Impact of Disturbance on Habitat Recovery in Habitat Management Areas on the Northern Edge of Georges Bank: Ecosystem Perturbation Experiment

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Summary

- A BACI whole ecosystem experiment was started in 2016 in Closed Area II, HAPC for the purpose of examining what level of impact from scallop dredges would cause irreparable damage in an area that is considered essential fish habitat for Gadids and other commercially important species.
- The Closed Area II HAPC has been closed to bottom tending gear since 1994 after being fished intensively for many years.
- In the HAPC, six sites representing two distinct habitats (epifauna/mussels'shell hash and sand/gravel/shell hash) were chosen and surveyed twice before and four times after impact by scraping with a commercial scallop dredge to base sediment.
- A Before After, Control Impact (BACI) experiment was designed and analyzed using a 3-way ANOVA to inspect a mixed effect model of fixed and random effects.
- Percentage change in either numerical abundance or percent cover two years and then six years (actual 68 months) after impact was examined using multi-way ANOVA with p value of 0.05.
- Percentage cover of Epifauna in Site 1 and sand/shell hash in Site 6 showed no significant difference from the control after six years, while Epifauna in Site 3 significantly increased beyond the control.
- Both Biodiversity and Species Richness decreased following impact and recovered to +4% of control after six years.
- Epifauna (sponge, mussels, bryozoa, hydrozoa, anemone, stalked tunicate) and infauna (Myxicola) in Sites 1 and 3 significantly decreased on impact but recovered to within +27 to +45% of control after six years of recovery.
- Indicator species Lacy Tube Worm remained -18% of control in complex habitat sites after six years but this was not statistically significant ($p = 0.2711$)

Conclusions

- Habitat recovery following two years after impact showed significant high order effects (Habitat X Control X Impact) in five out of 10 faunal classes indicating that the impact made by scallop dredging is strongly influenced by habitat with complex epifaunal habitat being significantly more susceptible to mechanical impact than sand/gravel habitats
- However, following six years of recovery no difference was detected between control and impacted areas (except for Monkfish)
- There was strong suggestion that some fish species (e.g., Monkfish) increased in all areas by more than 80% of control immediately following impact and remained elevated for six years
- It is clear that two years is not sufficient for complex habitat to recover to 100% of control, however by six years of recovery all impacted areas returned to or exceeded the control with no significant difference between control and impact
- It may be possible to target specific low complexity homogenous habitats for opening a limited fishery where scallop abundance is high while maintaining no-take zones in complex epifaunal habitat with a defined boundary of at least several 100 meters
- The impact of 9-10 dredge hauls (roughly equivalent to 9-10 trips by commercial scallopers) can be reversed over a period of at least six years

Forward
This overview of the BACI experiment in the CLAII HAPC is coordinated with a slide deck named RSA_HAPC_BACI_Exp_10-07-22-v3.pdf. The original slide deck released last year has been updated with data from the May 2022 survey by NOAA NEFSC and HabCam V4. Also, the original slide deck had an error concerning numbers of organisms removed during the impact component of the study. This has been corrected from $\#/km^2$ to just numbers of individuals removed.

Background

Georges Bank Closed Areas I and II, and Nantucket Lightship Closed Area were closed in December 1994 to fishing for groundfish in order to help rebuild these stocks. After these closures, scallop biomass rapidly increased (Murawski et al. 2000, Hart and Rago 2006), but the effects on groundfish were mixed. For example, yellowtail flounder and haddock increased within the closures, but cod did not (Murawski et al. 2005). Portions of each of the three closures have been reopened to scallop fishing for short periods (typically June 15 through January 31 of the following year), with quotas set both for scallop and yellowtail flounder catch. Some short term fishing for groundfish has also been allowed in these areas, most prominently, the special access program (SAP) for yellowtail flounder in 2004. A detailed historical review of each RCA may be found on the NEFC website, however, in this discussion we are only concerned with CLAII and the HAPC. The intent is to apply the information obtained from this area to others representing different habitats. These RCAs provide a wide range of habitats and temporal sequencing of closures and provide a "natural" experiment in disturbance of benthic community structure by bottom fishing.

Impact of bottom fishing on community structure. Many studies have documented a variety of impacts on benthic community structure resulting from bottom fishing (e.g., Aronson 1990; Messieh et al 1991; Jones 1992; Whitman and Sebens 1992; Thrush et al 1995; Dayton et al 1995; Auster and Langton 1999; Kaiser et al. 2002; Collie et al. 2000; Ragnarsson and Lindegarth 2009). In particular, Ragnarsson and Lindegarth (2009) succeeded in providing unequivocal projections of ecosystem recovery trajectories based on quantitative analysis of large scale responses of habitats to fishing disturbance. Studies designed to test the effects of different fishing gear on benthic communities often provide inconsistent results due to the wide variety of methods used in fishing, lack of replication and control sites, and a large variation of site-specific substrate and hydrographic conditions. The success of the Ragnarsson and Lindegarth (2009) study is due to, we believe, attention to statistically sound time series measurements and experimental design. The authors manipulated four sites and maintained four sites as controls. Benthic surveys were conducted immediately following dredging of areas previously closed to fishing and two and seven months later. A total of 160 taxa were observed in grab samples of the areas which were dominated by polychaetes and bivalves. No significant differences were detected in taxa abundance or multivariate structure after seven months, but strong effects of dredging were evident in diversity and species richness. There is consensus in the literature that in order to quantify the direct effect of disturbance on benthic community structure an experimental approach must be used which compares impacted against unimpacted areas (Van Dolah et al. 1987; Riemann and Hoffman 1991) using Before-After-Control Interaction (BACI) experimental models. There are examples of successful plot disturbance studies in the terrestrial world (Plotkin et al 2013; Carlton and Bazzaz 1998). For example, an experimental site in the Harvard Forest was subjected to a simulated hurricane in a disturbance/resilience study (Plotkin et al 2013). Translating this disturbance methodology to the oceanic environment would yield a better understanding of ecosystem resilience.

At their June 2015 meeting, the New England Fisheries Management Council (Council) approved two Habitat Management Areas (HMAs), both located on the northern edge of Georges Bank within the confines of Closed Area II HAPC (slide 2). Our overall goal of this project is to provide the Council with information on what temporal scales that scallop fishing could be allowed on a limited basis in the HMAs that would minimize impact to habitat and avoid disturbance to ground fish nursery and spawning areas. In order to accomplish this goal, we need to understand ecosystem resiliency, impact of scalloping at specific temporal and spatial scales on habitat, and to survey the location and boundaries of high density scallops and their habitat in the HMAs.

Goals and Objectives

Our overall goal of this project was to provide Council with information on what temporal and spatial scales scallop fishing could be allowed that would minimize impact to habitat. In order to accomplish this goal, we needed to understand ecosystem resiliency, impact of scalloping at specific temporal and spatial scales on habitat, and the location and boundaries of high density scallops and their habitat in the HMAs.

Our study had three objectives:

1. To determine the persistence of mechanical impacts of scallop dredging and long-term ecosystem resiliency as a function of substrate type (e.g., epifauna/shell hash, and sand/shall hash) measured by both acoustics and optics in the HMAs and surrounding regions where VIMs and NOAA have previously conducted survey tows,
2. To complete a series of high resolution Before-After Control-Impact (BACI) habitat characterizations in two habitat types (epifauna/sand/shell hash and sand/shell hash) to evaluate ecosystem and habitat resiliency. Metrics for Recovery Rate that relate Impact and Habitat Type over time allowed for a direct, statistical description of where and how often HMAs could be opened to target high density scallops with minimum impact on sensitive habitat. And
3. To complete high resolution surveys of scallop abundance in the CLA II HMAs to provide information to the Council as to where targeted scallop fishing might be allowed on a limited basis while concurrently mitigating impact on habitat.

We used both HabCamV4 (2016, 2022) and V5 (2016, 2017, 2018 with very high resolution (mm scale) stereo imagery and a sidescan unit (cm to 100m scale) for the fine scale BACI habitat studies and to collect fine scale distributional data on scallops in the entire Northern part of CLAII and surrounding regions. Sidescan data was not available for 2022.

Some of the important questions that needed to be addressed before the proposed Habitat Management Areas were enacted include the following: 1) What is the current fine scale (m) distribution of habitat types in the HAPC? 2) What would the impact be on the current communities (epifauna, scallops, groundfish) and habitat if regions of the HAPC were to have Partial Access? 3) How long do the mechanical impacts of scallop dredging persist as a function of substrate type (sand, sand/gravel, gravel/cobble) measured by both acoustics and optics? (e.g., slide 3), 4) How resilient are the different communities? (i.e., if allowed to rebound following episodes of dredging, how long would it take various communities to return to pre-impact condition)? 5) What is the distribution of the invasive tunicate species *Didemnum vexillum* in the HAPC (closed to ground fishing) and how would providing Partial Access impact that distribution?

Methods

Surveys.

HabCamV5 (slide 4) was used to conduct a high resolution grid survey of the HAPC at 0.5 nm spacing in the northern Northeast Reduced Impact Habitat Management Area (NERIA) and at a resolution of 1 nm in the southern part of NERIA, the Eastern Georges Shoals and Northeast Habitat Management Area (slide 5) in June 2012 and July 2016. This was followed by a third survey of the same area in October 2016, the initiation of the BACI impact experiment and a fourth survey of the impact sites. Fifth, sixth and seventh surveys were conducted in July 2017 June-July 2018, and in May 2022 by NOAA NEFSC for Sites 1,3 and 6 only (slide 6).

Following the second survey in July 2016, six sites were chosen in the HAPC that represented habitats of complex epifauna/mussels/shell hash and sand/gravel/shell hash (slides 6 and 7). A 1 nm strip was established in each site representing each of the habitat types. The impact part of the study was conducted in October 2016 using a commercial 15' New Bedford scallop dredge. Between 9 and 11 passes with the dredge were made in each 1 nm strip at a ship speed of 2 kts. Following each dredge pass, the contents were emptied onto the deck and analyzed by counting and sizing a subset of scallops and all finfish. Epifauna type, mussels and total scallops were estimated by the number of bushels collected of each type. The contents on the deck were then dumped downstream to the east at least 2 nm away from a particular study site.

Following each dredge pass, the HabCamV5 was deployed and an imaging pass was made to assess impact by the dredge. The sidescan imaging system clearly delineated the dredge tracks and allowed precise co-location of imaging and dredging. Each imaging pass was conducted to provide images within the dredged strip (impact) and outside the strip (control) by weaving in and out of the strip as the ship steamed forward (slide 8). Between 40,000 and 57,000 images were taken inside each strip and more than 180,000 images outside the strip as controls (slide 6). A 1 nm square buffer was established around each strip where initial survey data could also be used as control information (slides 8 and 9). The decrease in the number of bushels of scallops from each subsequent pass provided evidence of depletion.

In May 2022 the NEFSC conducted their annual scallop survey along the Northeast Continental Shelf. To get another time point for the BACI analysis, we requested their participation by surveying over as many sites as possible given their time constraints. Sites 1, 3 and 6 were prioritized and the R/V Hugh Sharp and V4 made two to three passes through each of the three sites. Large loops were made outside of the sites that allowed concurrent control information for the BACI (slides 10 and 11).

Substrate analysis.
In 2022 a different approach was developed for substrate composition. 1000 images from each Site 1,3 and 6 were used to train a Convolutional Neural Network by extracting regions of interest representing a particular substrate type (epifaina/sand/shell hash and sans/shall hash) (slide 12). Using this approach the two substrate types were labeled in each image at the pixel level providing highly accurate analytical approach to quantifying percentage coverage of each type.

BACI analysis.
For each survey that was conducted at an impact site, the following metrics were calculated for every image: bathymetry, rugosity, slope, gradient (from optics and acoustics where possible), epifauna (e.g., lacy tube worm, bryozoa, mussels, encrusting sponge, globular sponge, *Didemnum*, stalked tunicate, etc.), scallop abundance and size frequencies, and all of the potential fish targets provided in slides 13 and 14. Data on these variables within and between impact sites and within and between control sites provided data for a 3-way ANOVA analysis to examine the difference between impact sites and control sites relative to ecosystem recovery over time. This tested the null hypothesis that there are no differences between biological communities among controls and different times, before and after impacts (slide 15). Significance testing on selected individual abiotic and biotic variables was conducted using 1-way Analysis of Variance (ANOVA). Important elements of experimental design such as replication, randomization and blocking were integrated and incorporated in this repeated measures study.

Image Processing.
For surveys conducted before 2022, every 10th image was annotated by humans and every single image was annotated automatically by the Convolutional Deep Learning Neural Network described in Gallager et al. (2020). Automated classification of substrate and individual targets was possible based on our current research allowing rapid turn-around of data products. However, manual annotation, and particularly scallop assessment was conducted to test the automated analyses as a defined quality control step in the data product workflow. For the 2022 survey conducted by NOAA, there were so few passes through the impact zones and only three sites were surveyed producing 65,284 images, we decided to do 100% manual annotations on every image taken along 1 nm tracks (impact and control images) to ensure a high quality data set.

The main indices of impact and recovery was biodiversity and species richness (slide 16). A diversity index is a quantitative measure that reflects how many different types (such as species) there are in a dataset, and simultaneously takes into account how evenly the basic entities (such as individuals) are distributed among those types. Alpha-diversity, beta-diversity, species richness, the Shannon Index, and the Simpson Index were calculated to examine how the BACI sites were changing over time. With these diversity indices as our metrics for impact, we evaluated Recovery (R) as a function of time at each site as a function of habitat type.

Results

Habitat Type and Scallops.

Slides 17-21 show the fine scale delineation of habitat type along with bathymetery in the HAPC. In these figures, the color scale is depth and the black contours are sand, gravel and epifauna, respectively. Slide 20 shows the region of high epifauna that was originally described by Page Valentine in a 2008 cruise report as the “pristine area”. The use of the term pristine has since been discontinued since the entire HAPC was heavily fished prior to 1996 so this area could hardly be considered pristine. We prefer to use the term complex epifauna to describe this region. Slide 20 shows the combination of all substrate types as contours and the abundance of exploitable scallops as the color scale. The important point to note is that within the area of high epifauna denoted by the black contour lines, the abundance of exploitable scallops is very low. The highest concentration of scallops is to the northwest and south east of the region of complex epifauna. Low scallop concentration in the complex epifauna, to some extent, may be a function of human error associated with obscuration of scallops by epifauna; however, from the depletion dredging we did (slide 27), only 6.5 bushels were removed while over 422 in Site 2 and 470 bushels in site 3 were removed so the low concentration derived from imaging may be very real. Slide 21 shows the abundance of exploitable, medium sized (40-80 mm), and small (<40 mm) scallops in numbers per m^2.

Automated Classification.

The Convolutional Deep Neural Network algorithm used was from Darknet, YOLO3. This allowed the detection of single targets by blob detection and classification all in one process (slides 22 and 23). The holistic classification of substrate was also part of the training set so that the substrate type in every image could be evaluated. About eight images per second could be classified with an accuracy between 90-97%. Demersal and epifaunal finfish were classified as just fish and then a human taxonomist went back and reclassified the target to species.

Impact dredging and Organism Depletion.

Slides 24-26 show the types of organisms removed during the impact dredging in each of the habitat sites. Sites 1-3 (slide 24) consisted of hyrozoans and bryozoans, stalked tunicates, sponges and mussels on a sand/shell hash substrate. As previously mentioned, a relatively small number of scallops (6.5 bushels) were removed form Site 1 (slide 27) compared with Sites 2 (422 bushels) and Site 3 (470 bushels) and Site 5 (327 bushels). All sites showed strong depletion of scallops following the 9 to 10 passes with the dredge.

Slide 28 shows the abundance of organisms removed from each site. At Site 1, 380 bushels of mussels and epifauna were removed and a relatively small number of sea raven, cod, haddock and lobsters were removed. Note that mussels/epifauna, scallop and surf clams are in bushels while the remainder of organisms such as skate, yellow tail, monkfish and hake were recorded just as individuals Shell length of a subset of scallops and body length of all of the finfish were recorded.

Substrate.
Slide 30 shows frequency distributions of substrate type within the impact areas and outside the impact areas as a control of Sites 1,3 and 6 in 2022. Note the long tail of skewness indicating a wide variation in substrate existed in this site. The high degree of skewness drove the decision to use a non-parametric analysis to compare median values at each site. A Mann-Whitney test was used and displayed as box-whisker plots in slide 31. The p values for inside versus outside are displayed along the top of each site plot. The bottom of each box represents the 25th quantile, the red line the 50th quantile or median, and the top of the box the 75th quantile. Each of the red plus signs are indicators of extreme values or outliers showing how skewed the distributions were. Only the results from Site 3 for inside and outside the impact area are significant: Inside Site 3 epifauna was significantly greater than outside the impact area indicating that within six years of impact, epifauna grew back more quickly after impact than when not disturbed. Data shown in our previous report up to two years post-impact indicated that epifauna was less than 50% of the control indicating that there was a lag phase immediately after impact before epifauna growth rebounded.

Statistics.
The 3-way ANOVA conducted on the BACI data included as grouping variables Time (T) as two years of survey data before impact (2012 and 2016) and four years of post-impact surveys (2016, 2017, 2018 and 2022 at sites 1,3,6) (slide 32). Grouping variable for Habitat (H) was split into two categories (epifauna/sand/shell hash and sand/gravel/shall hash). Sites (S) consisted of the six habitat sites (3 and 3). Impact (I) was represented as before and after impact. Interactions between variables included HxT, IxT and HxI with fixed (HxIxT) and random (TxS(HxT)) effects. The between and within site variance was calculated. The mixed effects model was characterized by F-test for main and interaction effects. When an analysis indicated one or more sites were significantly different, linear contrasts among specific combinations of means were made using a 1-way ANOVA to determine the differing site.

Species Richness for each site along with the statistical results for comparing control to impact over time are shown in slide 33. Note that the vertical dashed red line represents the time of impact in each plot. All sites showed a significant difference between control and immediately following impact. Recovery from impact of Species Richness depended on habitat type with Sites 1, 2, 3, and 4 showing minimal recovery after two years and Sites 5 and 6 showing nearly full recovery after two years. All sites had fully recovered after six years. The multimeasure plot in the bottom right corner shows the marginal means of Species Richness for the two habitats (epifauna/mussel/shell hash and sand/gravel/shell hash) both before and six years after impact. Following two years of recovery, there was a significant difference for habitat 1 but not for habitat 2 suggesting that the sand/gravel/shell hash habitat was not as impacted as the epifauna/mussel/shell hash habitat was. After six years of recovery, no difference between impact and control was detected at any site for species richness regardless of habitat.

A similar result was found for biodiversity H’ between habitats (slide 34). Both habitat types were strongly impacted initially but only the sand habitat in Site 4 had fully recovered after two years. There was a strong effect of habitat on recovery (p=0.0067) with Sites 1-3 not significantly recovering over time. After six years' recovery, biodiversity in impacted areas reached or exceeded (Site 1) the control.

Indicator species.

Density (#/m^2) of individual species was calculated by determining the total area imaged by HabCam inside or outside each site and the number of individuals detected in the images noting that there was a 30% overlap between images taken along track. Density of individual representative species in each site showed highly variable results. The sponge *Iophon* is sensitive to mechanical disturbance and showed little recovery over two years (slide 35) but full recovery after six years. Changes in the bryozoan/mussel habitat remained strong in Sites 1 and 3 following two years but not in Site 2 where it apparently fully recovered (slide 36). Lacy Tube Worm *Filograna implexa* is another sensitive indicator species and was hard hit initially and remained low after two years (slide 37). There was no significant impact on the red sea anemone *Actina tenebrasa* (CI p=0.9164) (slide 38). The stalked tunicate *Boltenia olvifera* was significantly impacted but there was a strong habitat mixed effect (p=0.009) after two years recovery suggesting that its impact was habitat specific with recovery lowest in Site 3. After six years all sites had recovered and in Site 1 *Boltenia* had rebounded to nearly 50% higher than before impact (slide 39).

All epifauna taken together were significantly impacted (p=0.025) and had not recovered in any site after two years. After six years all sites had fully recovered (slide 40). Monkfish abundance was interesting since it significantly increased in all sites and remained relatively high throughout the six-year recovery period (slide 41). This is probably because of its highly mobile and exploitive behavior moving into the impacted sites. There was little impact on all finfish taken together in any of the sites with the exception of an increase in Site 1 dominated by Monkfish (slide 42).

The table in slide 44 shows the main and interaction effects of time and habitat for combinations of similar type organisms and individual species. A significant change at $p<0.05$ is indicated by the asterisks. The last two columns give the percentage change between controls and after six years' recovery for the two habitat types. Note neither biodiversity nor species richness were significantly impacted in either habitat, although species richness showed a significant difference between habitats, as expected. This reflects the substrate type being harder and less disrupted by the scallop dredge in habitat 2. Large losses in organisms such a *Myxicola*, Lacy Tube Worm, *Styela*, *Iophon* and bryozoa in habitat 1 reflect the sensitive nature of these soft bodied organisms, static lifestyle and relative slow rate of reproduction after two years. After six years there was no difference between CxI in these organisms although habitat still influenced Lacy Tube Worm and Iophon. The increase in *Didemnum vexillum* in habitat 2 reflects the opportunistic nature of this colonial tunicate when substrate is disturbed.

Summary and Conclusions

Both biodiversity and species richness initially decreased after impact and remained <30% of control in complex epifaunal sites two years following impact. Six years following impact both biodiversity and species richness had fully recovered and showed no response to CxI, while a significant difference in species richness was detected between habitats. Epifauna (sponge, bryozoa, Hydrozoa, Lacy Tube worm, anemone, stalked tunicate) and infauna (*Myxicola*) in Sites 1-3 significantly decreased on impact and remained <50% than control after two years of recovery. After six years all epifauna had fully recovered and in some cases exceeded control levels by 40-46%. It is clear that the softer substrate in Sites 1-3 were considerably more impacted than the sand/gravel/shell hash sites in Sites 4-6. There were significant high order effects (Habitat X Control X Impact) in five out of 10 faunal classes after two years indicating that the impact made by scallop dredging is strongly influenced by habitat with complex epifaunal habitat being significantly more susceptible to mechanical impact than sand/gravel/shell hash habitats. There was strong suggestion that some fish species (e.g., Monkfish) increased in impacted Sites 1-3 by more than 80% of control immediately following impact and remained elevated for six years. This reflects the mobile and opportunistic behavior of this species.

It is clear that two years is not sufficient for complex habitat to recover to 100% of control. Fortunately, we were able to collect additional images in May 2022with the assistance of NOAA NEFSC during their annual scallop survey allowing us to process these images and provide an additional time point in this BACI analysis following nearly six years of impact. The six-year time point indicated that all habitats had fully recovered from dredging impact of 9 to 11 passes with a commercial dredge. If a single pass of our impact dredge is equivalent to one trip by a commercial scallop boat, then it will require a minimum of six years for habitat to recover after 9 to 11 fishing trips have been made.

It may be possible to target specific harder homogenous habitats for opening a limited fishery where scallop abundance is high, such as in Sites 3 and 6, while maintaining no-take zones in complex epifaunal habitat (Sites 1 and 2) with a defined boundary of at least several hundred meters.

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