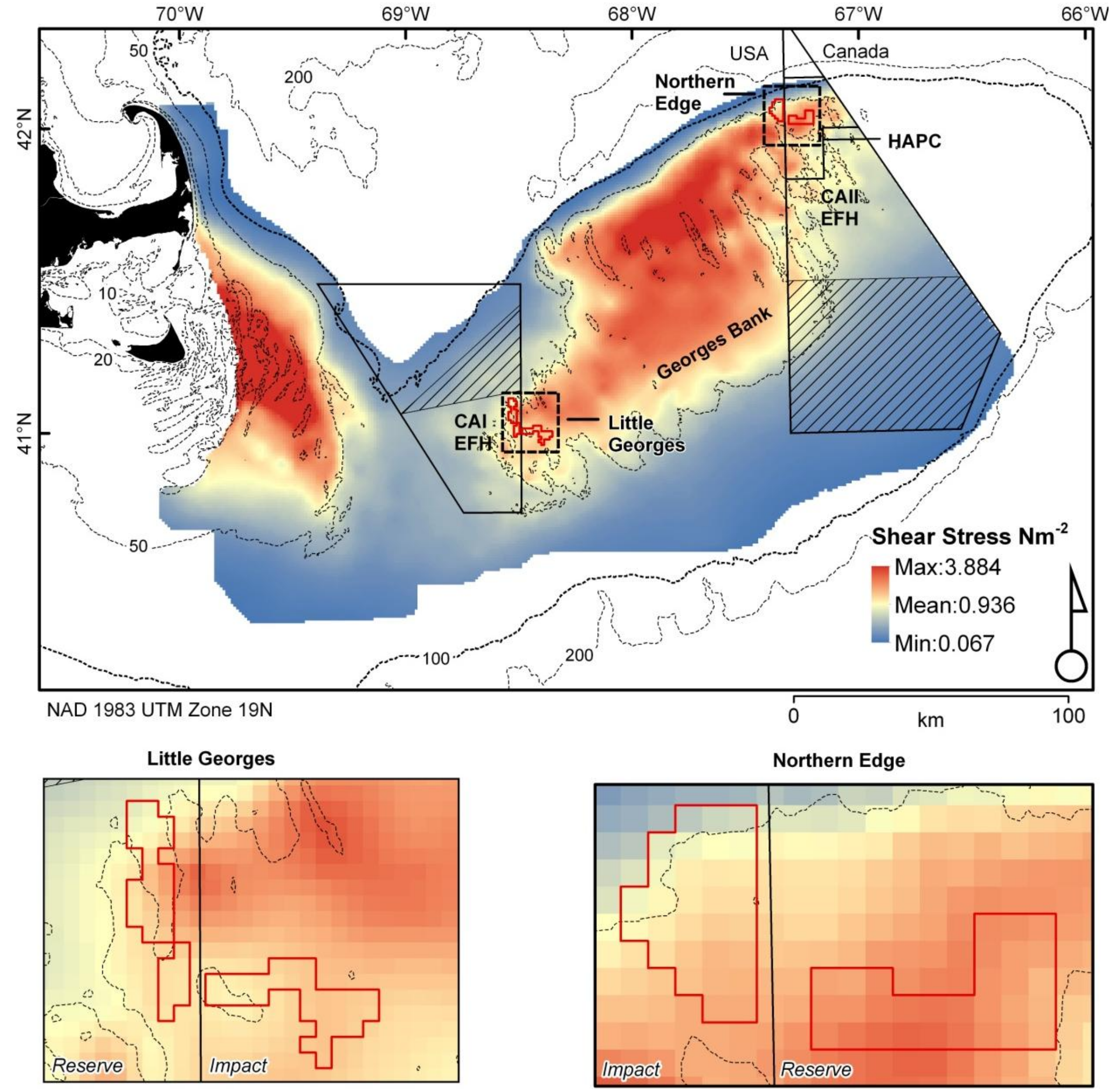


Figure 15. Map showing the benthic boundary shear stresses estimated using FVCOM. Lower panels show the *Impact* and *Reserve* areas at the Little Georges and Northern Edge study sites.

Shear stresses were high everywhere, and the *Reserve* and *Impact* areas were similar at Little Georges. Meanwhile, shear stress of the *Reserve* area was significantly higher than that of the *Impact* area at the Northern Edge site (0.48 Nm^{-2} difference, t = 10.26, df = 58, p = <0.001, Figure 16).

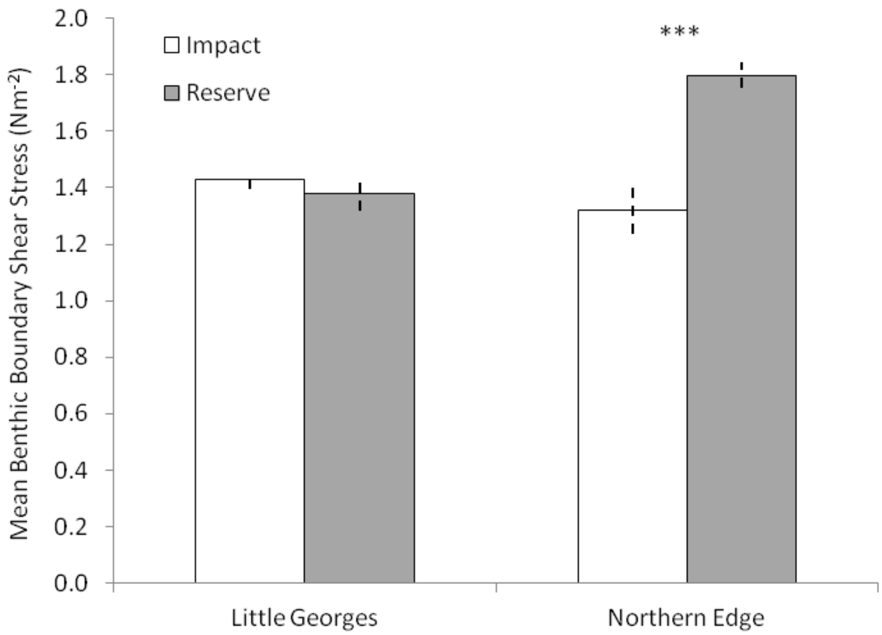


Figure 16. Mean benthic boundary shear stress (N m^{-2}) in the *Impact* and *Reserve* areas of the Little Georges and Northern Edge study sites. Dashed lines indicate 95% confidence intervals and asterisks indicate where shear stress differed (* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

3.2.5. Water Depth

The water depths in the Little Georges *Reserve* area ranged from 43.9 to 60.4 m and the *Impact* area ranged from 27.4 to 98.8 m. The difference in the median depths (3.6 m) was not statistically significant (T = 3847.5, $p = 0.255$). The depths in the Northern Edge *Reserve* area ranged from 36.6 to 51.2 m and the *Impact* area ranged from 45.7 to 60.4 m. The difference in the median depths (1.8 m) was not statistically significant (T = 3416.5, $p = 0.312$).

3.3. Comparing Geological and Biological Features in Impact and Reserve Areas

3.3.1 Density

Densities of sea stars and whelks were higher in the *Impact* than in the *Reserve* area at the Northern Edge site, moon snail density was higher in the *Reserve* area, and there were no differences in scallop, hermit crab or crab densities (Figure 17). In the Little Georges study site, sea star density was much higher in the *Reserve* area, crab density was higher in the *Impact* area and there were no differences in scallop, hermit crab, whelk or moon snail densities (Figure 18).

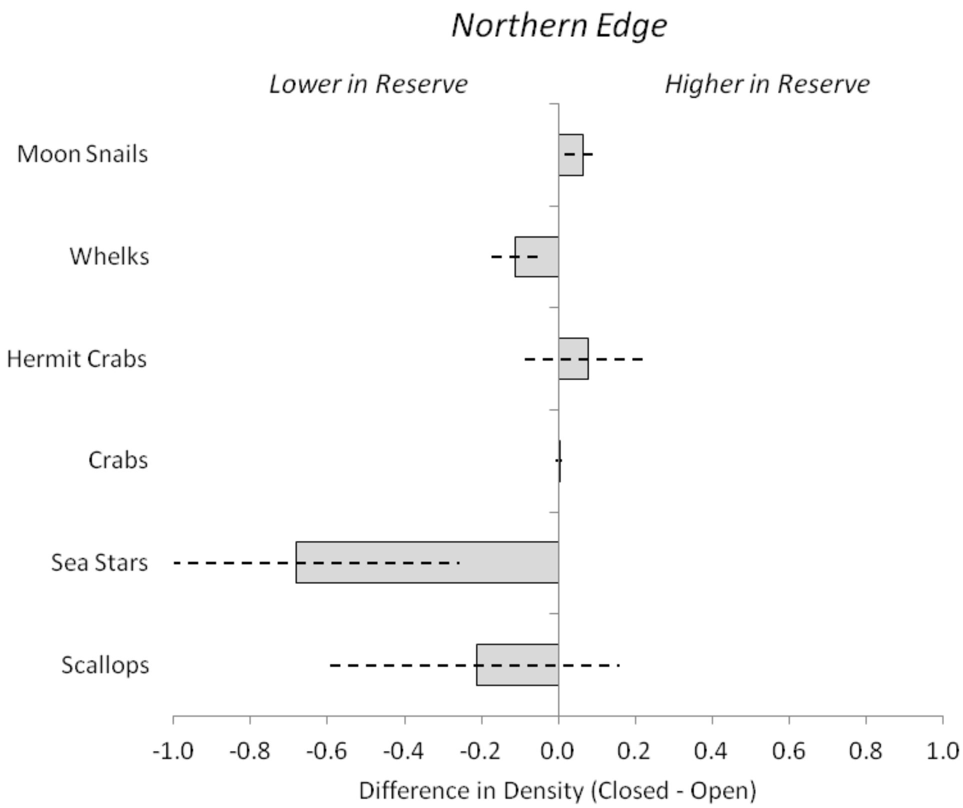


Figure 17. Plot of the differences in scallops, sea stars, hermit crabs, whelk, and moon snail density in *Reserve* versus *Impact* areas in the Northern Edge study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite.

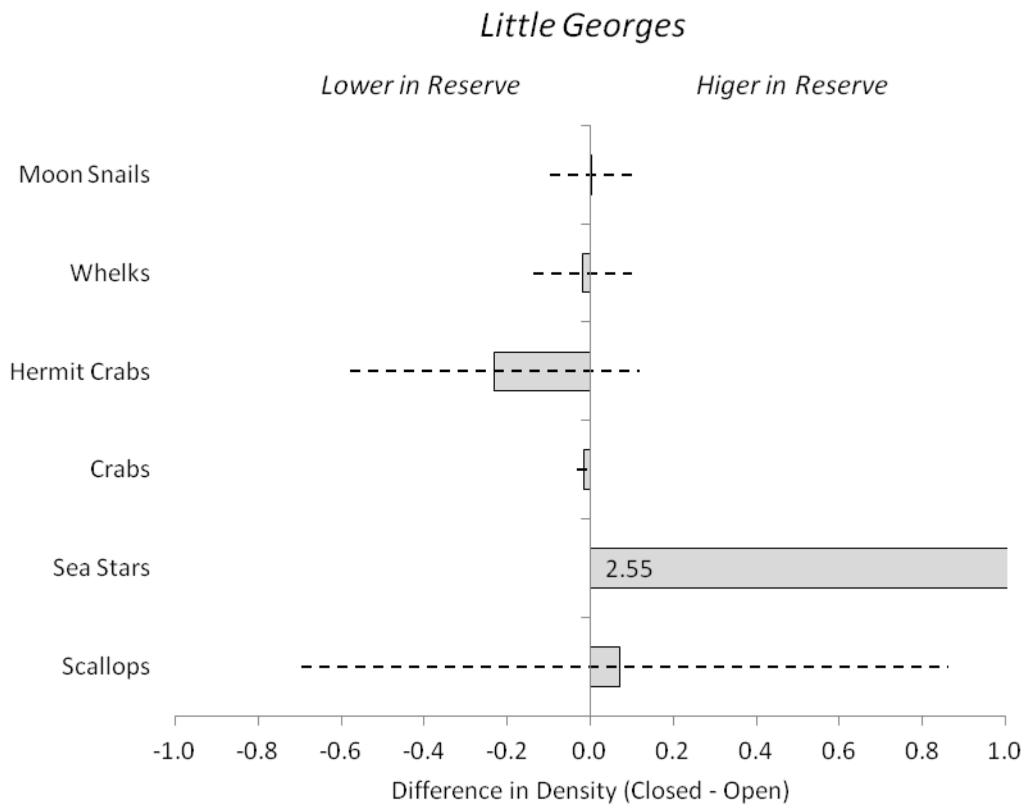


Figure 18. Plot of the differences in scallops, sea stars, hermit crabs, whelk, and moon snail density in *Reserve* versus *Impact* areas in the Little Georges study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite.

Of the 12 taxa density tests conducted, 2 indicated positive reserve effects, 3 negative effects and 7 indicated no difference in taxa density between *Impact* and *Reserve* areas (Table 6). The only agreement in density reserve effect results were that at both Little Georges and the Northern Edge sites, there were no differences in scallop or hermit crab density in *Impact* and *Reserve* areas.

Table 6. Taxa density "reserve effects" summary table for the Little Georges (LG) and Northern Edge (NE) study sites. The symbols "+" mean higher density in the reserve, "-" mean lower density in the reserve, and "≈" mean no difference.

	Reserve Effect	
Taxa	*LG*	*NE*
Moon Snails	≈	+
Whelks	≈	-
Hermit Crabs	≈	≈
Crabs	-	≈
Sea Stars	+	-
Scallops	≈	≈

3.3.2. Presence - Absence

Positive reserve effects were expected for all the biological structures except shell debris. However, the probability of structure forming taxa occurring in the Northern Edge *Reserve* area was lower or not different from occurring in the *Impact* area for all taxa except urchins and mussels (Figure 19). At the Little Georges study site infauna (holes), juvenile scallops, bryozoans, and stalk tunicate had higher probability of occurring in the *Reserve* area (Figure 20). Only *Ampilisca* tubes had a higher probability of occurring in the *Impact* area. There were no differences for all other taxa.

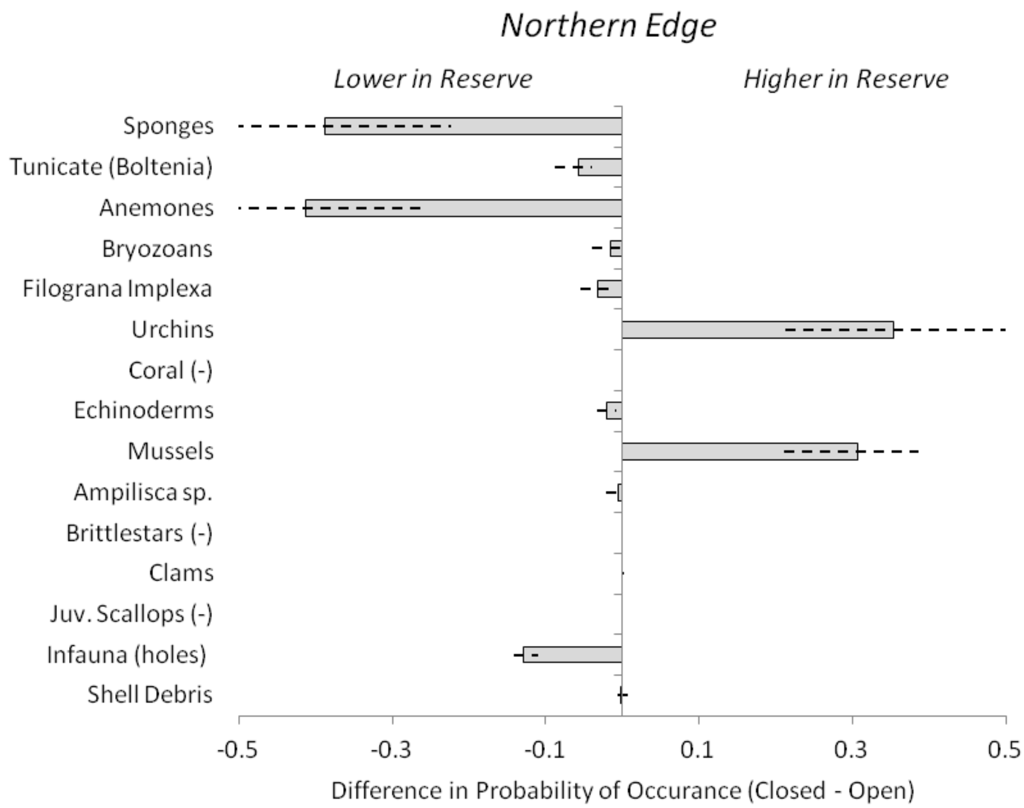


Figure 19. Plot showing the differences in probability of structure forming taxa occurring in *Reserve* versus *Impact* areas in the Northern Edge study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

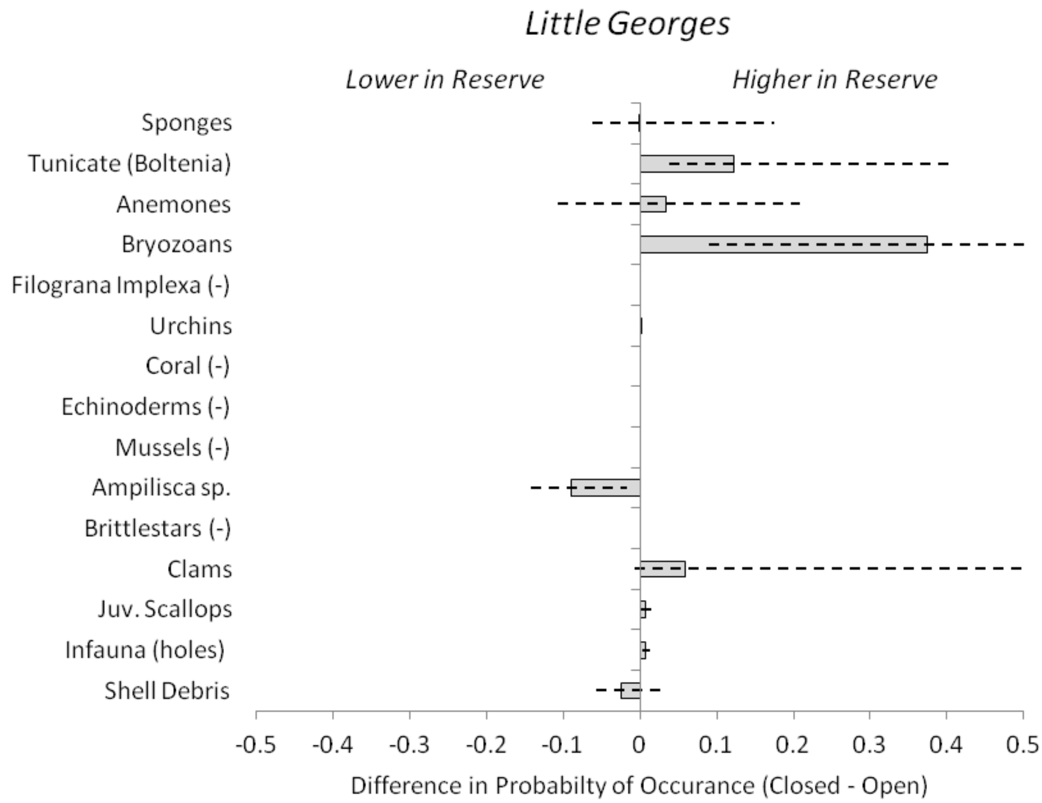


Figure 20. Plot of the differences in probability of structure forming taxa occurring in *Reserve* versus *Impact* areas in the Little Georges study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

Of the 21 biological structure presence-absence tests conducted, 6 indicated positive reserve effects, 9 negative effects and 6 indicated no difference between *Impact* and *Reserve* areas (Table 7). The only agreement in presence-absence reserve effect results were that at both Little Georges and the Northern Edge sites, the probability of Ampelisca tube occurrence was higher in the *Impact* areas and that there was no difference in the probability of shell debris occurrence in *Impact* and *Reserve* areas.

Table 7. Presence-absence "reserve effects" summary table for biological structures in the Little Georges (LG) and Northern Edge (NE) study sites. The symbols "+" mean more structure in the reserve, "-" mean less in the reserve, "≈" mean no difference, and "?" mean there were insufficient data to model the reserve effect.

	Reserve Effect	
Biological Structure	*LG*	*NE*
Shell Debris	≈	≈
Infauna (holes)	+	-
Juv. Scallops	+	?
Clams	≈	?
Brittlestars	?	?
Ampelisca tubes	-	-
Mussels	?	+
Echinoderms	?	-
Coral	?	?
Urchins	≈	+
Filograna Implexa	?	-
Bryozoans	+	-
Anemones	≈	-
Tunicate (Boltenia)	+	-
Sponges	≈	-

3.3.2.1. Geological Structures

Positive reserve effects were expected for gravel pavement and negative effects expected for scattered gravel. Both expectations were met in the Northern Edge site (Figure 21), but the results were reversed at the Little Georges study site (Figure 22).

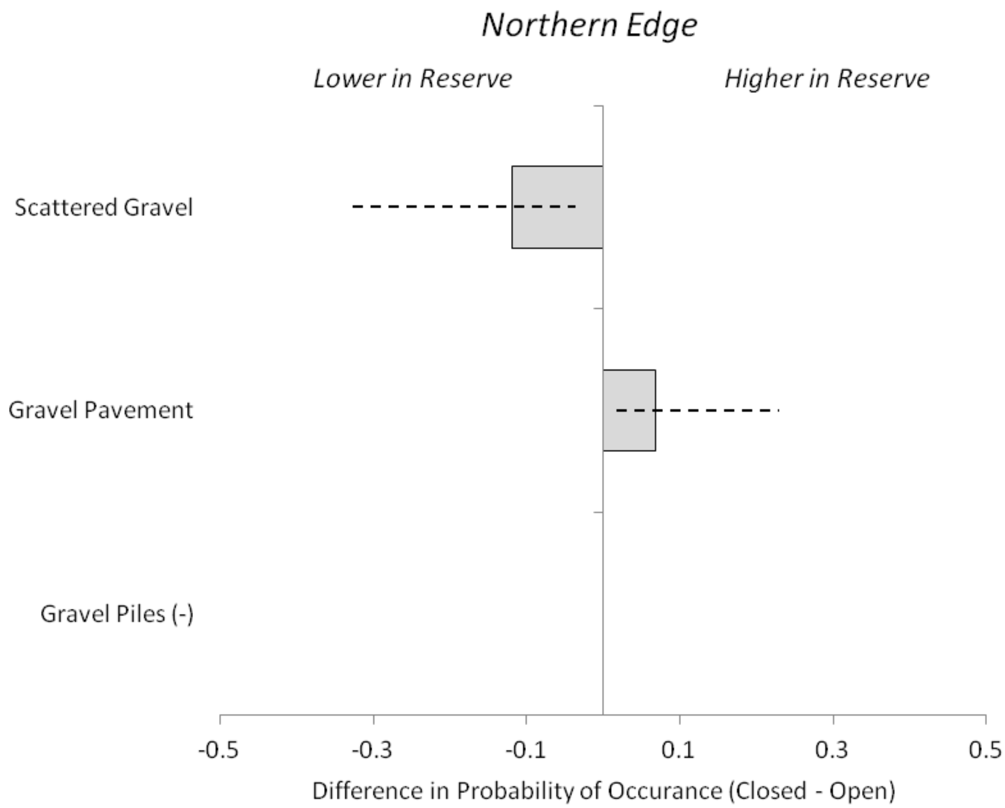


Figure 21. Plot of the differences in probability of geological structure types occurring in *Reserve* versus *Impact* areas in the Northern Edge study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Geological Structure ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

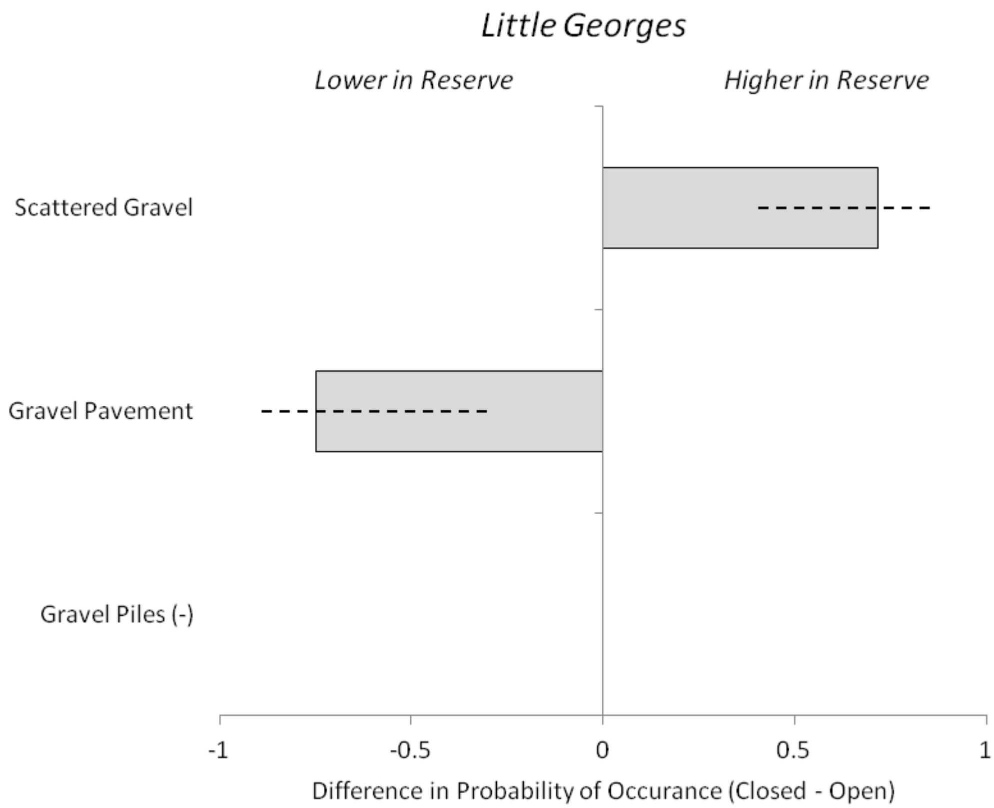


Figure 22. Plot of the differences in probability of geological structure types occurring in *Reserve* versus *Impact* areas in the Little Georges study site. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Geological Structure ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

Of the 4 geological structures presence-absence tests conducted, 2 indicated positive reserve effects and 2 negative, but there was no agreement in effects between the Little Georges and the Northern Edge study sites (Table 8).

Table 8. Presence - absence "reserve effects" summary table for geological structures in the Little Georges (LG) and Northern Edge (NE) study sites. The symbols "+" mean more structure in the reserve, "-" mean less in the reserve, and "?" mean there were insufficient data to model the reserve effect.

	Reserve Effect	
Geological Structure	*LG*	*NE*
Gravel Piles	?	?
Gravel Pavement	-	+
Scattered Gravel	+	-

3.3.3. Percent Coverage

Positive reserve effects were expected for all taxa except scallops. Macroalgae and mussels covered more area in the *Reserve* compared to the *Impact* areas, sponges, bryozoans, actinarian anemones and scallops all covered more area in the *Impact* area, and there were no differences in percent cover for all other taxa at the Northern Edge site (Figure 23). At the Little Georges site sponges, hydroids, bryozoans, cerianthid anemones, macroalgae, and polychaetes *(F. implexa*) all showed positive effects, and there were not differences in cover of the other taxa (Figure 24).

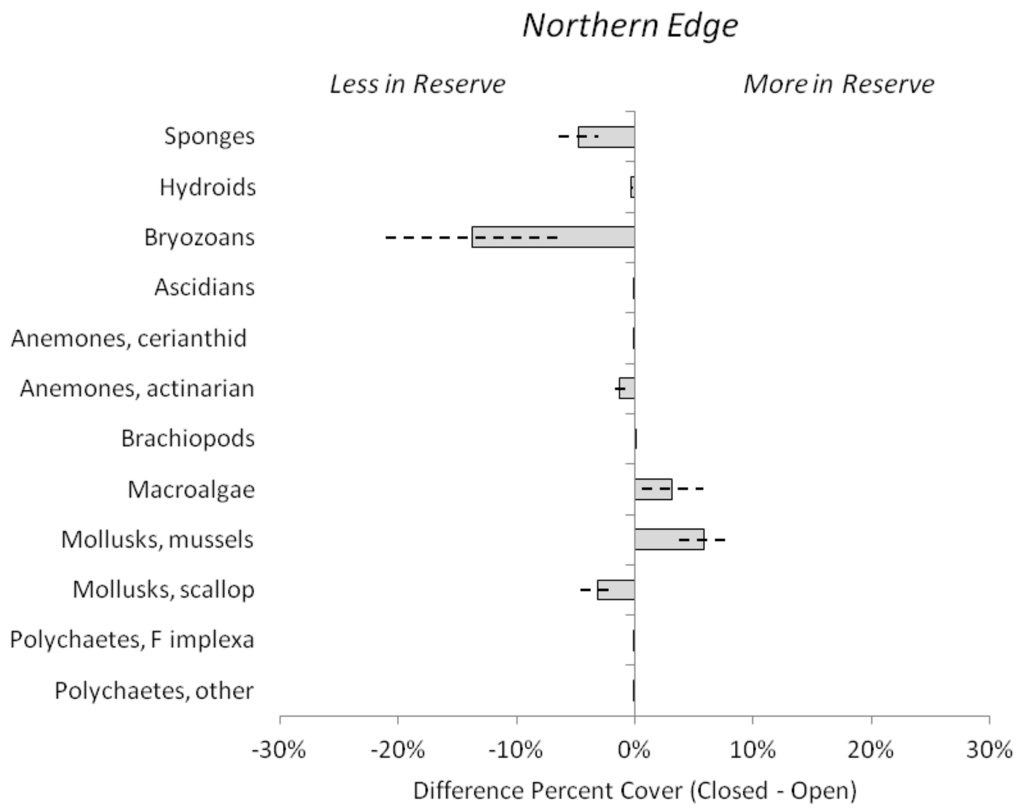


Figure 23. Plot of the differences in percent cover of structure forming taxa (in 1.04m^2 quadrats) in the Northern Edge *Impact* and *Reserve* areas. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

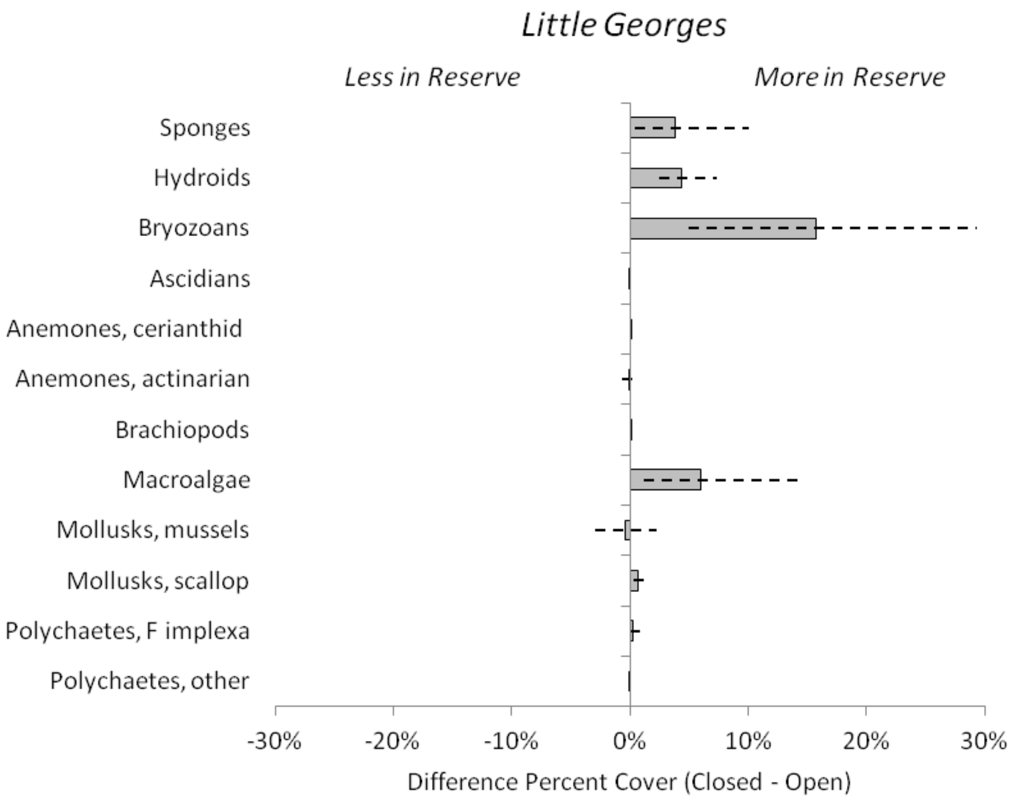


Figure 24. Plot demonstrating the differences in percent cover of structure forming taxa (in $1.04m^2$ quadrats) in the Northern Edge *Impact* and *Reserve* areas. Estimates are the posterior median difference (*Reserve* area – *Impact* area); dashed lines present 95% posterior credibility intervals. Results for each taxa represent separate GLMM regressions of the form Taxon ~ Reserve * Study Area + 1|Station (R pseudo code, see Hadfield 2010). Positive values indicate more structure in the *Reserve* area and negative values indicate the opposite. The symbol (-) indicates cases where the model was not run due to lack of detections.

Twenty four tests of percent cover were run and 8 indicated positive reserve effects, 6 negative effects and 10 no effect (Table 9). The only agreement in percent cover reserve effect results were that at both Little Georges and the Northern Edge sites macroalgae percent cover was higher in *Reserve* areas and that there were not differences in the percent cover of ascidians, brachiopods, polychaetes (other) in *Impact* and *Reserve* areas.

Table 9. Percent cover "Reserve Effects" summary table for the Little Georges (LG) and Northern Edge (NE) study sites. The symbols "+" mean more cover in the reserve, "-" mean less in the reserve, and "≈" mean no difference.

	Reserve Effect	
Biological Structure	*LG*	*NE*
Sponges	+	-
Hydroids	+	-
Bryozoans	+	-
Ascidians	≈	≈
Anemones, cerianthid	+	-
Anemones, actinarian	≈	-
Brachiopods	≈	≈
Macroalgae	+	+
Mollusks, mussels	≈	+
Mollusks, scallop	≈	-
Polychaetes, F implexa	+	≈
Polychaetes, other	≈	≈

3.3.4. Vertical Height

A total of 640 organisms (including: Anemones, Fig sponges, Finger sponges, Hydrozoans, Nipple sponges, Palmate sponges, and Tunicates) were measured at randomly selected quadrats in the *Impact* and *Reserve* areas of the Little Georges and Northern Edge study sites. Organisms were primarily found attached to gravel and sand substrates (Figure 25). Exceptions include Hydrozoa and Fig sponge which were attached to shell, sand and gravel, and Palmate sponge and Fig sponge which were observed unattached.

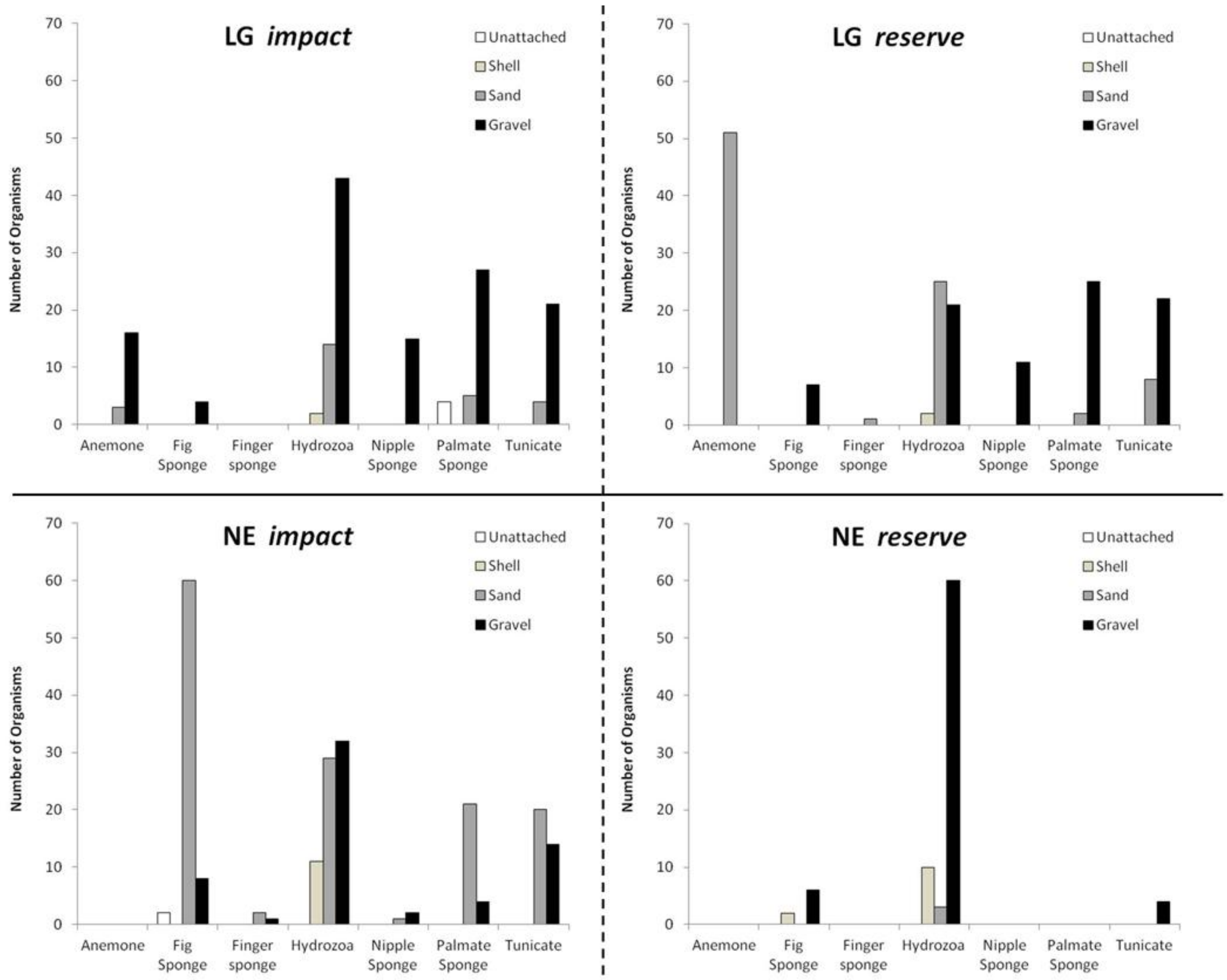
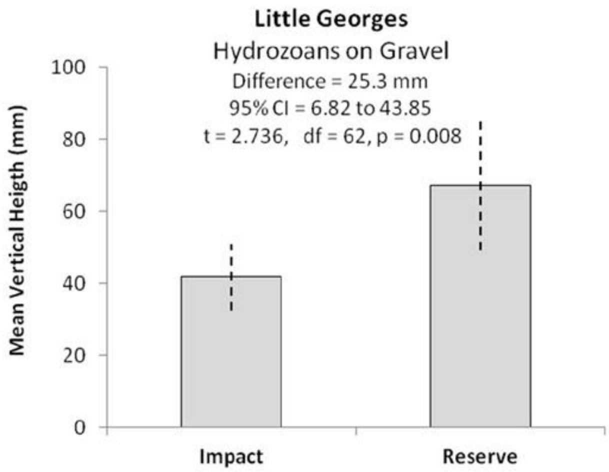


Figure 25. Substrate attachment types for the organism measured during examinations of feature vertical heights in sample quadrats. Upper panels show Little Georges (LG) *Impact* and *Reserve* areas and lower panels show Northern Edge (NE).

Only hydrozoans attached to gravel were measured in *Reserve* and *Impact* areas at both the Little Georges and Northern Edge study sites. At the Little Georges site the hydrozoans in the *Reserve* area were taller and at the Northern Edge site they were taller in the *Impact* area (Figure 26). Hydrozoans attached to sand and to shell, stalk tunicates attached to gravel, and nipple sponges attached to gravel were measured in *Reserve* and *Impact* areas at Little Georges; none were different (Figures 27-30). Palmate sponges attached to gravel were taller in the Reserve area at the Little Georges site (Figure 30).



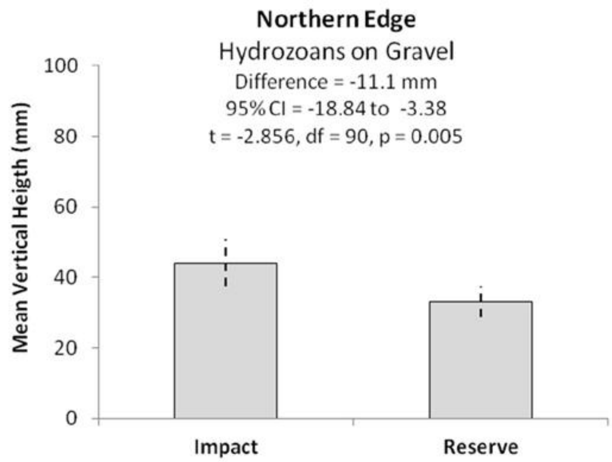


Figure 26. Comparison of mean vertical height (mm) of Hydrozoans attached to gravel substrate in the impact and reserve areas of Little Georges (left) and the Northern Edge (right) study sites.

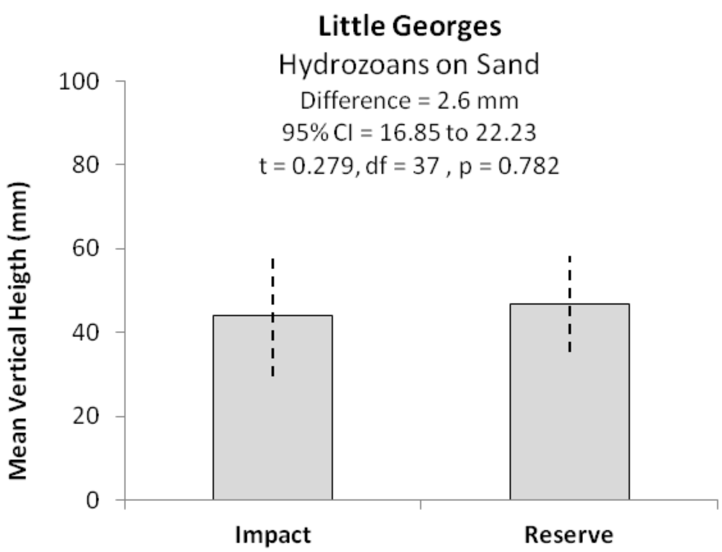


Figure 27. Comparison of mean vertical height (mm) of Hydrozoans attached to sand substrate in the impact and reserve areas of the Little Georges study site.

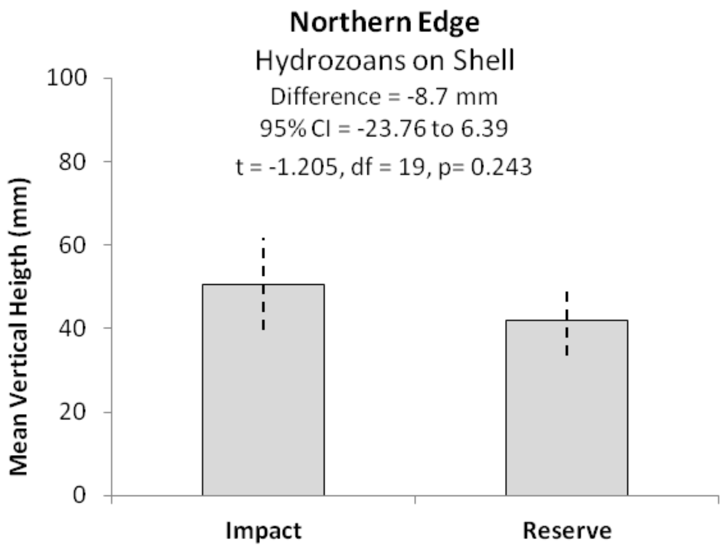


Figure 28. Comparison of mean vertical height (mm) of Hydrozoans attached to shell substrate in the impact and reserve areas of the Northern Edge study site.

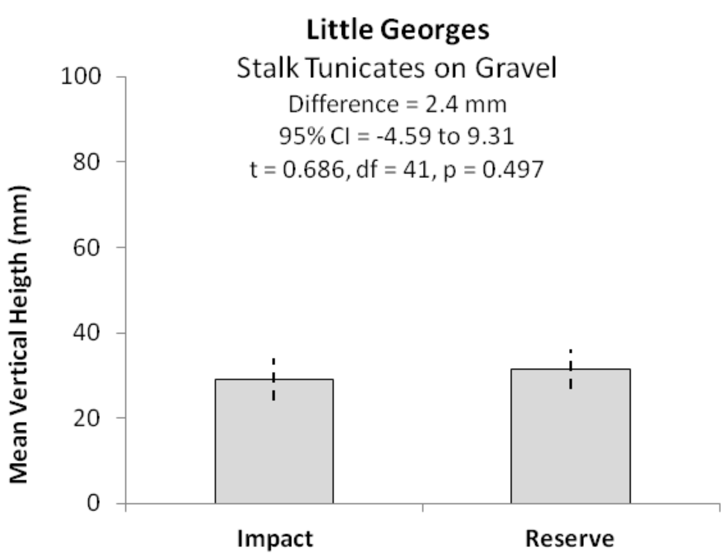


Figure 29. Comparison of mean vertical height (mm) of Stalk Tunicates attached to gravel substrate in the impact and reserve areas of the Little Georges study site.

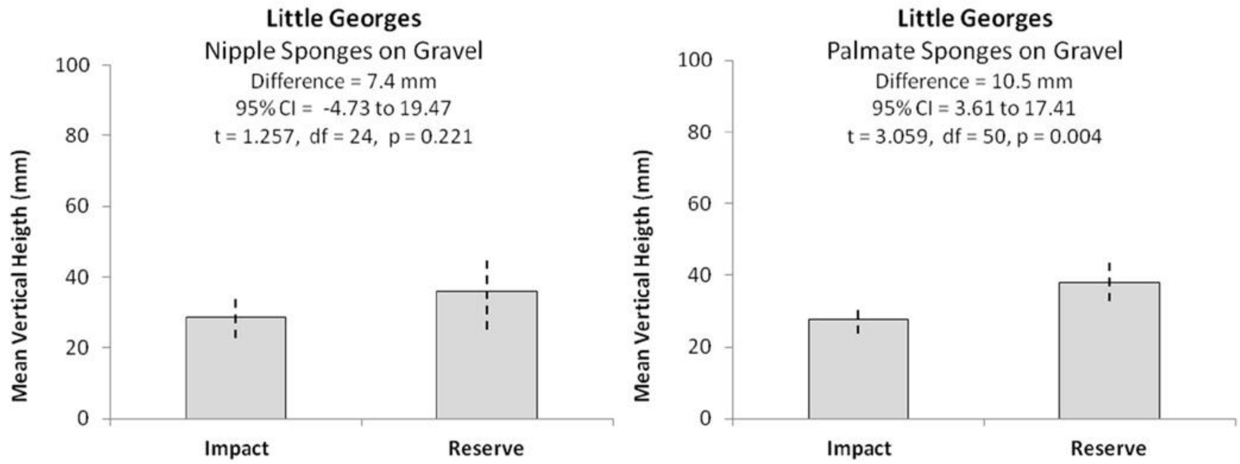


Figure 30. Comparison of mean vertical height (mm) of Nipple Sponges (left) and Palmate Sponges (right) attached to gravel substrate in the impact and reserve areas of the Little Georges study site.

Of the 7 vertical height tests run, 2 showed positive reserve effects, 1 negative effect and 4 showed no differences (Table 10).

Table 10. Vertical height "Reserve Effects" summary table for the Little Georges (LG) and Northern Edge (NE) study sites. Organisms are listed with attachment substrate. The symbols "+" mean more cover in the reserve, "-" mean less in the reserve, "≈" mean no difference, and "na" mean the taxa-substrate combination was not detected.

	Reserve Effect	
Biological Structure	*LG*	*NE*
Hydrozoa - gravel	+	-
Hydrozoa - sand	≈	na
Hydrozoa - shell	na	≈
Nipple sponge - gravel	≈	na
Palmate sponge - gravel	+	na
Stalk Tunicate - gravel	≈	na

3.4. Community Structure

The biological and geological communities were predicted to be dissimilar in the *Impact* and *Reserve* areas with higher richness, diversity and evenness in *Reserve* areas. However, the communities had similar richness, diversity, evenness and dissimilarity indices (Tables 11 - 14). Of the 13 biological taxa assessed all were detected in both the *Impact* and *Reserve* areas at the Little Georges site and 10 were detected in both the *Impact* and *Reserve* at the Northern Edge site (Table 11). Therefore, Richness (*S*) was equal in the Little George's areas and 2 more taxa (Actinarian Anemones and Other polychaetes) were detected at the *Impact* area at the Northern Edge site.

Table 11. Biological structures detected (+) or undetected (-) in the Impact and Reserve areas of the Little Georges (LG) and Northern Edge (NE) study sites. Total counts of detections in each area are equal to Taxa Richness.

	LG		NE	
Biological Structures	**Reserve**	**Impact**	**Reserve**	**Impact**
Anemones, actinarian	+	+	-	+
Anemones, cerianthid	+	+	+	+
Ascidians	+	+	+	+
Brachiopods	+	+	+	+
Bryozoans	+	+	+	+
Coral	+	+	-	-
Hydroids	+	+	+	+
Macroalgae	+	+	+	+
Mollusks, mussels	+	+	+	+
Mollusks, scallop	+	+	+	+
Polychaetes, F implexa	+	+	+	+
Polychaetes, other	+	+	-	+
Sponges	+	+	+	+
Richness (*S*)	**13**	**13**	**10**	**12**

Three of five geological structures assessed were detected in both the *Impact* and *Reserve* areas at both sites and richness was similar in the *Impact* and *Reserve* areas at both sites: 1 more structure type was detected in the *Reserve* area at Little Georges and an equal number in the areas at the Northern Edge site (Table 12). Shell deposits were detected only in *Reserve* areas at both sites.

Table 12. Geological structures detected (+) or undetected (-) in the Impact and Reserve areas of the Little Georges (LG) and Northern Edge (NE) study sites. Total counts of detections in each area are equal to Richness.

	LG		NE	
Geological Structures	**Reserve**	**Impact**	**Reserve**	**Impact**
Scattered Gravel	+	+	+	+
Gravel Pavement	+	+	+	+
Gravel Piles	-	-	-	+
Shell Debris	+	+	+	+
Shell Deposit	+	-	+	-
Richness (*S*)	**4**	**3**	**4**	**4**

Table 13. Biological Structure community Diversity, Evenness and Dissimilarity indices comparing the Reserve and Impact areas of LG and NE study sites.

	LG		NE	
Community Indices	*Reserve*	*Impact*	*Reserve*	*Impact*
Shannon Diversity (H')	2.02	1.77	1.65	1.95
Pielou's Evenness (J')	0.79	0.69	0.64	0.76
Bray-Curtis Dissimilarity (D)	0.25		0.32	

Table 14. Geological Structure community Diversity, Evenness and Dissimilarity Indices in the Reserve and Impact areas of LG and NE study sites.

	LG		NE	
Community Indices	*Reserve*	*Impact*	*Reserve*	*Impact*
Shannon Diversity (H')	0.89	0.66	0.75	0.89
Pielou's Evenness (J')	0.55	0.41	0.47	0.55
Bray-Curtis Dissimilarity (D)	0.15		0.64	

4. Discussion

Bottom-tending fishing gear, otter trawls and scallop dredges in particular, are expected to damage and/ or remove vertical biological and geological seabed structures at high rates (see Grabowski et al. 2014). We examined the differences in taxa density, the presence- absence of biological and geological structures, the percent area covered by the structures and the vertical heights of structure-forming taxa at two study sites on Georges Bank with adjacent fished (*Impact*) and 17-year old closure (*Reserve*) areas. Using a battery of tests on physical and biological characteristics, we established that *Impact* and *Reserve* areas within the study site were appropriately similar replicates which differed in the amount of trawl and dredge fishing effort they had endured over the past 17 years (i.e. study site "treatments"). Based on the high levels of ongoing and observed past trawl and dredge fishing in the *Impact* areas, we expected to find clear and profound evidence of damage compared to the *Reserve* areas with mobile fishing gear prohibitions. In contrast, we found no clear pattern in density, presence-absence, areal coverage or vertical height of biological or geological features between *Impact* and *Reserve* areas within the two study sites. Overall 68 tests were expected to show positive reserve effects, 16 had insufficient data for modeling and of the remaining 52, 33% were positive, 31% were negative and 37% showed no reserve effects (Figure 31). Twenty eight tests were expected to show negative reserve effects, 18% were positive, 32% were negative and 50% showed no reserve effect (Figure 32).

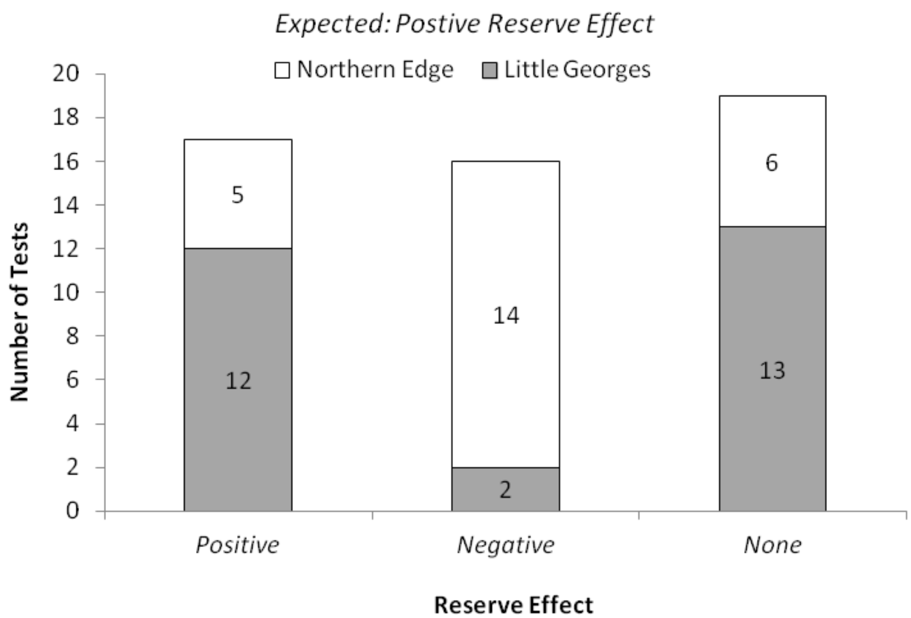


Figure 31. The number of tests indicating significant (positive or negative) and non-significant (none) reserve effects for the Little Georges and Northern Edge study sites. All were expected to show positive effects.

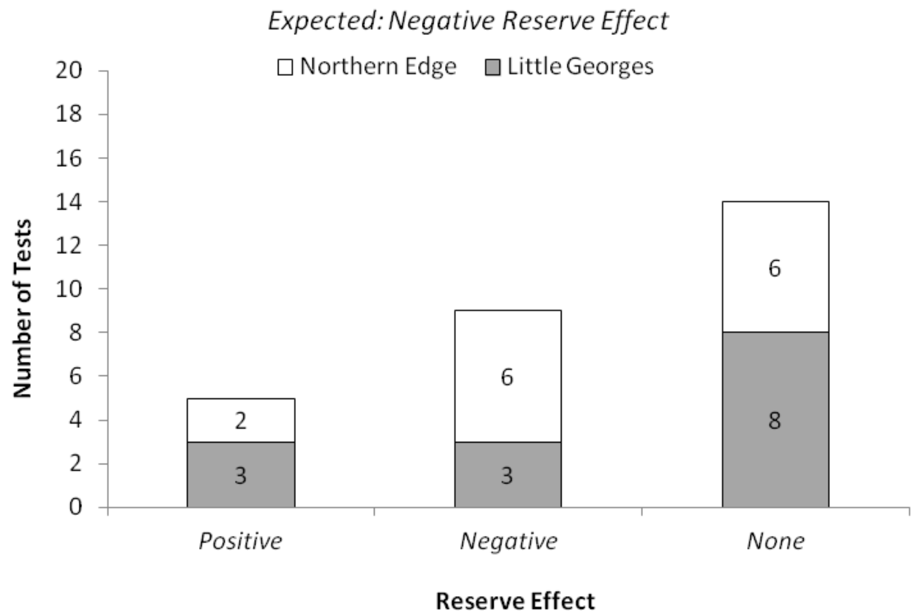


Figure 32. The number of tests indicating significant (positive or negative) and non-significant (none) reserve effects for the Little Georges and Northern Edge study sites. All were expected to show negative effects.

Results varied by study site, test type and feature. For example, we found that Bryozoans were more likely to occur and covered more area in the Little Georges *Reserve* area, but the opposite pattern occurred in Northern Edge; Gravel pavements were more likely to occur in the Northern Edge *Reserve* areas but were less likely in the Little Georges *Reserve.* The reserve effects were inconsistent across study sites and were manifest in a broad range of biological and geological features. The use of replicate study areas at two sites and an array of measures (density, presence-absence, cover, vertical height) provided substantial insight into the localized nature of fishing impacts. For example, data analysis would have led to different conclusions about the effect of fishing on benthic structures had we focused on only a single study site or feature type. Evidence from Little Georges suggests that Closed Area I largely had no effect (51%) or a positive effect (37%) on features. In contrast, the Northern Edge tests indicate that Closed Area II typically had a negative effect on biological and geological structures (51%), with the remainder of structures exhibiting no effect (31%) or a positive effect (18%).

Based on a review of 97 published studies, Grabowski et al. (2014) identified 6 biological or geological features found in high-energy gravel habitats that were expected to experience more than 25% removal per trawl or dredge tow and require more than 2 years for recovery (Table 15). Of these, no piled gravel was detected in either study site and only mussels showed a positive reserve effect (in the Northern Edge site). All other structures showed no effect or were either more likely to occur or covered more area in the *Impact* areas.

Table 15. Table indicating the susceptibility (% of structure removed) and recovery times (years) for six features expected to show strong positive reserve effects. Test results for the Little Georges (LG) and Northern Edge (NE) study sites are shown with symbols where "+" means significantly more in the reserve, "-" means significantly less in the reserve, "≈" means no difference, and "na" means the feature was not detected.

	Susceptibility	**Recovery**	**Reserve Effect**	
Feature	*% of structure removed per tow*	*years*	*LG*	*NE*
Piled Gravel	> 50	> 5	na	na
Actinarian Anemones	25 - 50	2 – 5	≈	-
Brachiopods	25 - 50	2 – 5	≈	≈
Mussels	25 - 50	> 5	na	+
Filograna implexa	25 - 50	2 – 5	na	-
Sponges	25 - 50	2 – 5	≈	-

Prior to 1994, both the *Impact* and *Reserve* areas had experienced a long term historical regime of intensive fishing. It is possible that the recovery period since the 1994 closures was too short to initiate substantial benthic community recovery. However, a recent review by Grabowski et al. (2014) indicates that 17 years is ample time for a wide range of benthic taxa to recruit and reach mature sizes, as well as time for some geological features to recover. The failure of geological features such as gravel piles to recover, which they found to be an important determinant of why coarse substrates are more vulnerable to mobile fishing gear, could explain the mixed results observed here on reserve effects. Collie et al. (2005) found fishing effects on gravel habitats near our Northern Edge study sites, and they speculated that 10 years may be required for community recovery. For both study sites, the reserve effect was significant for 49-69% of the metrics quantified, albeit with effects in both positive and negative directions, suggesting that the *Reserve* and *Impact* areas are substantially different. These differences could stem from inherent differences in the sites independent of reserve status. We found interaction between *Reserve* and sheer stress, with higher sheer stress observed at the Northern Edge where reserve effects were more commonly found to be negative. For many sessile erect species, increased sheer stress likely has a negative effect on their ability to recruit, survive, and grow tall in these environments.

This research suggests that the question regarding the relative importance of the drivers behind the observed distribution of biological and geological features which may provide essential habitat for managed fish species remains open. These drivers include natural physical disturbance regimes (e.g. currents and storms), recruitment delivery and settlement dynamics, trophic interactions, and mobile fishing gear contact. Generally, disturbances due to fishing are considered the primary driver of these distributions, but our findings suggest that in high energy regimes, natural disturbance and other ecological processes may be equally or more important. It is plausible that the distribution of biological and geological features in our study areas are more influenced by powerful tidal currents and frequent winter storm events (Harris et al. 2012), and frequent strong recruitment events (*sensu* Tian et al. 2009a and b) than by sustained and intensive fishing.

We intend to publish the findings reported here in the peer-reviewed literature and to further investigate the role of these drivers in future studies.

5. Acknowledgements

We would like to thank the captains and crews of the F/V Diligence and F/V Westport for their help during the field surveys. The research team at the University of Massachusetts Dartmouth – Department of Fisheries Oceanography did the field work and video/ image analyses. M. Naschak and A. Milano at the Fisheries, Aquatic Science & Technology (FAST) Lab at Alaska Pacific University did the percent cover and vertical height measurements. S. Sethi (FAST Lab) was essential to the development and implementation of the GLMMs and provided critical review of this report.

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