Great South Channel Habitat Management Area Survey

Final Report for
Exempted Fishing Permit #19066

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Submitted By

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EXECUTIVE SUMMARY

Coonamessett Farm Foundation's (CFF) project entitled "The Great South Channel Habitat Management Area Habitat Survey," under Exempted Fishing Permit (EFP) #19066, was designed to provide detailed information about the distribution of biotic and abiotic habitat features in a 24 km^2 sample zone of the Rose and Crown research area in the Great South Channel Habitat Management Area (HMA). A forward facing high-definition camera was installed on a hydraulic dredge fishing onboard the F/V Seafox owned by Nantucket Sound Seafood (NSS) to capture footage of the benthos and species present in the area.

Beginning in June 2020, 3,236 tows, executed in 104 fishing trips, were accomplished under EFP #19066. On these trips, a subsample of the catch was taken, separated and weighed, while a camera mounted on the dredge recorded continuous footage approximately three meters in front of the dredge path. The sample area was divided into a grid and videos were chosen for all squares that contained tow data for each season of sampling. Tow videos were collected from June 3, 2020 through February 4, 2022. Objectives for the project were as follows:

1) Use dredge-mounted cameras to document substrate, habitat features (e.g. sand, mussel clumps, mussel beds), fishes, and invertebrates within the Rose and Crown area of the HMA.
2) Create spatiotemporal distributions of biotic and abiotic habitat features to be used to inform future management actions regarding the HMA.
3) Establish relationships between high clam catch per unit effort (CPUE) and habitat complexity.
4) Determine spatiotemporal presence of Atlantic cod in this area.

Two hundred and sixty-six dredge videos were annotated in the Behavioral Observation Research Interactive Software (BORIS) for a total 91,680 discrete data points to document in time where each biotic or abiotic event occurred. Coupled with tow information taken at-sea, these events were mapped spatially and analyzed for trends and changes over time. In addition, dredge path damage, and videos taken from a benthic sled were also analyzed with BORIS.

Habitat maps were interpolated to visually represent substrate coverage and distribution of benthic and epifaunal features including mussel beds and clumps, boulders, shell hash, macroalgae, and peat. The total substrate composition annotated on video was 0.09, 0.23, 0.31, 0.18, and 0.20 for sand (0%), <25%, 25-50 %, 51-75%, and >75% pebble/cobble coverage, respectively. Substrate composition for a portion of the sample area which was evenly surveyed throughout the study period changed from higher proportions of pebble/cobble in summer to sand in the fall and was consistent between 2020 and 2021. The summer proportion of pebble/cobble coverage was 0.57, 0.68 in winter and 0.46 in fall. From the exploratory optical survey trips, the area surveyed in Davis Bank East was 51% sand coverage.

Generalized linear mixed models were used to assess surfclam catch information taken onboard the vessel and the most commonly observed commercially valuable species in the annotated videos, including black sea bass, dogfish, and flatfishes. Four variables were significant predictors of surfclam catch. Surfclam catch increased at a rate of 0.18 kg/m^2 area swept, and 1.45 kg for every percent increase in pebble/cobble coverage. Mean surfclam catch

increased by 103.38 kg/tow in 2021 relative to 2020, and it was highest in the summer with a mean catch per tow of 412.26 ± 9.86 kg/tow. Black sea bass, dogfish, and flatfish increased by swept area by 5, 7, and 2 fish per km^2 respectively. Black sea bass, dogfish, and flatfish were most abundant in the summer at 8.7, 9.8, and 2.1 fish per tow, respectively. Dogfish were ten times more abundant during night tows. Additionally, black sea bass and dogfish were negatively correlated with mussel clump coverage. Flatfish were positively correlated with rocks and boulders.

It was observed that intersecting dredge paths from different time intervals were undetectable beyond a 24-hour period following disturbance. Due to the nature of our sampling, distinguishing between natural and fishing disturbance was difficult.

Overall, the GSC HMA survey provided a wealth of data that can be used to address a wide range of issues that impact the ecosystem on the GSC HMA. The data collected by this project can be used to evaluate changes in substrate coverage and populations of multiple fish species, supplying fisheries managers with critical information required to determine appropriate conservation measures to coexist with a healthy fishery.

BACKGROUND

Atlantic surfclam (*Spisula solidissima*) is a large suspension-feeding bivalve species found along the continental shelf from Virginia/North Carolina to Canada on the east coast of North America (Merrill and Ropes 1969). Latitude, depth, currents, and temperatures all play a role in determining distributions for surfclams, which may live up to 30 years (Jones *et al.* 1978). Due to their shallow habitat (<60 m) and their large habitat range, regional environmental factors greatly effect recruitment, mortality and growth (Jacobson and Hennen 2019). Spawning occurs in the summer and early fall, though specific month depends on regional temperature shifts (Cargnelli *et al.* 1999). Predators of surfclams include moon snails, the sea star *Asterias forbesi*, lady crabs (*Ovalipes ocellatus*), Jonah crabs (*Cancer borealis*), horseshoe crabs (*Limulus polyphemus*), haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*). The species is prosecuted by fishing a hydraulic dredge which was designed to reduce bycatch while efficiently removing the buried surfclam individuals from sediment. The fishery is not overfished nor is overfishing occurring (NOAA 2022).

Historically, the Southern New England (SNE) Atlantic surfclam fishery represented only a small portion of the overall species landings; however, regional landings have been significantly increasing since 2010 (**Figure 1**, MAMFC 2018). While vessels homeported in SNE can access productive fishing grounds on Georges Bank, the limited capacity of the smaller vessels, which comprise a majority of the SNE fleet, make it economically unfeasible to do so. In addition to limited vessel capacity, harmful algal blooms (HAB) that intermittently occur on Georges Bank can contaminate surfclams and cause Paralytic Shellfish Poisoning to consumers. Therefore, vessels harvesting surfclams must adhere to testing protocols developed by the National Shellfish Sanitation Program, which further increases operating costs when fishing on Georges Bank (MAFMC 2018). Because fishing grounds southeast of Nantucket do not experience HABs and its close proximity to key deep-water ports like Hyannis, MA a vibrant surfclam fishery has developed in SNE over the last four decades. This fishery is unique in that it is predominantly hand-shucked meats, meaning the products are of higher quality and largely fuel the market for clam strips and chowder parts popular in New England.

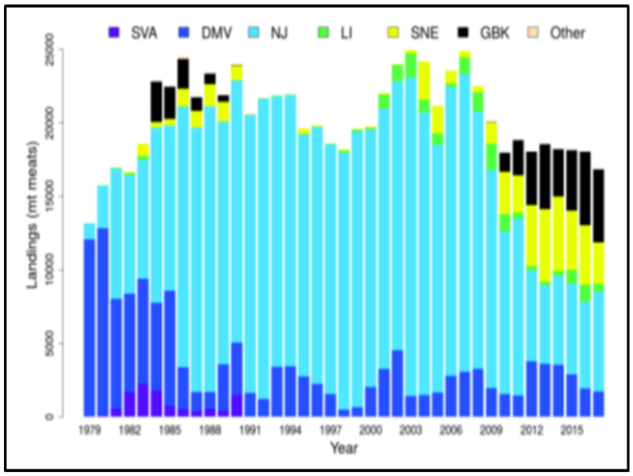


Figure 1. Landings of Atlantic surfclam from 1979-2016, including preliminary data for 2017. Southern New England is highlighted in yellow, while Georges Bank is in black (MAFMC 2018).

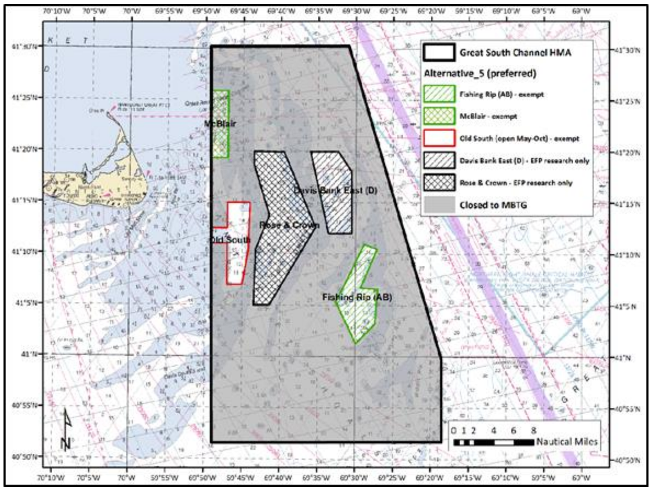


Figure 2. The Great South Channel Management Area showing exemption and research areas.

In 2018 the Omnibus Essential Fish Habitat Amendment 2 went into effect, updating essential fish habitat (EFH) designations and selecting an area east of the island of Nantucket and encompassing a portion of Nantucket Shoals as The Great South Channel Habitat Management Area (HMA); thereby closing the area to all mobile bottom-tending fishing gears. A one-year exemption was granted to hydraulic dredge surfclam vessels while a framework was developed to create a long-term exemption area program to provide the fishermen access to the productive fishing ground. This resulted in five designated areas, two open for year-round fishing, one for seasonal access dependent on Atlantic cod spawning activities believed to occur there, and two reserved for fishing under the EFP process and scientific research purposes (**Figure 2**). The New England Fishery Management Council's (Council) intent was for the research to support the potential development of future exemptions (NEFMC 2018) and to collect detailed information of the area.

The Habitat Planning Development Team (PDT) created a two-stage progressive research framework (**Figure 3**). The development of the progressive research framework was done with the acknowledgment that the resources to achieve Council's priorities regarding the HMA are limited and that a strategic, collaborative approach which builds upon itself was deemed necessary (NEFMC 2019). The first stage of the framework addresses the Council's priority to improve the understanding of the distribution of living and non-living habitat features within the HMA. During this stage, pilot studies would be conducted to identify study sites and refine the methods for evaluating surfclam habitat. The second stage of the research framework would address the Council's priorities to improve their understanding of habitat stability and vulnerability (NEFMC 2019; **Figure 3**).

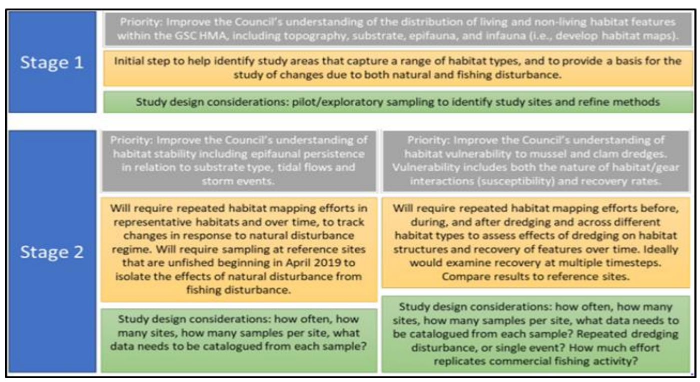


Figure 3. The two-stage progressive research framework developed by the PDT to aid managers in their ability to identify areas where the surfclam fishery can operate without adverse impacts to habitats (NEFMC 2019).

Nantucket Shoals is an area of high energy, with varying shallow depths ranging from 1 to 30 meters and strong tidal current velocities ranging 4-5 knots (Twitchell 1983). Coupled with frequent large storm events and the presence of a terminal moraine from the last ice age; the

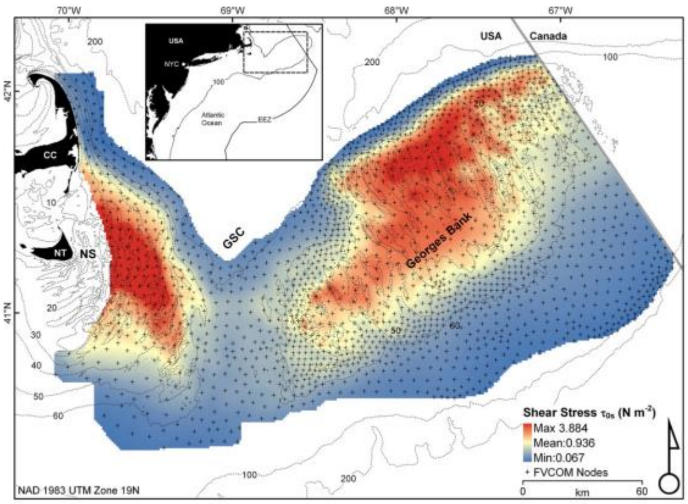


Figure 4. Map of t0s and FVCOM nodes (N¼1809). Estimates of the shear stresses made at 1809 locations using a regional tidal database application of the FVCOM.

region is characterized by mobile sand-rich sediments mixed with cobbles, pebbles, rock, and occasional boulders; and roving meter-high sand dunes (Emery and Uchupi 1965). Modeled values of sediment stability on eastern Nantucket Shoals show that strong stresses by flowing water exceeded the critical shear stress of the surficial sediments inversely related with water depth (**Figure 4**); suggesting that the benthos becomes unstable on a bi-weekly basis (Harris *et al.* 2012). This creates a network of patchy substratum persistently disturbed by high energy tidal currents and an area constantly in flux. Powell et al. (2020) found that frequent barnacle scars on rocks suggests a pattern of burial and exhumation along with an abrasive impact from sediment scour. These processes could limit the importance of substrate complexity as an ecosystem value.

PROJECT GOALS AND OBJECTIVES

Initially, the project had wide ranging goals to be carried out in two large areas; one in Rose and Crown and the other in Davis Bank East. Multiple fishing vessels were to operate in the areas resulting in video of the seafloor in a larger percentage of the HMA while generating research funds in a research set-aside type agreement. The overall goal of this project was to develop an ecological survey that assesses habitat types in high and low dredge impact areas and determine spatiotemporal occurrence of Atlantic cod and other species in these habitats that are subjected or adjacent to commercial fishing activities. This goal was to be met through specific objectives: 1) Develop juvenile cod habitat associations in this area and identify areas where juvenile cod do not occur at certain times of the year. 2) Use BUVs for assessing occurrence of juvenile cod and other species. 3) Characterize habitat types in which dredging does and does not occur. 4) Establish areas of high clam CPUE and low habitat complexity. This goal and concurrent objectives were driven by these research questions: 1) How much does cod occurrence overlap with high and low dredge impact areas over time in a variety of habitat types? 2) How do high and low dredge impact area habitat types and species occurrence compare? 3) How much structure do dredges remove relative to contact? 4) How frequently do sandy habitat types shift in the HMA? 5) How can dredge mounted cameras optimize fishing decisions to reduce habitat impact? These questions were going to be answered by “Phase I” fishing trips and subsequent data analysis from the selected areas in Rose and Crown and Davis Bank East.

The scope of the project was considerably scaled back due to concerns of swept area and habitat damage, resulting in a shift of objectives and goals. The major intent to improve manager's understanding of the distribution of biotic and abiotic habitat features within the HMA to assist in informing management entities remained the same. The following objectives were developed as the Rose and Crown sample area was designated and sampling began: 1) Use dredge-mounted cameras to document substrate, habitat features (e.g. sand waves, mussel beds), fishes and invertebrates within the Rose and Crown area of the HMA. 2) Create spatiotemporal distributions of biotic and abiotic habitat features to be used to inform future management actions regarding the HMA. 3) Establish relationships between high clam CPUE and habitat complexity. 4) Determine spatiotemporal presence of Atlantic cod in this area. As the research progressed, the following questions were raised: 1) Did the percent composition of the substrate change over time? 2) Is there a clear relationship between Atlantic cod presence and substrate? 3) Is there a clear relationship between surfclam catch and substrate? 4) How frequently do sandy habitat types shift in the HMA? 5) How can dredge mounted cameras optimize fishing decisions to reduce habitat impact?

METHODS

At-Sea Data Collection

Fishing trips were carried out aboard the F/V Seafox homeported in Hyannis, MA. The knife edge of the hydraulic dredge was 48 inches across and was fished using 90 psi from the water jets, towed two to three knots. Each trip to the research area was accompanied by an at-sea technician to manage the dredge-mounted cameras, record tow data, and subsample the catch pile. These trips were vital to the research because the project was unfunded and the agreement was made with NSS in which every bushel landed garnered $1 to go towards covering research costs. This agreement was later increased to $2 per bushel due to a need for more funds to cover the project analysis.

Information per tow included start and stop times, GPS points, depth, speed and a surfclam bushel count. A one-bushel subsample was taken from the catch pile every tow possible. This sample was taken from the stern side of the pile and separated by species or substrate components, counted and weighed to the nearest 0.1 kg. Substrate components included shell hash, cobbles and mussels; while species caught included skate, crabs and an occasional fish species. Mussels and cobbles were photographed to look for epibiont presence and the presence of damage due to dredging. Periodically, while the at-sea technician was busy handling the cameras and/or lights on the dredge, a subsample was skipped to facilitate the continuation of deck activities. Additionally, at the end of a fishing trip the cages of surfclams were rearranged to even out the vessel weight distribution rendering subsampling impossible. This usually consisted of two to eight tows without catch sampling per trip; tow information and video footage collection continued.

The camera and light system consisted of a steel frame welded to the dredge and outfitted with a GoPro Hero+ camera and battery extender in a protective housing and 2 SCUBA diving type flashlights in mounted housings (**Figure 5**). These were changed periodically during the fishing day and could be monitored by a simple visual check. The camera captured continuous video of the seafloor in the towpath. Depending on oceanographic conditions including current strength, turbidity levels, wave height and time of day, video quality ranges from completely obscured to very clear. These videos were subsequently separated into tows by trip and organized for annotation.

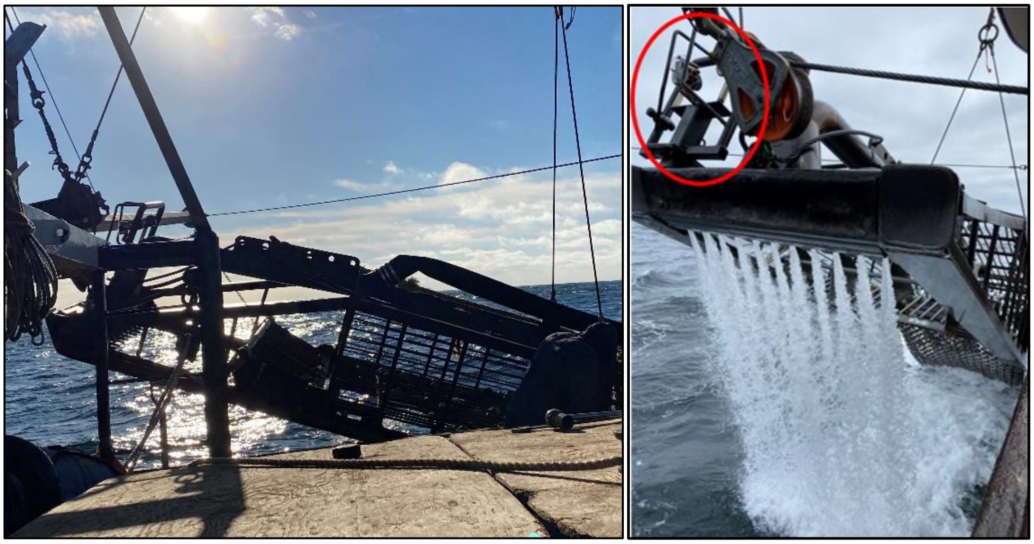


Figure 5. Camera and lights mounted on the hydraulic dredge.

Fisheries Independent Surveys

The idea behind the fisheries independent optical surveys was to couple the data gathered from reference areas, that were established as no fish zones within our sample area, with the fisheries dependent camera mounted dredge footage from the fished areas (**Figure 6**). Originally, the project was reliant on a large sample area (103 km^2) and multiple fishing vessels fishing at the same time to generate revenue via the set aside to cover research costs. After the survey area was restricted to 24 km^2 and one active vessel, research funds generated were not enough to cover a once-per-season optical trip and the data analysis costs.

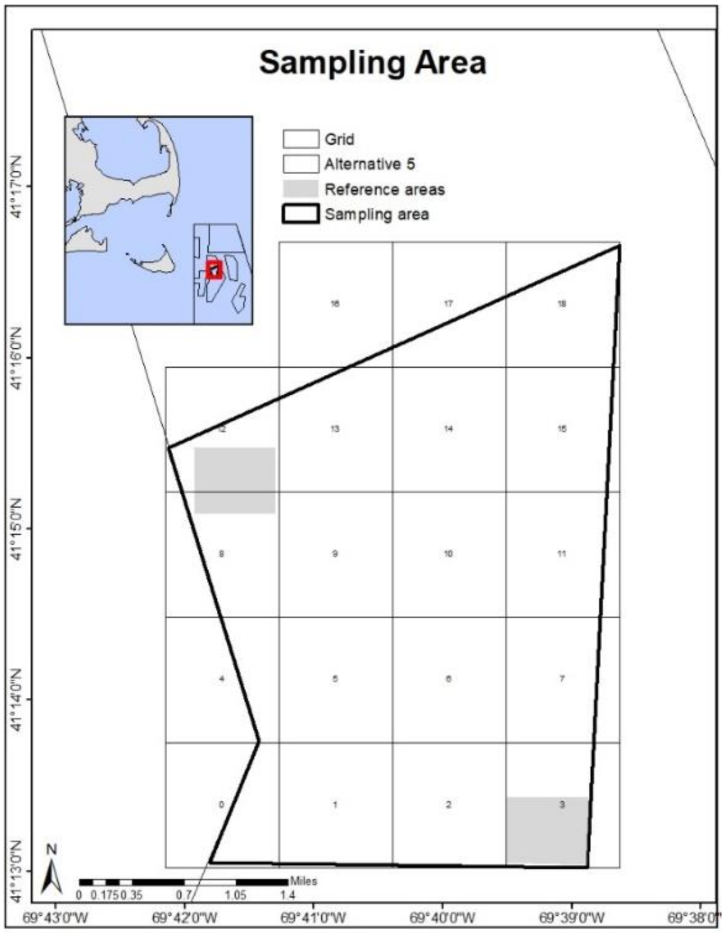


Figure 6. Reference areas (not fished) in gray in the sampling zone.

Figure 7. CFF benthic sled built in 2014. Red arrows indicate the location of the forward-facing camera, blue arrow indicates the location of the bottom-facing camera, and green arrows indicate the location of lights.

Two optical surveys were completed using two or three camera types including a video camera-outfitted benthic sled (**Figure 7**), a stationary stereo-camera stand and a baited underwater video camera (BUV). The first optical survey was accomplished May 14, 2020 utilizing the benthic sled and camera stand. Two camera stand drops in the Rose and Crown and nine tows, seven in the Rose and Crown and two in Davis Bank East, were accomplished. The second trip took place February 5, 2021 using the three camera systems. The benthic sled and camera-stand took the most useful footage; however, that day experienced strong currents which suspended matter in the water column and obscured footage at various time stamps. Two camera-stand drops, one BUV drop and 10 benthic sled tows were completed. The camera stand was deployed in the Rose and Crown and the benthic sled tows took place in the Rose and Crown and Davis Bank East (**Figure 2**). The camera-stand images and BUV videos were not high enough quality to be annotated. The benthic sled tows were annotated and data is presented in the following sections.

Annotations

The most simple and useful timescale for separating the 3,236 tows was by calendar month. Three sets of annotations were analyzed. The largest consisting of the highest volume of videos is a seasonal comparison of 218 videos analyzing substrate coverage and species presence. Seasons were broken down into summer (June 1 to August 31), fall (September 1 to November 30), winter (December 1 to February 28) and spring (March 1 to May 31). We chose three videos from each of the eighteen 1.3 x 1.2km grid-squares (**Figure 6**), distributing coverage as evenly as possible throughout each square. Care was also taken to have both night and day videos in the analysis to account for any diel trends. Secondly, a heavily fished area shown in **Figure 8** was separated from the larger sampling zone and analyzed on a smaller scale comparing tows from paired seasons, i.e. 4 tows from winter 2020-2021 and 4 tows from winter 2021-2022 on similar if not identical track lines (within 20 m at the furthest point). A third subset of 24 videos were chosen with the intent to locate signs of dredging from previous tow tracks that directly intersected one another. Three time series were analyzed, a set with several months between tows that intersected, a one-month separation between tows, and a set with tows from the same trip.

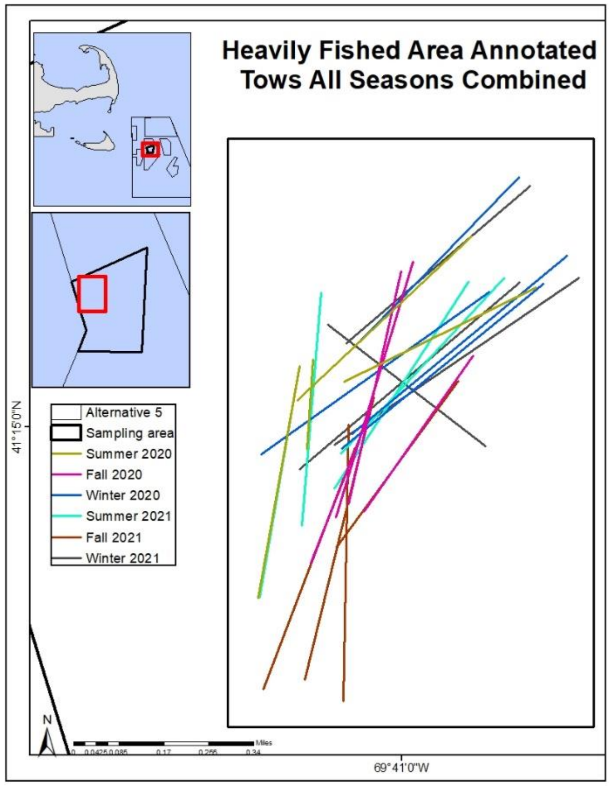


Figure 8. Heavily fished area.

Videos were annotated by CFF staff and one contracted employee. An ethogram of set characteristics was designed in the open sourced Behavioral Observation Research Interactive Software (BORIS; Friard and Gamba 2016). Three categories of characteristics were documented by time-stamp: substrate, epifauna and mobile fauna such as crustaceans and finfish species. Substrates were separated into sand and pebble and cobble. Pebble and cobble percent coverage was further specified at <25%, 25-50%, 51-75% and >75%. Other layers that could be added to sand or pebble/cobble coverage were shell hash, sand waves and/or sand dunes, rocks and boulders and peat veins. Epifaunal events included mussel beds, mussel clumps and macroalgal coverage. Macroalgae was lumped together with bryozoans and hydrozoans ("MBH") in the interest of simplifying the annotation scheme. Finfish, flatfish, dogfish and skate were identified down to species level whenever possible.

Each annotation was exported from BORIS to a CSV file where the documented events were listed along with the time they were marked. The event information was coupled with start and stop latitudes and longitudes of the associated tow to calculate where geographically the event was documented in the sampling area. After mapping these two pieces of information in ArcMap, we transformed the data from a continuous line to points along the tow transect every three meters. This was the approximate distance we could see in front of the dredge during annotation. Using this method, the number of data points per substrate or epifaunal event could be calculated and analyzed per grid square.

Spatial interpolation is a type of estimation by which a set of known point values are used to predict values at unknown points. ArcGIS offers the inverse distance weighted (IDW) interpolation tool, a method in which known points are weighted during interpolation where the influence of one point to another declines with distance from the unknown point (ESRI 2016, Harman *et al*. 2016, Maleika 2020). In our analysis, we calculated each season's average number of points per grid square. This number was assigned to tell the IDW tool how many points around the predicted location to pull substrate information. In addition, mean lengths of substrate and epifauna patches along a tow path were measured to determine the appropriate maximum distance around the tow path for interpolation.

Variation in surfclam catch and the presence of black sea bass, flatfishes, and dogfishes identified from the dredge-mounted video were assessed from 218 tows using generalized linear mixed models (GLMMs) with the 'glmer' package in RStudio 1.3.1056 (R Core Team 2021). Models were fit using backward selection to identify the combination of variables that best fit the data based on Akaike Information Criteria (AIC, Crawley 2012, Faraway 2016). Twenty-three temporal, benthic substrate, and environmental variables were included in the selection procedure predicting surfclam catch (see **Appendix A**). The models predicting black sea bass, flatfish, and dogfish abundance included 16 variables (**Appendix A**). Selection was constrained to maximum of seven variables for all models based on degrees of freedom. All models included a random effect for trip to account for clustering of tows within areas during each fishing trip. The clam catch model was fit using a gaussian distribution with the identity link and the models for black sea bass, flatfish, and dogfish abundance were fit using poison distributions with the log link. Environmental data not measured in the field was extracted from the Nantucket Shoals NOAA Data Buoy Center station 44008, with the exception of tide, which was extracted from the Great Point station 8448566.

Temporal variation in substrate composition was assessed from a subset of 24 tows that occurred within the heavily fished area using a repeated measures approach. Four sets of six tows were selected with overlapping tow tracks surveyed in the summer, fall, and winter of 2020 and 2021. This assessment used a fine-scale approach that subdivided each tow into 3-m intervals for a total of 4,500 discrete sediment composition estimates. Proportions of pebble and cobble substrate were compared between years and among months. The model included a random effect for tow nested within trip to account for clustering of tows during the same sampling event and non-independence of substrates characterized within the same tow (Agresti 2007). The model was fit using a gaussian distribution with the identity link. The unit of dispersion reported for all analyses was one standard error unless otherwise specified.

RESULTS

Seasonal Annotations

Data was collected without interruption from June 2020 to February 2021, when the vessel underwent necessary maintenance. It began again in April and continued to the end of May 2021 when the initial EFP expired. An extension request was granted and fishing activities resumed mid-August 2021 and continued until February 4th, 2022 when the extension expired. Trips and total number of tows per trip varied according to weather conditions and catch rates (**Table 1**). Fishing activity was not distributed evenly throughout the sampling area (**Figure 9**) with several grid squares experiencing little to no activity. This is a result of the vessel captain's historical knowledge of catch in the HMA and where >5 ft boulders exist, which the small dredge cannot handle. This information is shared amongst surfclam fishermen who prosecute the area. Additionally, the captain assumes that after a tow path is fished, the surfclams dig further into the sediment and should be given time to come back to a fishable depth and the area should be given a break from fishing pressures (Comm. pers. Captain Wood). Two of the areas that were not fished, grid squares 3 and 12, were chiefly because of the small amount of fishable space due to the reference zones. Three trips lost all videos and approximately 150 random video files were lost due to micro-SD card corruption or flooding of the camera housing. Just under 85% of all tow videos were successfully recorded. Tow length was 0.77 km ± 0.215, while area swept was 0.00096 km^2 ± 0.0009 per tow. A total of 16 unique species were caught in the dredge and consistency of catch varied by season (**Table 2 and Table 3**). A total of 22 unique species were seen in the video annotations (**Table 4**).

Table 1. Trip and tow information during the GSC HMA survey.

Season/Year	Trips	Tows	Area Swept (km^2)	Bottom Contact Time (hrs)	Annotated tows
Summer 2020	14	421	0.41	81.7	33
Fall 2020	26	884	0.82	143.2	50
Winter 2020-2021	12	486	0.51	92.5	44
Spring 2021	15	508	0.47	96.5	35
Summer 2021	2	65	0.055	11.5	14
Fall 2021	26	626	0.59	125.3	29
Winter 2021-2022	10	246	0.26	56.3	13
Total	**104**	**3236**	**3.12**	**606.9**	**218**

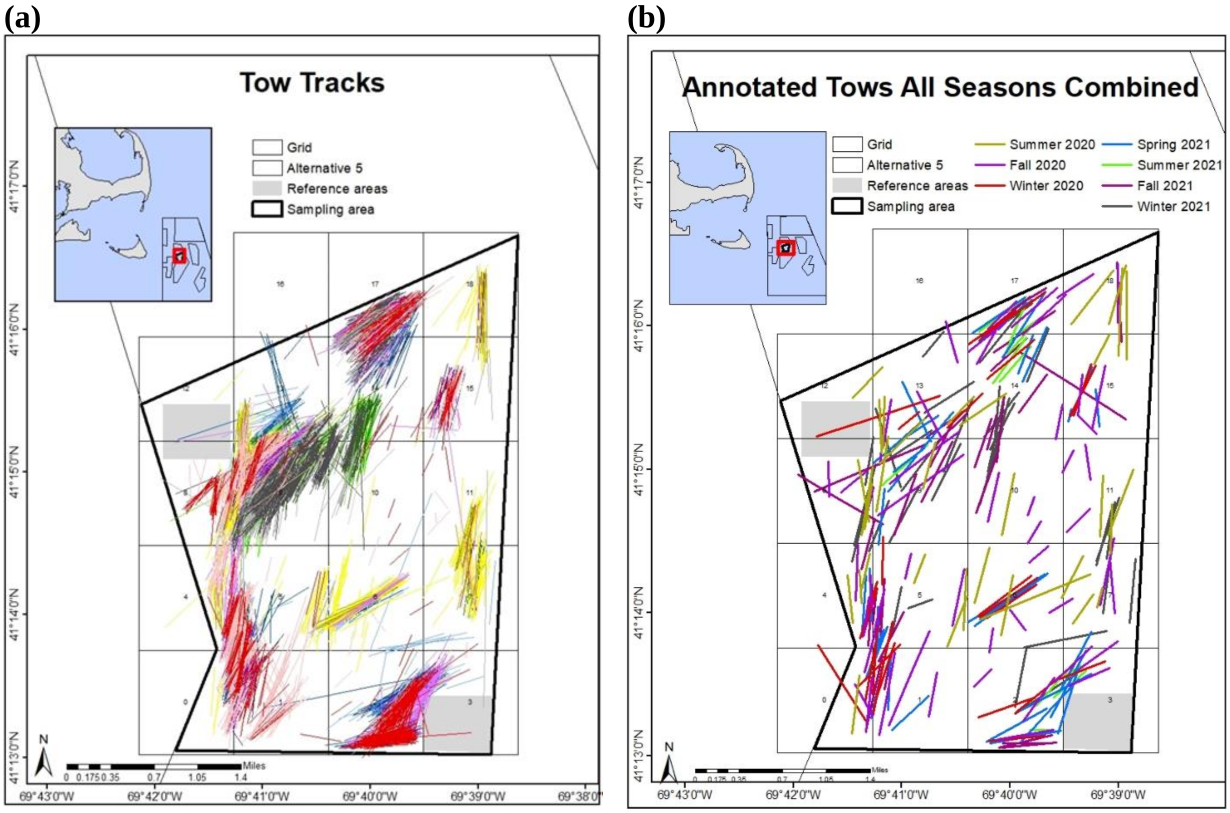


Figure 9. Tow tracks from June 2020 to May 2022 in the GSC HMA **(a)**. Annotated tow tracks used for the data analysis **(b**). Tow tracks by season are shown in **Appendix B**.

Table 2. Species caught in the dredge throughout the survey period.

Common Name	*Scientific Name*
Atlantic surfclam	*Spisula solidissima*
Blue mussel	*Mytilus edulis*
Horsemussel	*Modiolus modiolus*
Winter skate	*Leucoraja ocellata*
Little skate	*Leucoraja erinacea*
Winter flounder	*Pseudopleuronectes americanus*
Spiny dogfish	*Squalus acanthias*
American lobster	*Homarus americanus*
Jonah crab	*Cancer borealis*
Atlantic rock crab	*Cancer irroratus*
Hermit crab	*Pagurus pollicaris*
Northern moon snail	*Neverita duplicata*
Common whelk	*Buccinum undatum*
Atlantic slippersnail	*Crepidula fornicata*
Atlantic purple sea urchin	*Arbacia punctulate*
Orange footed sea cucumber	*Cucumaria frondosa*

Table 3. Major species caught in the dredge by season.

Season/Year	Mean Surfclam	St. Dev	Mean Mussels	St. Dev.	Mean Shell	St. Dev	Mean Cobble	St. Dev
Summer2020	438.07	162.54	33.89	37.16	68.82	75.25	16.34	40.14
Fall2020	443.68	143.11	34.18	67.09	45.87	52.27	11.29	21.80

Season/Year	Mean Surfclam	St. Dev	Mean Mussels	St. Dev.	Mean Shell	St. Dev	Mean Cobble	St. Dev
Winter2020	365.60	111.83	24.96	29.31	42.86	26.94	6.39	11.24
Spring2021	456.55	131.19	34.56	52.68	43.14	33.59	9.21	18.21
Summer2021	402.89	153.70	42.27	38.28	56.95	34.09	5.63	11.09
Fall2021	559.08	157.25	27.13	36.61	42.13	34.31	10.40	17.59
Winter2021	650.29	174.34	9.47	9.05	34.14	23.09	11.14	20.21

Table 4. Species seen in video annotations.

Common Name	*Scientific Name*
Atlantic surfclam	*Spisula solidissima*
Blue mussel	*Mytilus edulis*
Horsemussel	*Modiolus modiolus*
Winter skate	*Leucoraja ocellata*
Little skate	*Leucoraja erinacea*
Winter flounder	*Pseudopleuronectes americanus*
Windowpane flounder	*Scopthalmus aquosus*
Yellowtail flounder	*Pleuronectes ferruginea*
Spiny dogfish	*Squalus acanthias*
Smooth dogfish	*Mustelus canis*
Striped bass	*Morone saxitilis*
Black sea bass	*Centropristis striata*
Atlantic cod	*Gadus morhua*
Sculpin	*Myoxocephalus octodecemspinosus*
Sea robin	*Prionotus evolans*
Scup	*Stenotomus chrysops*
American lobster	*Homarus americanus*
Jonah crab	*Cancer borealis*
Atlantic rock crab	*Cancer irroratus*
Hermit crab	*Pagurus pollicaris*
Northern moon snail	*Neverita duplicata*
Common whelk	*Buccinum undatum*

Generalized Linear Mixed Models

Seven variables were retained in the surfclam catch model, including swept area, substrate composition, year, season, diel phase, tidal stage and wind speed (**Figure 10**; **Table A1: Appendix A**). Of these variables, four were significant predictors of catch, including swept area, substrate composition, season, and tidal stage; while year had a marginally-significant effect (**Table A6: Appendix A; Figure 11**). Surfclam catch increased at a rate of 0.18 kg/m^2 area swept, 1.45 kg for every percent increase in pebble/cobble coverage. Mean catch increased by 103.38 kg/tow in 2021 relative to 2020, from a 301.79 ± 9.44 kg to 405.17 ± 10.02 kg (± 1 standard error). Mean surfclam catch was highest in the summer with a mean catch per tow of 412.26 ± 9.86 kg/tow. Mean catch was similar in the fall and winter, with a mean catch of 369.88 ± 9.75 and 373.06 ± 9.76 kg, respectively. Surfclam catch was substantially lower in the spring with a mean catch of 256.49 ± 8.92 kg/tow.

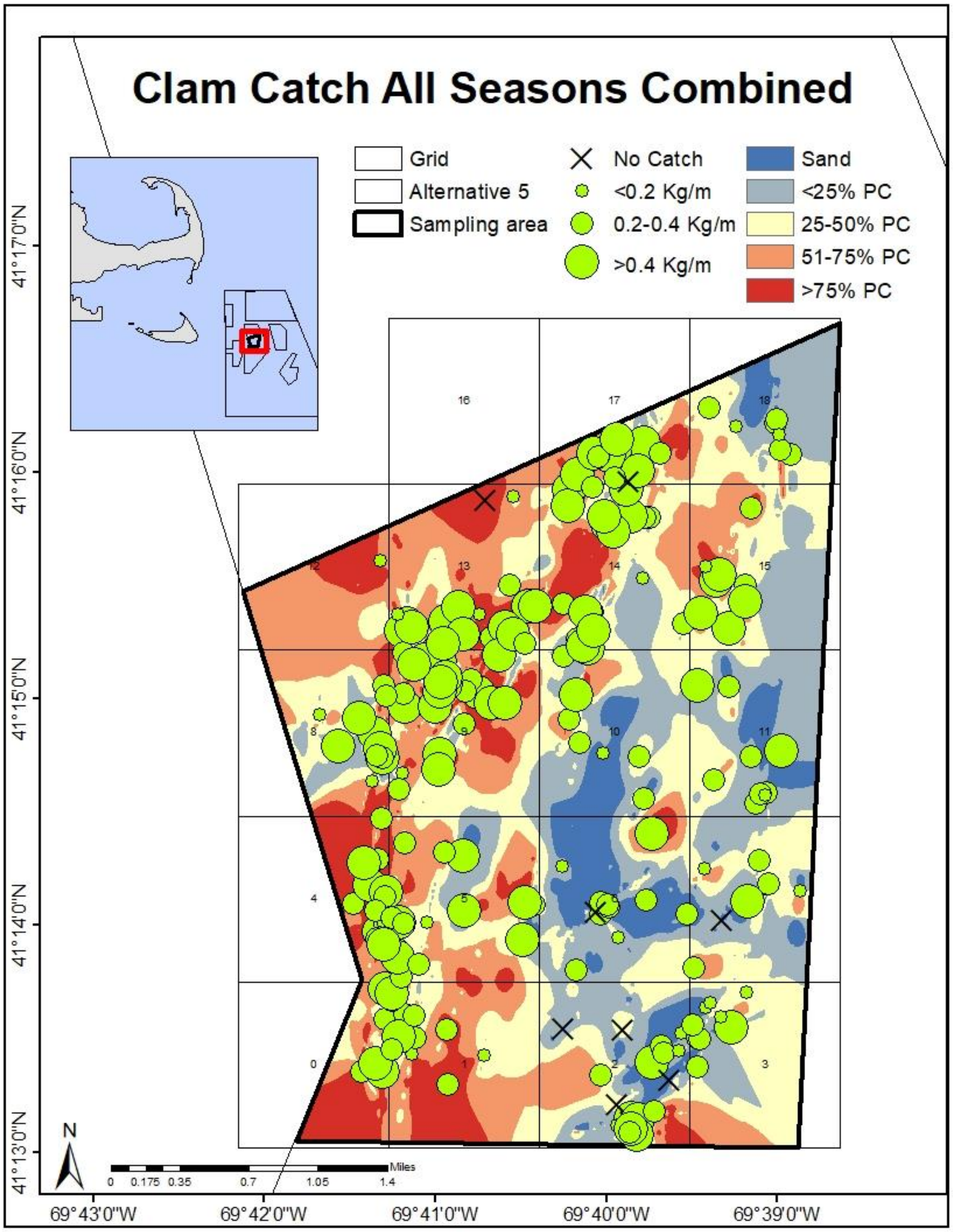


Figure 10. Surfclam harvested in the research area overlayed on the substrate coverage distribution map all seasons combined. Visual example of the relation between substrate coverage and surfclam catch.

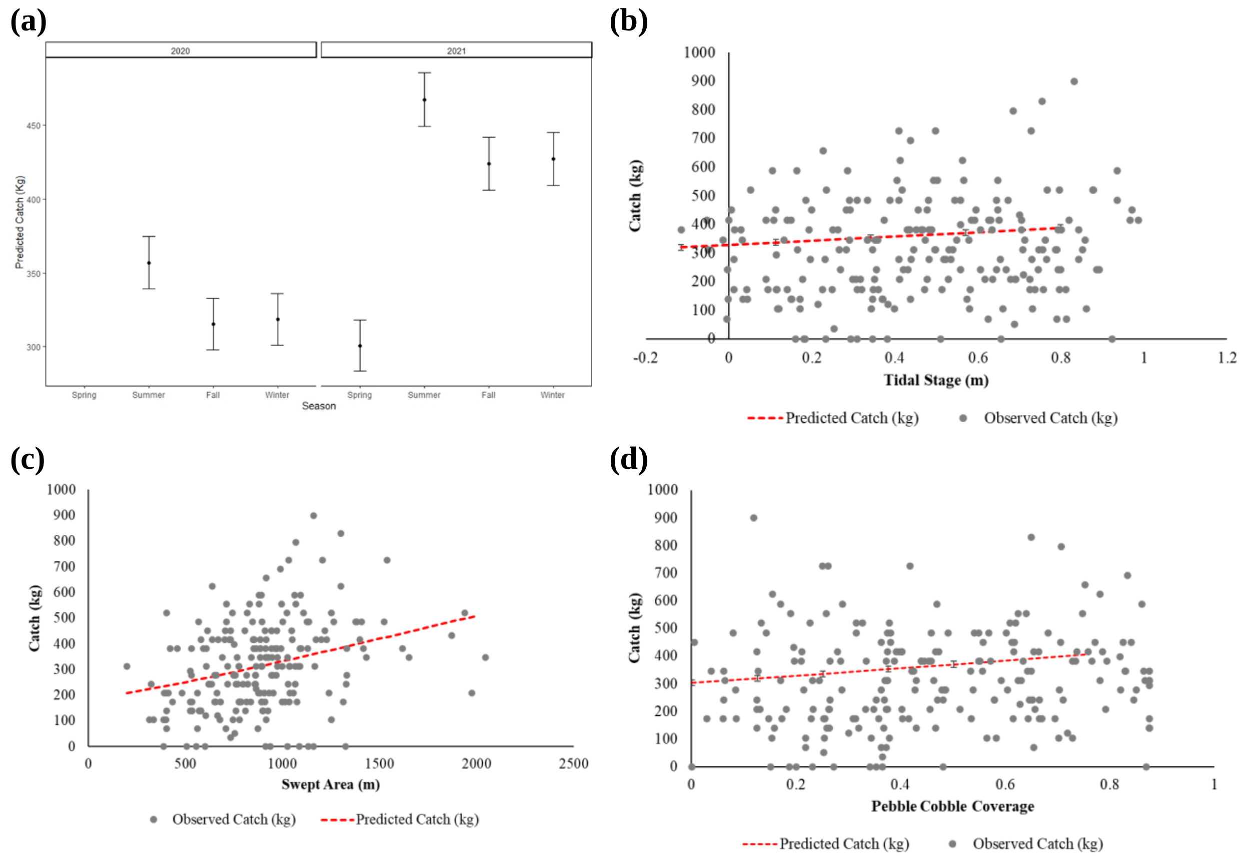


Figure 11. Surfclam catch prediction by season **(a)**, tidal amplitude **(b)**, swept area **(c),** and pebble/cobble coverage**(d)**.

Three variables were retained in the model predicting black sea bass abundance from the dredge-mounted video footage, including swept area, seafloor mussel clump coverage, and season (**Table A2: Appendix A**,). Black sea bass abundance increased at a rate of 0.005 individual per m^2 towed (**Figure 12 (a)**) and -0.076 individual for every percent increase in seafloor with mussel clump coverage (**Figure 12 (b)**). Abundance was highest in the summer with a mean number of observations of 8.7 ± 1.9 individual per tow (**Figure 12 (c)**). Abundance decreased in the fall to a mean number of 3.1 ± 0.7 individual per tow; this species was absent in the winter and spring. Four variables were retained in the model predicting dogfish abundance from the dredge-mounted video footage, including swept area, seafloor mussel clump coverage, diel phase, and season (**Table A3: Appendix A**). Dogfish abundance increased at a rate of 0.007 individual per m^2 (**Figure 12 (a)**) towed and -0.089 individual for every percent increase in seafloor with mussel clump coverage (**Figure 12 (b)**). Abundance was substantially higher at night relative to day, with a mean of 10.14 ± 1.99 dogfish per tow at night and 0.78 ± 0.27 individual per tow during the day (**Figure 12 (d)**). Dogfish abundance was highest in the summer with a mean number of observations of 9.8 ± 2.3 individuals per tow. Abundance decreased in the fall to a mean of 7.0 ± 2.1 dogfish per tow (**Figure 12 (c)**). They were absent in the winter and spring. Three variables were retained in the model predicting flatfish abundance from the dredge-mounted video footage, including swept area, number of boulders per tow, and season

(**Table A4**: **Appendix A**). Abundance increased at a rate of 0.002 individual per m^2 towed (**Figure 12 (a)**) and 0.016 individual for every boulder occurrence (**Figure 12 (e)**), although the trend was not significant (**Table A6: Appendix A**). Flatfish abundance was highest in the summer with a mean number of observations of 2.1 ± 0.2 individual per tow (**Figure 12 (c)**). Abundance decreased in the fall and winter to a mean number of 1.7 ± 0.2 0.5 ± 0.1 individual per tow, respectively, and increased again in the spring to a mean number of 1.3 ± 0.1 individual per tow.

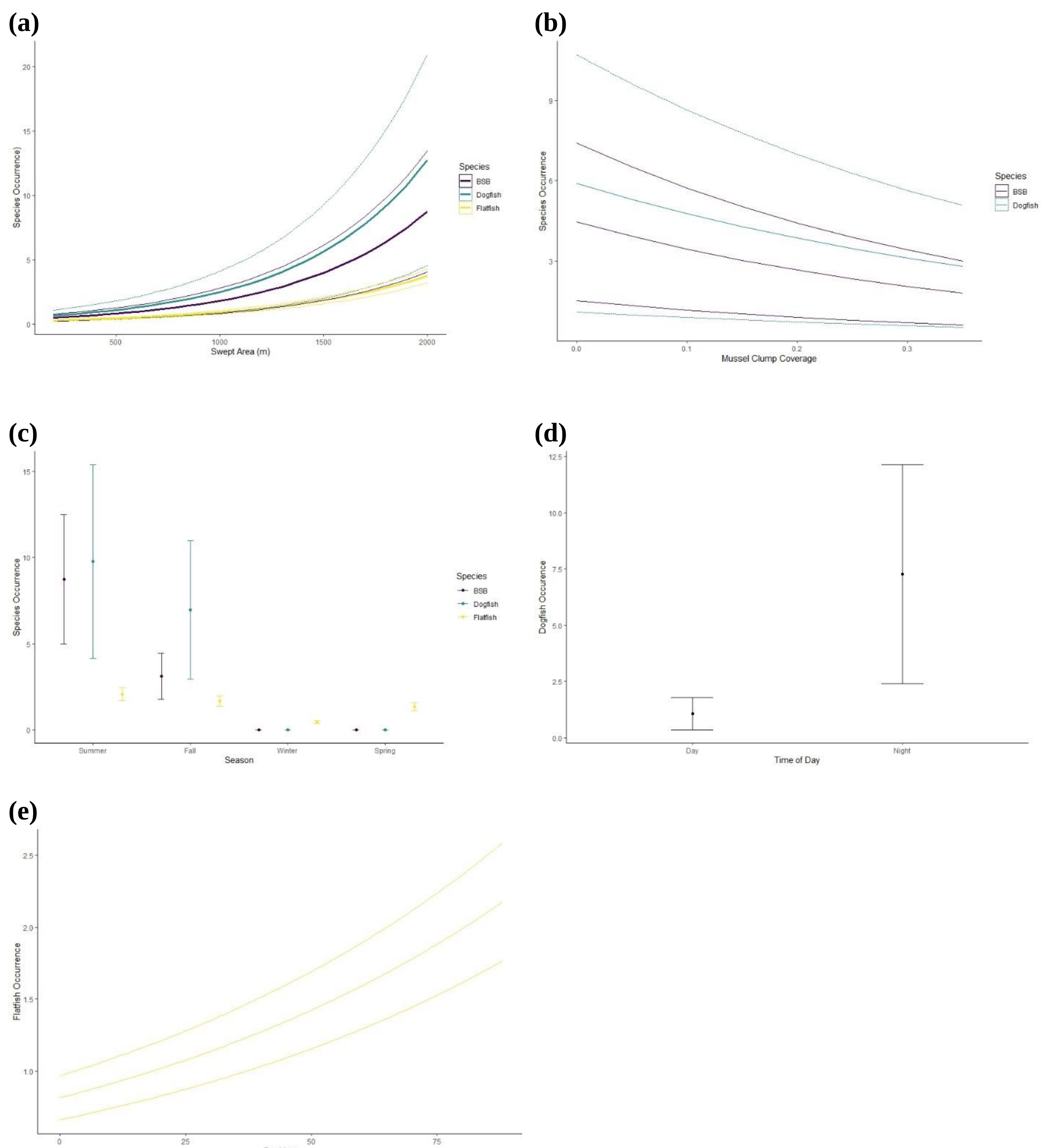


Figure 12. Fish model by swept area **(a),** mussel clump coverage **(b),** season **(c)** time of the day **(d)** and boulders **(e).**

Substrate composition within the heavily fished area was modeled using main effects for year and season after finding no significant interaction and a reduced AI by eliminating the interaction. Within the heavily fished area, substrate composition changed among seasons ($F_{2,20} = 1.183662$, $p = 0.04992$), but not between years ($F_{1,20} = 3.493857$, $p = 0.289549$). The mean proportion of pebble/cobble substrate composition was greatest in the winter with a mean of 0.68 ± 0.40, intermediate in the summer with a mean of 0.57 ± 0.47, and lowest in the fall, with a mean of 0.46 ± 0.40 (**Figure 13**).

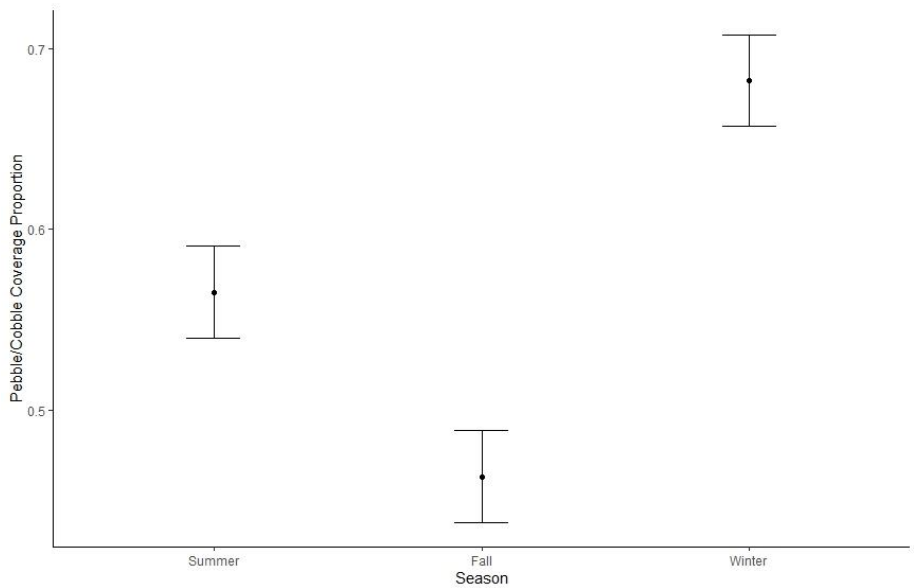


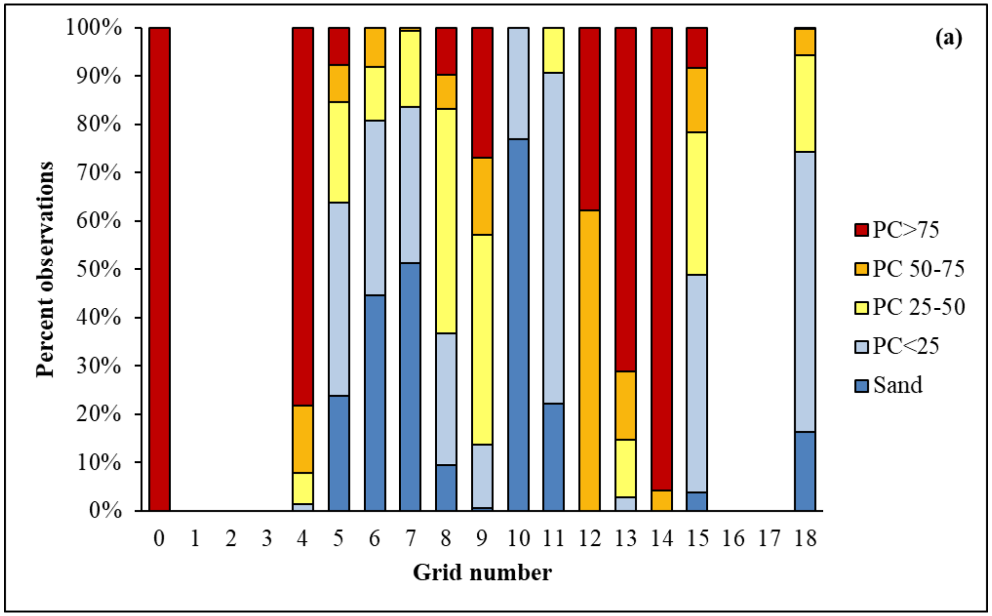
Figure 13. Substrate composition by season

Habitat maps

The number of categorical points per grid square (for mussel beds, sand, etc.) were calculated to determine the mean number of points to set as a reference for the IDW (**Table 5**). Due to PDT comments voiced at the February 2021 meeting concerning assumptions the IDW tool was making about the whole sampling area, we restricted the interpolation around the tow transect; the distance was calculated based on mean lengths of substrate patches along a tow path. Then, substrates and macroalgae coverage data were interpolated with a maximum distance radius of 58.58 m using the IDW tool. The total substrate composition from annotated video tows is shown in **Table 6**. For substrate coverage, all 39,595 data points from all seasons were combined and interpolated to the whole sampling area using IDW (**Figure 21**). In addition, bar plots by grid comparing substrate coverage were generated seasonally (**Figure 14** through **Figure 20)**. Clam catch (CPUE), mussel beds, mussel clumps, boulders, peat and shell hash were plotted using hard data points and are displayed on the interpolated substrates to determine if the substrates and epifauna/topographical features showed any consistent association (**Appendix B**). Sand dunes were removed from the analysis due to annotators documenting sand dunes and waves interchangeably.

Table 5. Number of data points per grid square per season.

	Summer 2020	Fall 2020	Winter 2020	Spring 2021	Summer 2021	Fall 2021	Winter 2021
Mean	569.6428571	406.7647059	547.375	342.1538462	278.6	622.9166667	526.2
Standard Error	70.95971672	42.65736691	69.04128445	41.56040494	36.00638832	81.48372754	113.4043209
Median	586	390	630.5	348	311	608.5	599
Mode	#N/A	#N/A	#N/A	348	#N/A	#N/A	#N/A
Stnrd Deviation	265.5069482	175.8808295	276.1651378	149.848171	80.51273191	282.2679122	253.5797705
Variance	70493.93956	30934.06618	76267.18333	22454.47436	6482.3	79675.17424	64302.7
Kurtosis	-0.4992753	1.7782236	-0.8210897	1.5861164	-2.7053021	0.7173496	-1.0586163
Skewness	0.200095643	1.314151032	-0.48664408	-0.52496089	-0.48775120	0.75098581	-0.34037554
Range	901	657	874	586	179	971	644
Minimum	185	202	47	4	179	245	186
Maximum	1086	859	921	590	358	1216	830
Sum	7975	6915	8758	4448	1393	7475	2631
Count	14	17	16	13	5	12	5
Largest(1)	1086	859	921	590	358	1216	830
Smallest(1)	185	202	47	4	179	245	186
Con.Level(95.0%)	153.2991479	90.42957816	147.1580144	90.55234348	99.96976061	179.3444751	314.8608717



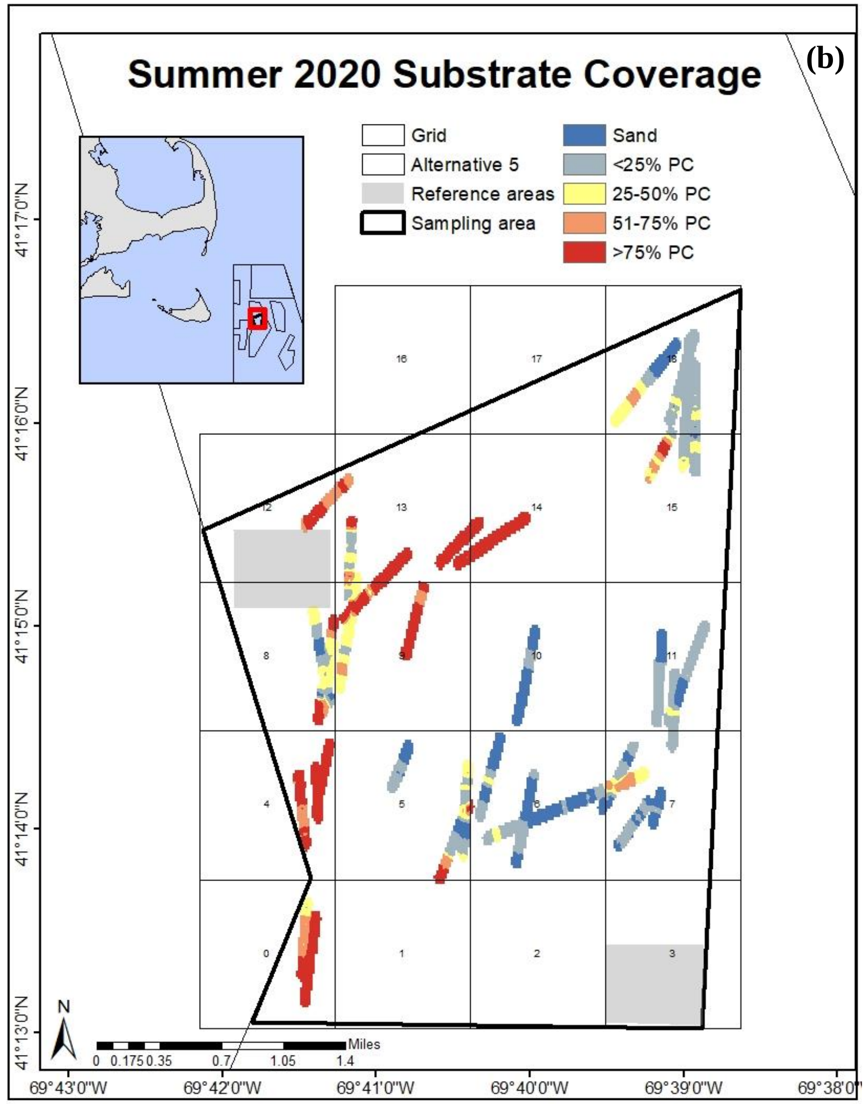
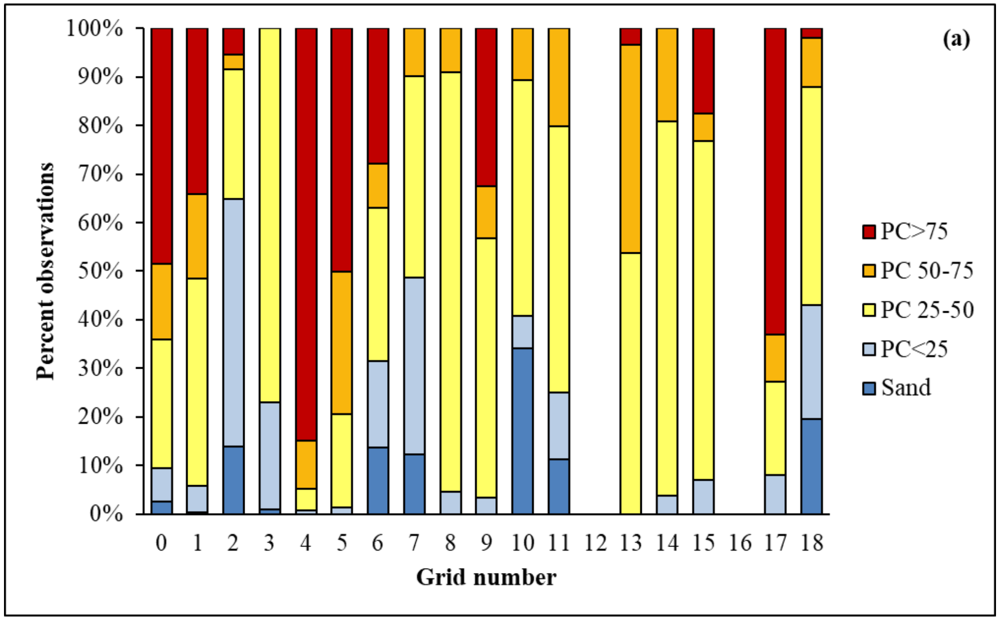


Figure 14. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Summer 2020 **(b)**. PC=Pebble/cobble.



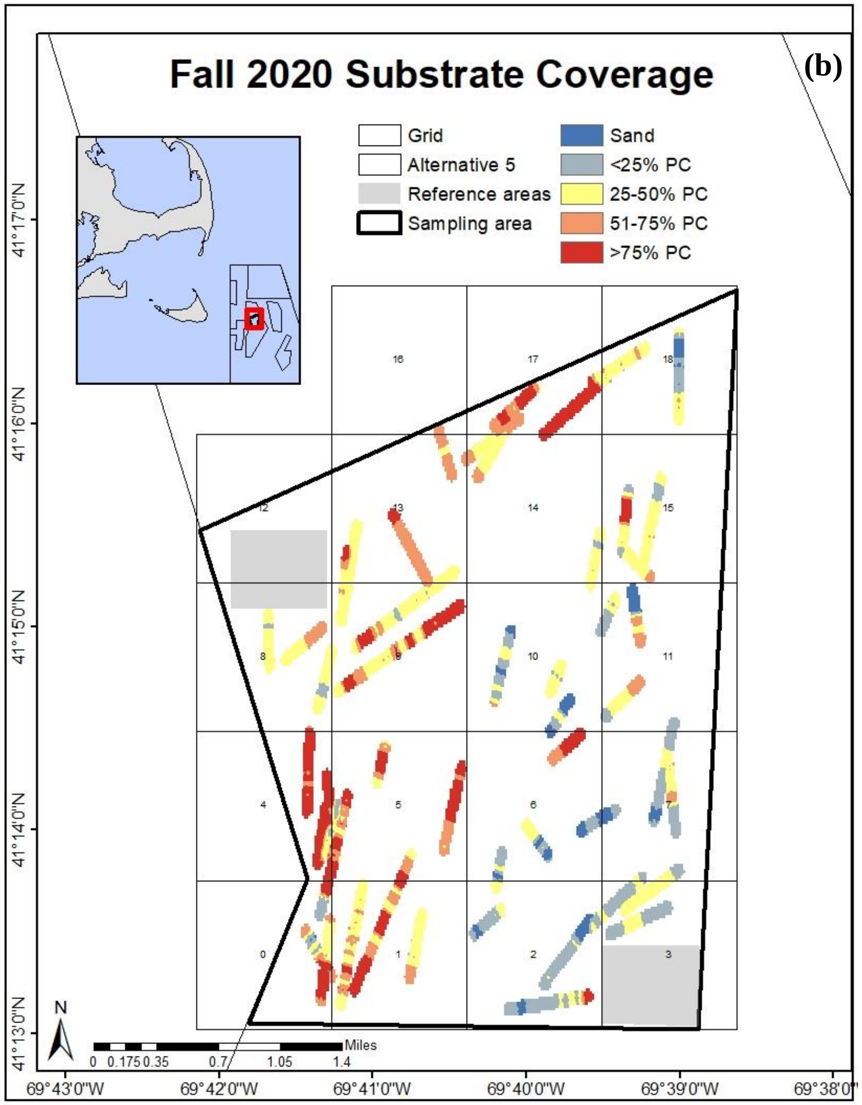


Figure 15. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Fall 2020 **(b)**. PC=Pebble/cobble.

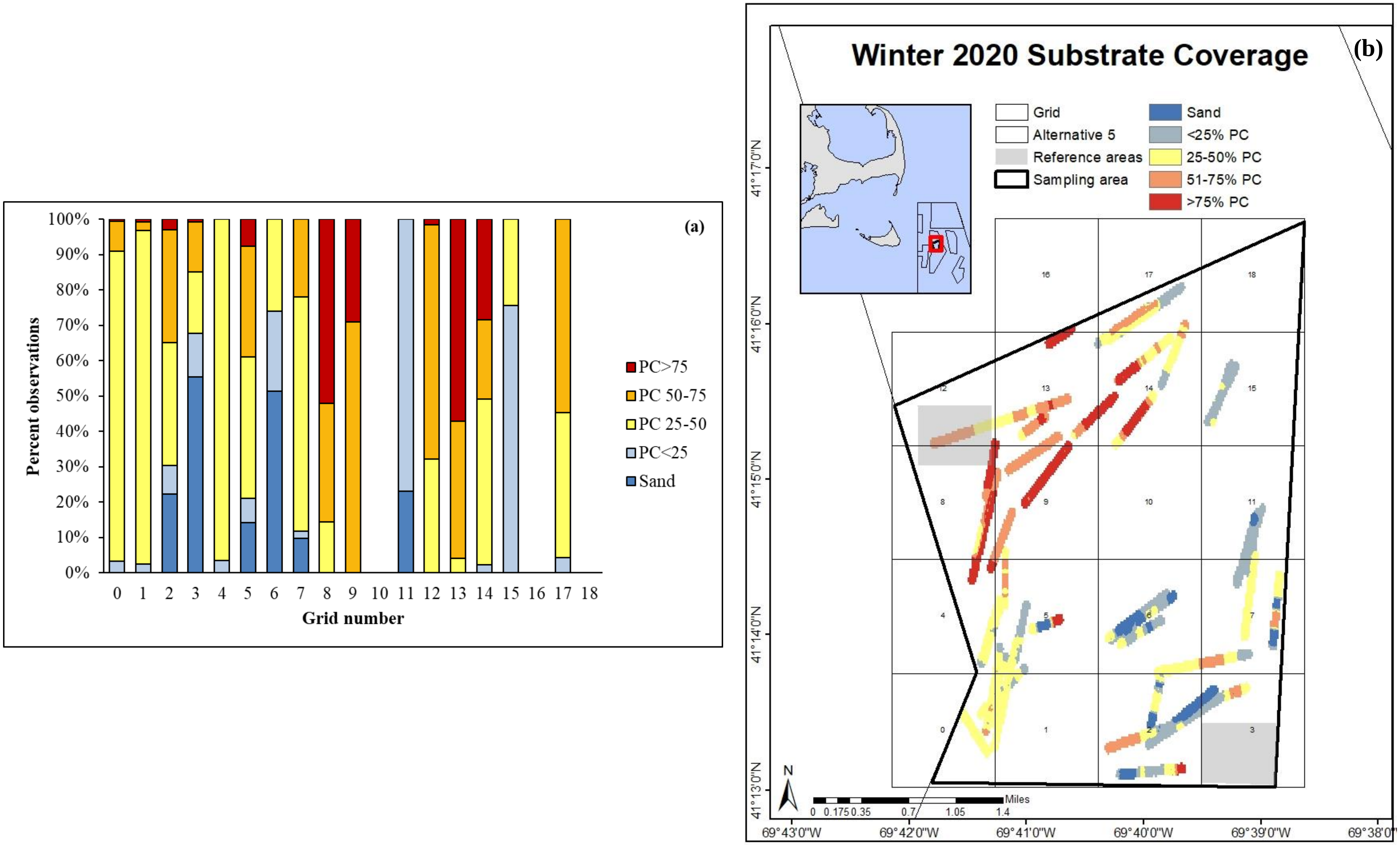


Figure 16. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Winter 2020-2021 **(b)**. PC=Pebble/cobble.

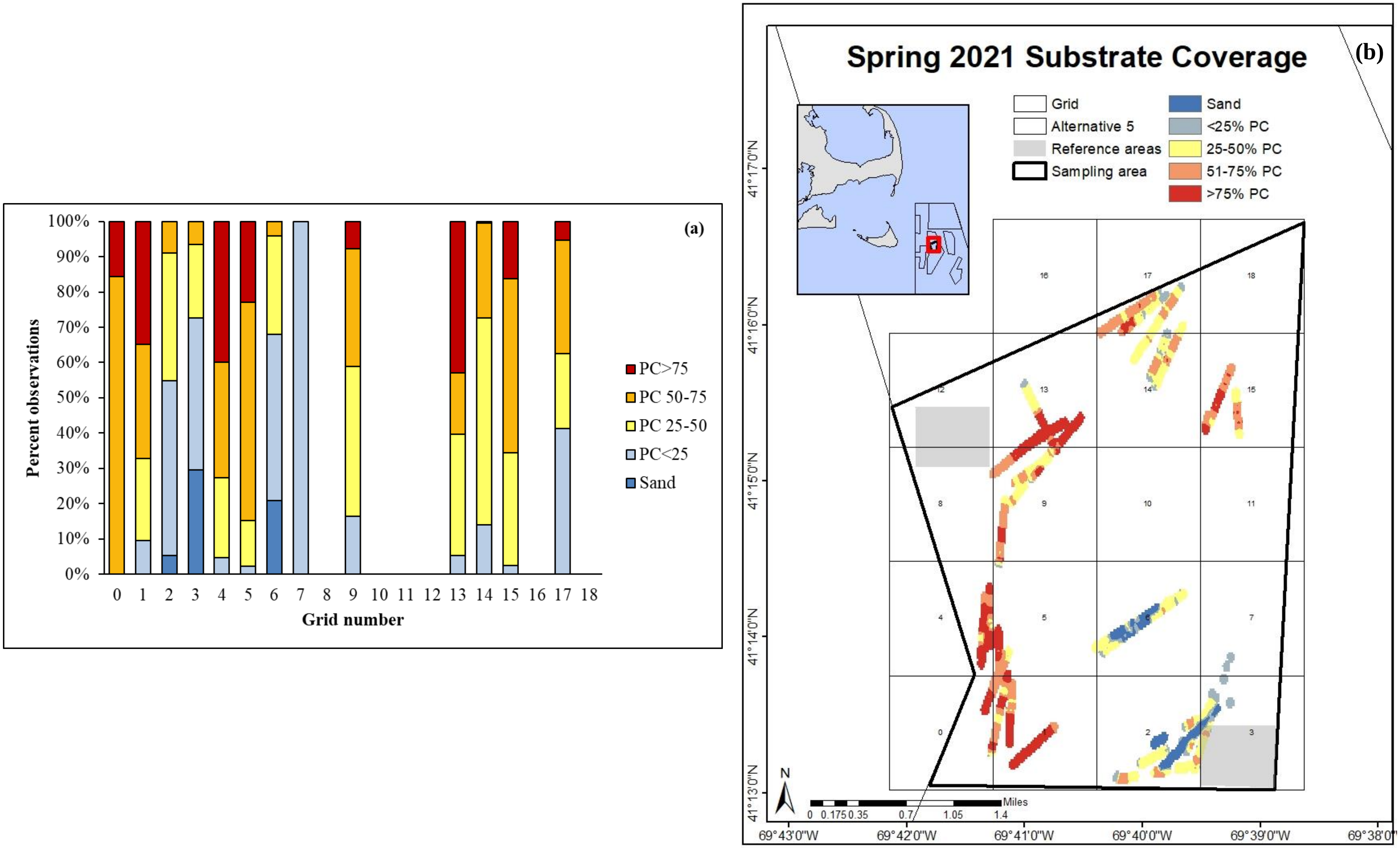


Figure 17. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Spring 2021 **(b)**. PC=Pebble/cobble.

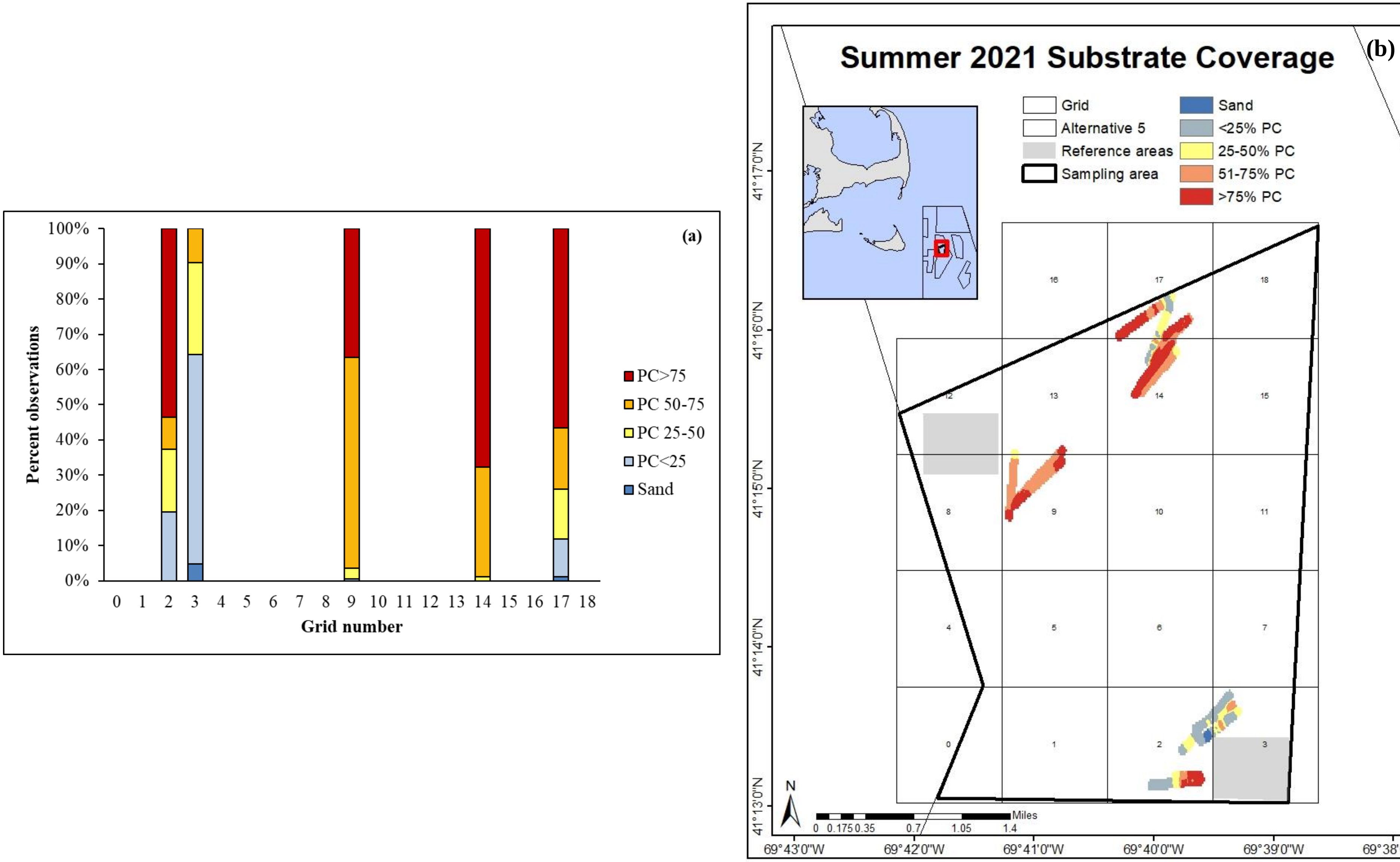


Figure 18. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Summer 2021 **(b)**. PC=Pebble/cobble.

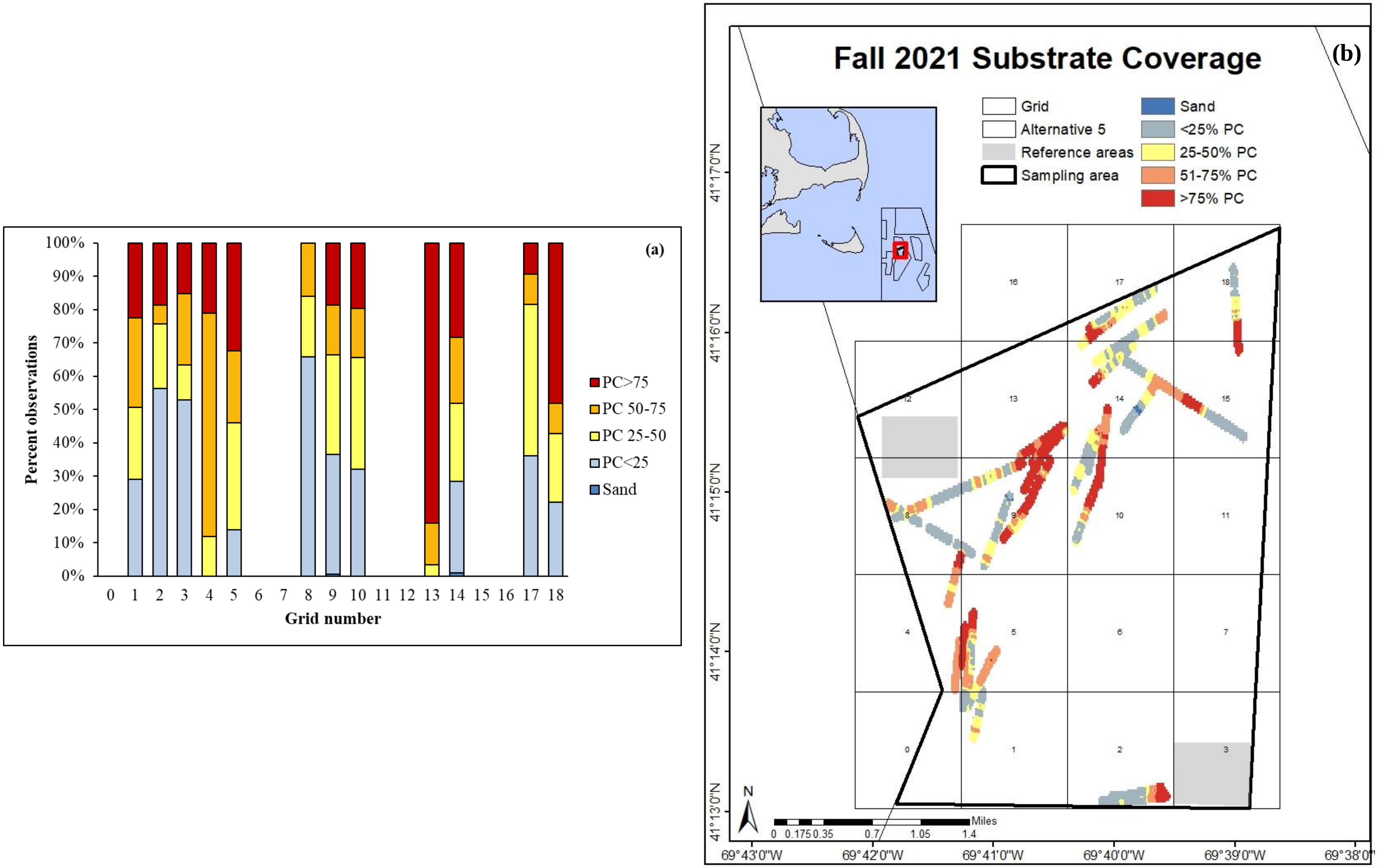


Figure 19. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Fall 2021 **(b)**. PC=Pebble/cobble.

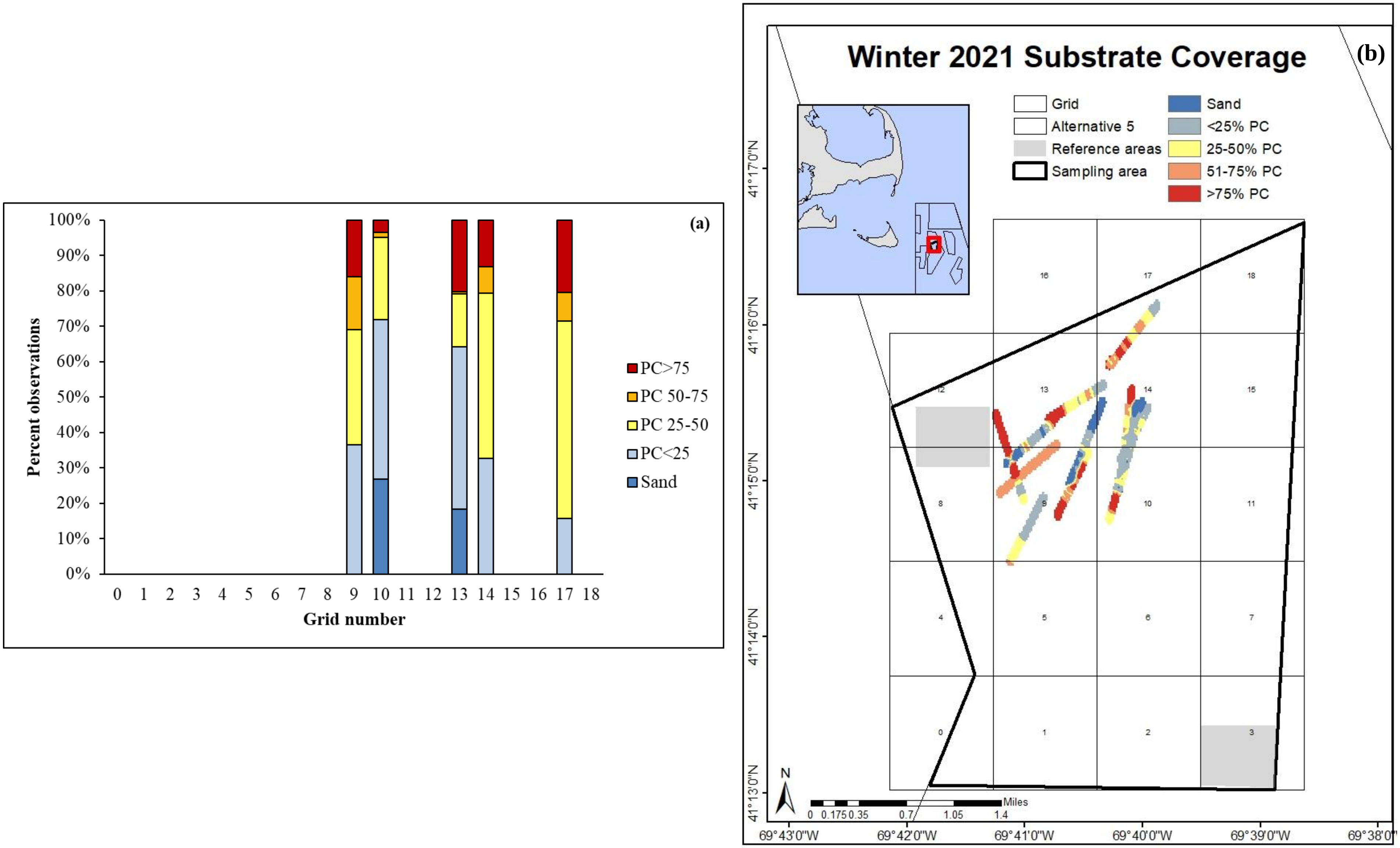


Figure 20. Percent coverage of substrates per grid square **(a)** and interpolated map of substrate coverage for Winter 2021-2022 **(b)**. PC=Pebble/cobble.

Table 6. Total substrate composition from the annotated video tows.

Event	Proportion
Sand	0.09
<25% PC	0.23
25-50% PC	0.31
51-75% PC	0.18
>75%	0.2

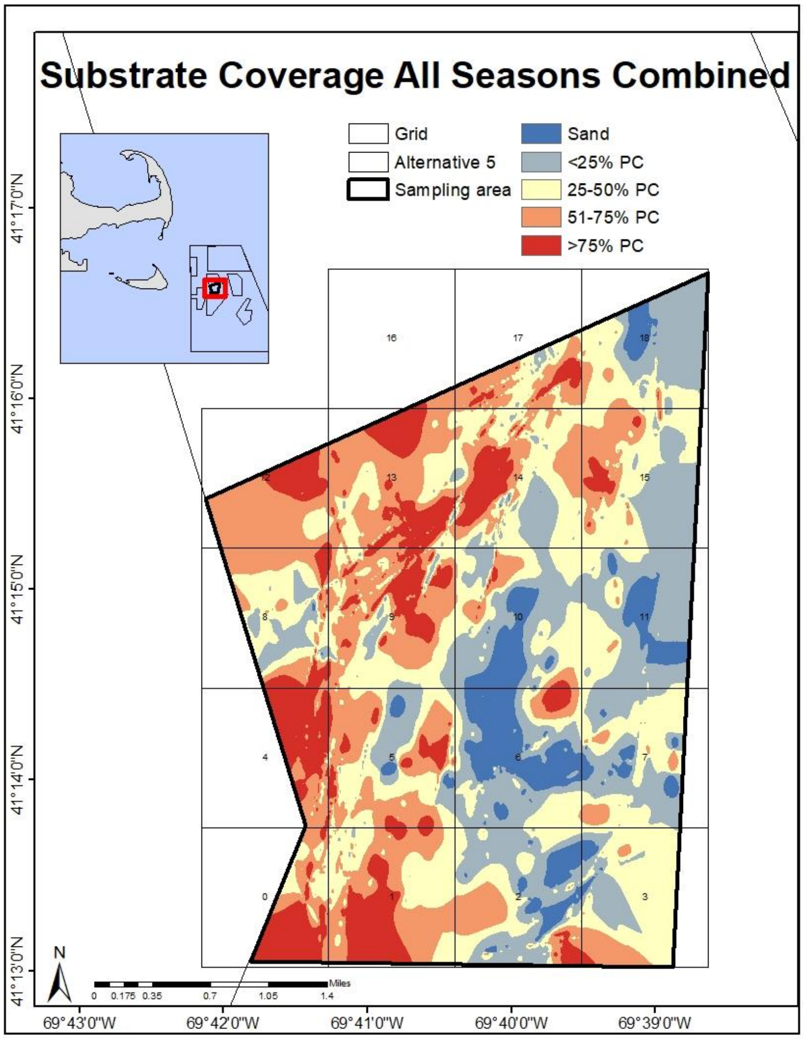


Figure 21. Interpolated map showing substrate coverage from all seasons combined in the research area. PC=Pebble/cobble.

Dredge Path

Twenty-four annotated videos were analyzed at several time scales (**Figure 22**, **Table 7**). Clear indications of paths were a sudden coverage difference in pebble, cobble, and hydroid coverage, as well as live surfclams visible on the sediment. They were often scattered about and clearly were lifted from the sediment (**Figure 23**).

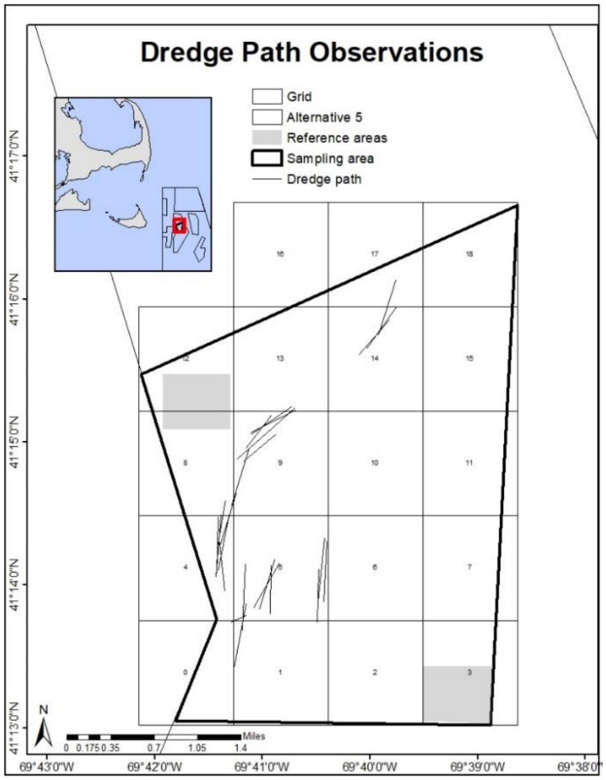


Figure 22. Location of tows annotated for signs of previous dredge paths.

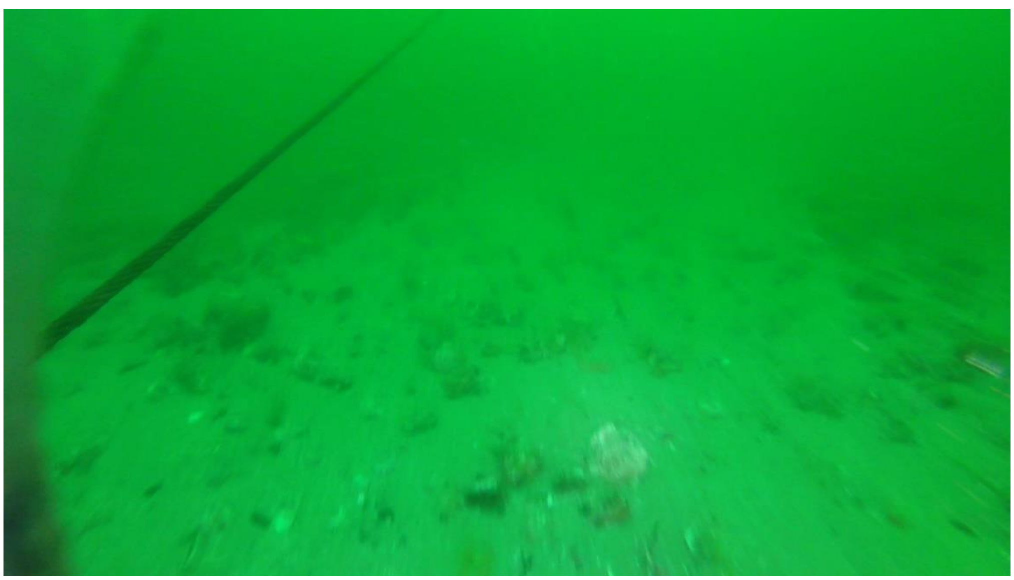


Figure 23. Dredge path seen in trip 16, tow 30. Paths were identified by a change in pebble/cobble or hydroid coverage as well as clams present on the sediment.

Table 7. Number of dredge paths annotated in videos three months apart, one month apart, and hours apart.

	Three Month	**One Month**	**Hours**
Number of Dredge Paths Annotated	0	0	10

Heavily Fished Area

Within the sample area, one region east of the northern reference area was fished the most regularly throughout the fishing period (**Figure 9**) Four tows for each season were selected in this area (**Figure 24**). Since year was not a significant variable in the substrate coverage model, tows from 2020 were combined with tows from 2021 in the heavily fished area (**Figure 25**). See habitat features by season in **Appendix C**.

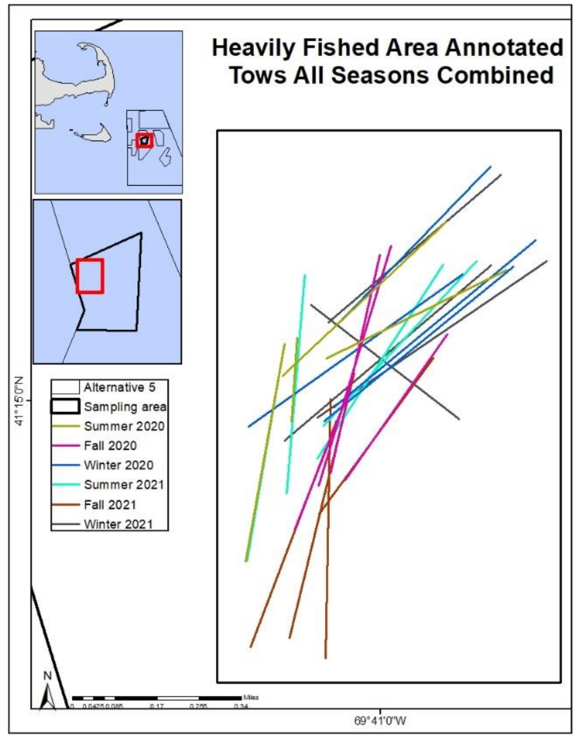
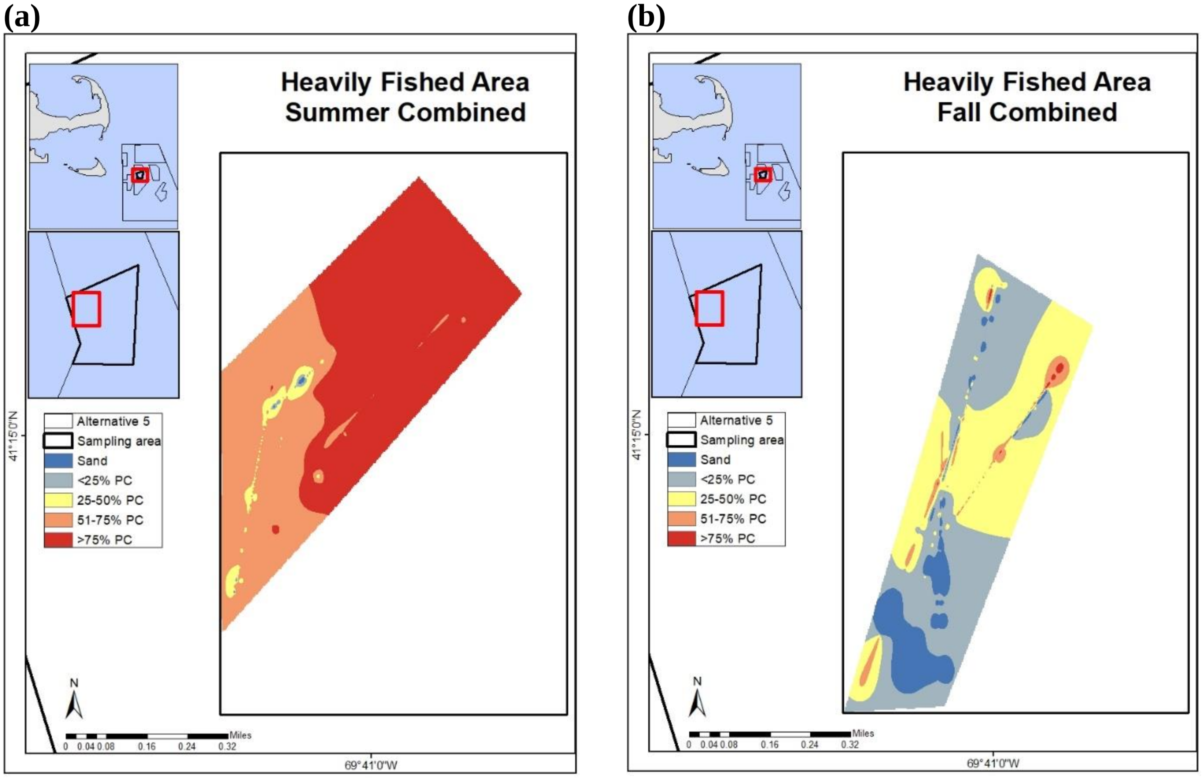


Figure 24. Annotated tow track for the heavily fished area.

(a) **(b)**



(c)

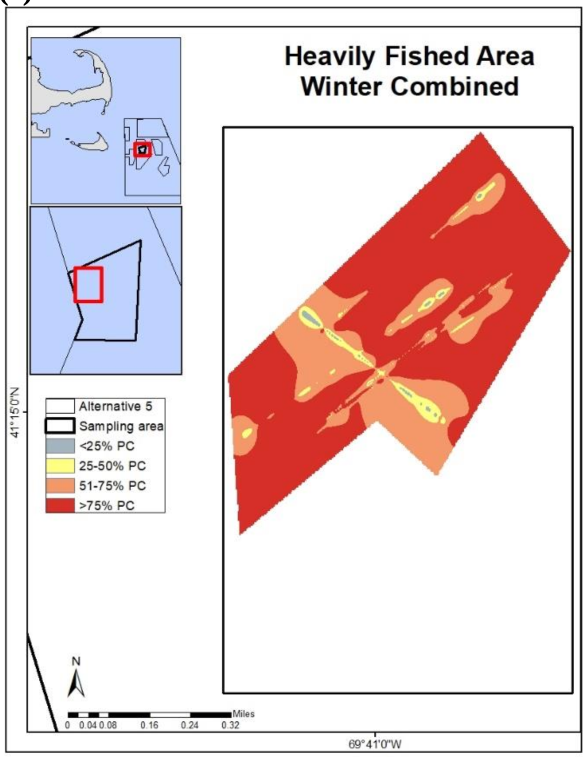


Figure 25. Heavily fished area substrate coverage by season. Summer **(a),** fall **(b)** and winter **(c).**

Benthic Sled

From the two optical surveys, nineteen tows were annotated from the benthic sled, nine from 2020 and ten from 2021 (**Table 8**, **Figure 26**). The annotations were plotted, showing the same fine scale spatial heterogeneity of substrate depicted in the other annotations of the Rose and Crown. The tows from Davis Bank East are more homogenous with sand documented as the most common substrate(51%, **Figure 27**).

Table 8. Area swept per tow with the benthic sled.

Area Swept	2020	2021
Tow 0	0.000911	0.000820
Tow 1	0.000558	0.001714
Tow 2	0.001131	0.000134
Tow 3	0.002445	0.001514
Tow 4	0.002297	0.001589
Tow 5	0.002224	0.002661
Tow 6	0.001773	0.002059
Tow 7	0.001427	0.001279
Tow 8	0.001765	0.001306
Tow 9		0.001547
Total	**0.014532**	**0.014624**

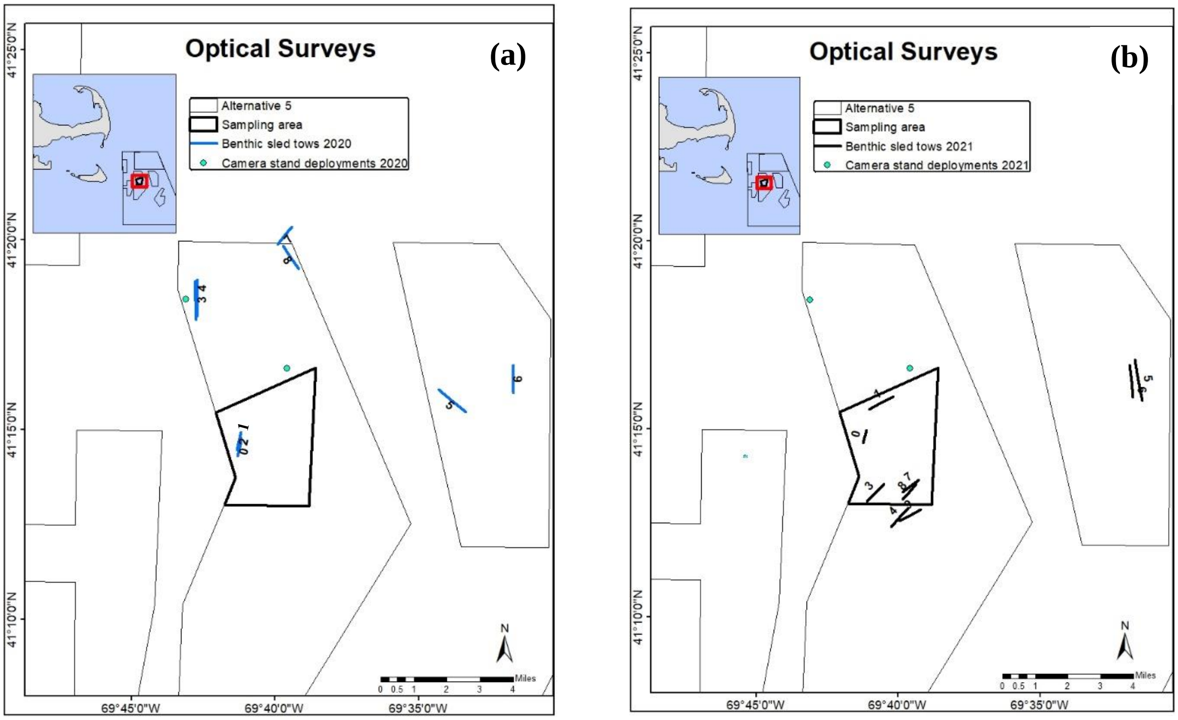
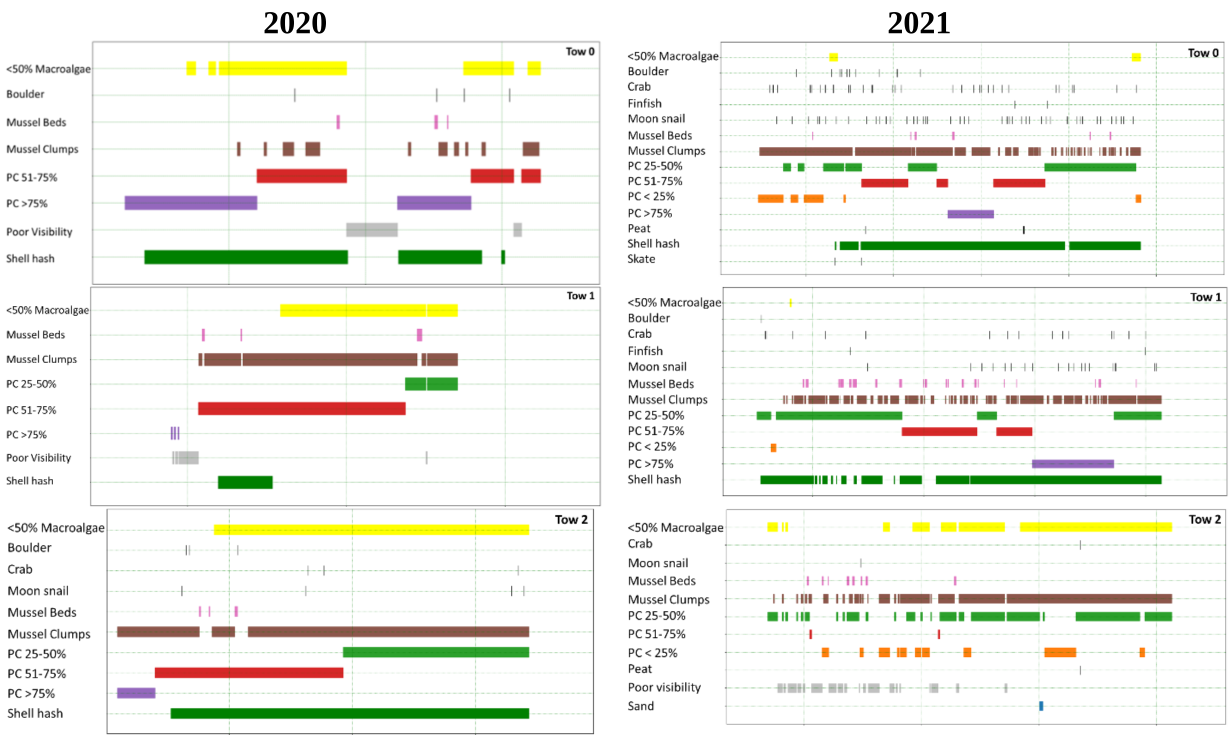


Figure 26. Visual representation of the optical surveys executed in 2020 **(a)** and 2021**(b)**.



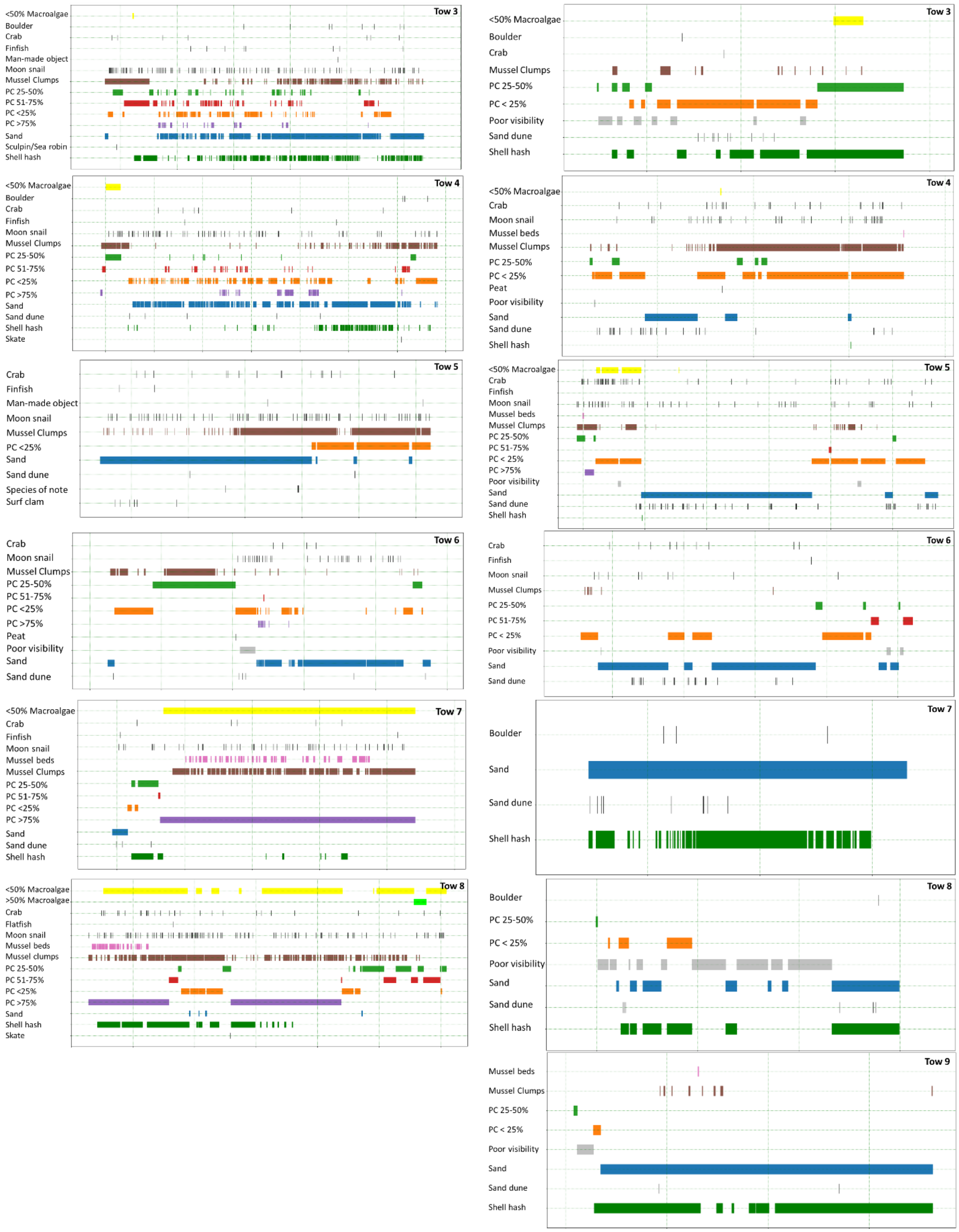


Figure 27. Optical surveys benthic sled BORIS plots by tow by year. Tow number is spatially represented on the optical survey maps (**Figure 26**).

DISCUSSION

This report documents substrate coverage and species presence in areas that experienced fishing effort over a 19-month period. The surfclams landed during the project partially covered research costs. Through our analysis, it was evident that this portion of the HMA is a highly productive surfclam fishing ground. After 3,000 tows, CPUE remained high (**Table 3**). Using dredge-mounted video and fishery-dependent catch estimates, this study provides the first fine-scale depiction of substrate coverage and species composition in a 24 km^2 subarea of the HMA. In addition to video footage, bycatch data was gathered each trip showing this fishery has notably low flatfish and finfish bycatch levels despite observed regular presence in video due to the low towing speed and design of the dredge (Wallace and Hoff 2004).

The Atlantic surfclam fishery is estimated to be worth $40 million nationwide, not including on-shore ancillary businesses, and in the past was the second highest grossing species for the Port of New Bedford (second to scallops). Landings from the closed portions of the HMA totaled around $5.2 million from 2011-2017; while the three exemption areas that remain open accounted for $0.8 million annually (NEFSC 2019). The nearshore proximity and high productivity of the fishing grounds on Nantucket Shoals makes harvesting surfclams in this area economical for the Southern New England small vessel fleet. The high concentration of surfclams allows fishermen to make fewer and shorter tows, supporting the theory that shorter tows improve dredge efficiency (Chai *et al*. 1992). Our model showed that in addition to swept area, oceanographic and temporal processes as well as substrate composition significantly impacts surfclam catch (**Figure 11**). Turbulence, tides, and stratification affect biological behaviors of marine species including schooling, feeding, and vertical migrations. Their behavioral changes affect catchability by commercial fishing gears (Perry *et al*. 2000). This is understandable for swimming species; however, Atlantic surfclams rarely move from their burrows, except due to displacement from strong current and storm events (Fay *et al* 1983).

The bottom habitat maps created in this report are intended to identify the main habitat types in the study area (bottom-habitat patches). The general trend we observed was a high percent of pebble and cobble in the northwest region of the sampling area and a higher percent of sand and less pebble/cobble in the southeast region (**Figure 21**). Consistent seasonality of substrate coverage of the whole area was not observed **(Figure 14** through **Figure 20**). For example, in summer of 2020, 71% of observations saw less than 50% coverage of pebble /cobble while summer of 2021 consisted of 4% of observations (**Figure 14** and **Figure 18**). Rock and boulders are widely distributed in the sample area, showing no seasonal pattern. In addition, the presence of barnacle scars on some rocks and barnacles in the annotated video demonstrates that rocks can be subjected to sediment scour and burial due to the strong hydrodynamic processes that define this area (Powell *et al*. 2020). There is no persistent pattern in seasonal and interannual substrate coverage, lending to the concept that Nantucket Shoals is a high energy environment with frequent strong hydrodynamic events that directly affects sediment movement.

Blue Mussel and Northern horsemussel beds are common to Nantucket Shoals where they serve as a foundation species enhancing local biodiversity (Norling and Kautsky 2008). Mussel bed presence show no seasonal trends but there is a clear visual relationship between higher pebble/cobble coverage and distribution of mussel beds in the sample area. The presence of mussel beds in the tow path may be correlated with sand movement, as seen in the decrease of mussel bed occurrence and in pebble/cobble coverage between fall and winter 2020 (**Figure B4: Appendix B**). Mussel clumps are nearly ubiquitous in the sample area across all seasons, the average tow consisted of 11.7% ± 0.77 mussel clumps and 2.7% ± 0.46 beds. Not only were clumps common in tracts between where beds were found, they were located on all substrate types.

Despite the uneven distribution of the tows, the presence of hydroids and macroalgae remained similar throughout the sampling period with the exception of winter 2021 where we did not observe >50% coverage (**Figure B3: Appendix B**). There were several areas in the southeastern portion of the sampling area that had <50% or no hydroid/macroalgal coverage throughout multiple seasons. Visual representation shows a possible relationship between >50% macroalgal coverage and higher pebble/cobble distribution. Higher algae coverage is noted in areas with more pebble and cobble cover. Coverage of macroalgae and hydroids is persistent year-round, with an observed decline seen in the winter season (**Figure B3: Appendix B**). Shell hash provides additional hard substrate throughout the study area and is noted so often and in all grid squares, though no seasonality or relationship to substrate is demonstrated (**Figure B8: Appendix B**).

Seasonal storm events beginning in mid-fall and lasting through mid-spring naturally alter the substrate composition (Twitchell 1983, Harris *et al*. 2012). From the highly fished area subset of videos, our model showed a strong seasonal effect independent of year. We observed, and the model predicted, that sand coverage increased in fall (**Figure 25**). While we observed variation in substrate coverage among seasons, composition within seasons was similar between years. The shifts in sediment coinciding fall and winter storm events can also bury or exhume boulders, mussels, and other benthic features. An unexpected finding of this study was tracts of forest peat amidst the sandy and rocky substrate following a nor'easter in October 2021. Peat and woody debris embedded in the seafloor of this region was discovered by Emery et al. (1965) and used to determine the sea level following the last ice age. Exposed patches of peat were visible in the video footage prior to the dredge's passing. While the ecological significance of this material is as yet known, it contributes to the substrate composition of the Nantucket Shoals system and could be important to marine life. We observed peat not only following the storm event, but regularly throughout the 19-month period (see **Figure B7: Appendix B**).

Traditionally, Atlantic cod have been observed spawning on Nantucket Shoals from November to April, with peak activity in December and January (Schroeder 1930). DeCelles et al. (2014) conducted interviews with fishermen where they often described sandy areas and sand "lumps" as preferred spawning habitat, but hard bottom habitats with gravel substrate were also important. Furthermore, the fishermen determined that spawning grounds for cod often included complex bathymetric features such as ridges, valleys, and deep holes. Dense concentrations of shellfish such as surfclams and mussels also play a role in where cod spawning occurs. On Nantucket Shoals, fishermen noted that cod aggregated in narrow deeper channels often surrounded by shoals, in depths ranging from 19 to 38 meters. We found individual cod in video annotations from early November and December, as well as May and early June; however, our observations were limited to 6 of 2114 total fish events (**Figure D1: Appendix D**). The individuals were seen over several habitat types. It is well documented that cod stocks are significantly below target population levels, are overfished and overfishing is occurring (NOAA 2022). The removal of the once-dominant cod from Nantucket Shoals caused trophic linkages to change and opened the area for other large predatory fish to inhabit (Frank *et al*. 2005). In addition to the existential threat of commercial fishing to cod stocks, climate change is significantly impacting their distribution range and abundance (Drinkwater 2005).

Ocean warming-induced range shifts have become more prevalent in recent decades (Parmesan and Yohe 2003). Cape Cod, Massachusetts (MA) was historically the northern limit for the black sea bass which was thought to be constrained by offshore winter temperature (Miller *et al*. 2016). Increased bottom-water temperature on the Continental Shelf associated with climate change has extended the suitable thermal range for black sea bass, leading to a poleward expansion into waters of northern MA and the Gulf of Maine (Bell *et al.* 2015, Miller *et al*. 2016). Commercial and recreational regulations have been slow to adjust to the increasing black sea bass biomass of the northern stock, leading to an estimated spawning stock biomass of 2.4 times that of the reference point (NEFSC 2020). Interspecific competition may also play a role in the sea bass increase, due to large groundfish species generally having lower stock biomass in recent decades and being replaced by smaller fish including sculpin and cunner. Sea bass are aggressive and territorial and can easily outcompete smaller bodied fish for space and resources (McMahan *et al*. 2020).

A total of 520 individual black sea bass were observed during the study. There was a clear seasonal trend in the abundance of black sea bass with the highest instances in summer and fall (**Figure 12**, **Figure D2: Appendix D**). This pattern was also observed for dogfish (**Figure D3: Appendix D**). Flatfish prefer transitional habitat in areas at the edge of pebble/cobble substrates (**Figure D4: Appendix D**). There was a positive relationship between flatfish and the presence rocks and boulders as predicted by our model (**Figure 12**). There was as negative relationship between the total proportion of the tow occupied by mussel clumps and the abundance of black sea bass and dogfish. Spiny dogfish (the majority of the documented dogfish) are highly migratory and generalist feeders not known to associate with structured habitat (Bigelow and Schroeder 1953). Black sea bass are usually associated with structure (NEFSC 2020); however, the video footage showed the individuals distributed over all habitats observed.

In addition to identifying high levels of spatial heterogeneity in the study area, the work conducted also noted high levels of temporal heterogeneity. Bottom types in the area changed not only between seasons, but also over shorter time spans of weeks or even days following disturbance events like storms. Because the study was funded by the catch, there was a bias in the sampling effort guided by the vessel captain's choice of area based on catch efficiency and prior experience fishing the area. This led to uneven sampling across the sampling grid, seasons, and years. To account for this, the subset of videos was selected to mimic a stratified, random survey; however, some sampling bias due to fisherman's choice remained. By restricting our assessment of the changes in substrate coverage over year and season to the heavily fished area we avoided drawing conclusions from the fisherman's choice in the whole sampling area. A subset of videos was annotated to look for evidence of dredge impact on substrate and other benthic features at various time intervals (**Table 7**). It was difficult to detect dredge paths which could only be confidently identified during the same 24-hour period following disturbance. This suggests the impacts are relatively short-lived; however, our inability to visually detect dredge paths at time intervals greater than 24 hours leaves uncertainty regarding longer term affects.

The parameters in play and the limiting factors to productivity and hard bottom are less understood in areas like the HMA than in areas of low energy regimes. It is our speculation that productivity is a function of disturbance in this area, following disturbance theory norms (Sousa 1984). Heavily disturbed areas are hypothesized to have lower levels of diversity. This raises the question of whether fishing impacts are significant relative to natural disturbance. Due to the nature of our sampling, distinguishing between the two factors is difficult. Our sampling area is without a doubt a productive surfclam fishing ground that experiences strong current and storm events that seem to naturally alter the benthos. There are definite seasonal trends in area usage for finfish and dogfish as seen in our annotations; however, fish bycatch in the dredge was markedly low relative to other fisheries.

Research under this EFP was a collaborative effort between industry members, scientists and members of management agencies. It was an iterative development of research goals, objectives, and methods while approaching a controversial issue surrounding allocation of ocean area use. Moving this method of data collection to an area larger than <1% of the HMA will provide useful information to fill data gaps concerning fine-scale habitat distribution in the HMA. Future efforts could be altered to provide an even distribution of data collection in both time and space. For example, a stratified random sampling approach applied to a larger area in the HMA could provide robust estimates of substrate and species compositions observed. If funding was secured, regular optical surveys could be accomplished, and the addition of acoustic mapping techniques would produce precise bathymetrical measurements and help scale the features identified in video footage.

LITERATURE CITED

Agresti, A., 2018. An introduction to categorical data analysis. John Wiley & Sons.

Bell, R.J., Richardson, D.E., Hare, J.A., Lynch, P.D. and Fratantoni, P.S., 2015. Disentangling the effects of climate, abundance, and size on the distribution of marine fish: an example based on four stocks from the Northeast US shelf. ICES Journal of Marine Science, 72(5), pp.1311-1322.

Bigelow, H.B., and Schroeder, W. C. 1953. Fishes of the Gulf of Maine. Washington: U.S. G.P.O.

Cargnelli, L., Griesbach, S., Packer, D., Weissberger, E. 1999. Essential fish habitat source document: Atlantic surfclam, *Spisula solidissima*, life history and habitat characteristics. NOAA Tech Memo NMFS NE 142: p 13.

Chai, A., Homer, M., Tsai, C., Goulletquer, P. 2011. Evaluation of oyster sampling efficiency of patent tongs and an oyster dredge. North American Journal of Fisheries Management, 12:4, p 825-832.

DeCelles, G. R., Martins, D., Zemeckis, D. R., and Cadrin, S. X. 2017. Using Fishermen's Ecological Knowledge to map Atlantic cod spawning grounds on Georges Bank. – ICES Journal of Marine Science: 74: 6, p1587–1601.

Drinkwater, K.F. The response of Atlantic cod (Gadus morhua) to future climate change. ICES Journal of Marine Science, Volume 62, Issue 7, 2005, p 1327–1337.

Emery, K.O., Uchupi, E., 1965. Structures of Georges Bank. Mar. Geol. 3, p 349-358.

ESRI (Environmental Systems Research Institute). 2016. ArcGIS 10.4.

Fay, C.W. Neves, R.J., Pardue, G.B. 1983. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): surf clam. U.S. Fish Wildlife Services, Division of Biological Services. FWS/OBS-82/11: p 13.23.

Frank, K.T., Petrie, B.P., Choi, J.S., Leggett, W.C. 2005. Science: 308, p 1621.

Friard, O. and Gamba, M. 2016. BORIS: a free, versatile open-source event-logging software for video/audio coding and live observations. Methods in Ecology and Evolution 7, 211: p 1325-1330.

Harman B.I., Koseoglu, H., Yigit, C.O. 2016. Performance evaluation of IDW, Kriging, and multiquadric interpolation methods in producing noise mapping: A case study at the city of Isparta, Turkey. Applied Acoustics. 112, p 147-157.

Harris, B.P., Cowles, G.W., Stokesbury K.D.E., 2012. Surficial sediment stability on Georges Bank, in the Great South Channel and on eastern Nantuckey Shoals. Continental Shelf Research, 49, p 65-72.

Jacobson L., Hennen D . 2019. Improving the NEFSC clam survey for Atlantic surfclams and ocean quahogs. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 19-06; 89 p. Available from: http://www.nefsc.noaa.gov/publications.

Jones, D.S., Thompson, I., and Ambrose, W. 1978. Age and growth rate determinations for the Atlantic surfclam Spisula solidissima (Bivalvia: Mactracea), based on internal growth lines in shell cross-sections. Marine Biology 47: p 63-70.

MAFMC. 2018. Mid-Atlantic Fishery Management Council Atlantic Surfclam Information Document. Dover, DE: Mid-Atlantic Fishery Management Council. 15 p.

Maleika, W. 2020. Inverse distance weighting optimization in the process of digital terrain model creation based on data collected from a multibeam echosounder. Applied Geomatics, 12, p 397-407.

McMahan, M.D., Sherwood, G.D., Grabowski, J.H. 2020. Geographic variation in life-history traits of black sea bass (Centropristis striata) during a rapid range expansion. Frontiers in Marine Science: 7:567758.

Merrill, A.S. and Ropes, J.W. 1969. The general distribution of the surf clam and ocean quahog. Proc. Nat. Shellfish. Assoc. 59: 40-45.

Miller, A.S., Shepherd, G.R. and Fratantoni, P.S., 2016. Offshore habitat preference of overwintering juvenile and adult black sea bass, Centropristis striata, and the relationship to year-class success. PloS one, 11(1), p.e0147627.

NEFMC. 2019. Clam Dredge Framework Adjustment. Available: https://s3.amazonaws.com/nefmc.org/2020-04-21-Final-Clam-Dredge-Framework_signed.pdf.

NEFSC (Northeast Fisheries Science Center), 2020. Operational assessment of the black sea bass, scup, bluefish, and monkfish stocks, updated through 2018.

NOAA Fisheries. 2022. Stock SMART data records. Retrieved from www.st.nmfs.noaa.gov/stocksmart. 06/05/2022

Norling, P. and Kautsky, N., 2008. Patches of the mussel Mytilus sp. are islands of high biodiversity in subtidal sediment habitats in the Baltic Sea. Aquatic Biology, 4(1), pp.75-87.

Parmesan, C. and Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature: 421, 37-42.

Powell, E.N., Mann, R.L., Long, M.C., Timbs, J.R., Kuykendall, K.M. 2021. The conundrum of biont-free substrates on a high-energy continental shelf: Burial and scour on Nantucket Shoals, Great South Channel. Estuarine, Coastal and Shelf Science, 249, 107089.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Schroeder, W. C. 1930. Migrations and other phases in the life history of the cod off southern New England. Bulletin of the Bureau of Fisheries, 46: 136 pp.

Sousa, W. 1984. The role of disturbance in natural communities. Annual Review of Ecological Systems. 15: p 353-391.

Twichell, D.C., 1983. Bedform distribution and inferred sand transport on Georges Bank, United States Atlantic continental shelf. Sedimentology, 30(5), p 695-710.

Wallace, D.H. and Hoff, T.B. 2004. Minimal bycatch in the Northeast Atlantic surfclam and ocean quahog fishery. In: Bycatch in Northeast Fisheries: Moving Forwards. National Marine Fisheries Service, Gloucester, MA. Page 83.

Appendix A: Statistical Analysis Outputs

Table A1. Table of ALL GLMM variables

Variable	Factor type	Range	Catch	Fish
Effort				
Survey number	Random	81 surveys	X	X
Swept area	Continuous	200.13–2044.62 m	*	*
Spatial and temporal				
Year	Categorical	2 categories	*	X
Season	Categorical	4 seasons	*	X
Julian day	Continuous	1–366 days	X	X
Days since June 03, 2020	Continuous	1–589 days	X	X
Diel phase	Categorical	Day or night	*	*
Oceanographic				
Lunar phase	Categorical	8 phases	X	X
Tidal stage	Continuous	−0.38–+0.99 m	*	X
Tidal phase	Categorical	Rising or falling	X	X
Tidal amplitude	Continuous	0.64–1.37 m	X	X
Wind direction	Continuous	0–359°	X	
Sustained wind speed	Continuous	0.60–12.30 m s^{-1}	*	
Wind gust speed	Continuous	1.20–16.00 m s^{-1}	X	
Wave height	Continuous	0.36–2.91 m	X	
Dominant wave period	Continuous	4–13.79 s	X	
Average wave period	Continuous	4–8.76 s	X	
Dominant wave direction	Continuous	1–341°	X	
Environmental				
Depth	Continuous	68.2–100 m	X	X
Substrate	Continuous	0–0.88 % pebble/cobble	*	X
Boulders	Continuous	0–88	X	*
Mussel beds	Continuous	0–0.51% of tow	X	X
Mussel clumps	Continuous	0–0.36% of tow	X	*

Table A2. Model fixed coefficients for surfclam catch.

	Fixef (model_fit)
(Intercept)	-1.5904
SweptArea	0.180221
Coverage	149.4583
SurveyYear2021	112.1608
SeasonSpring	-131.217
SeasonSummer	40.48018
SeasonFall	-3.32939
DayNightNight	32.8178
GP_TidalStage	25.01474
WSPD_m.s	4.43623

Table A3. Model fixed coefficients for black sea bass

	fixef(bsb.model)
(Intercept)	-22.1678
scale(SweptArea)	0.477277
scale(MusselpClumps)	-0.29486
SeasonSpring	0.750269
SeasonSummer	22.28806
SeasonFall	21.25729

Table A4. Model fixed coefficients for dogfish

	fixef(dogfish.model)
(Intercept)	-21.8398
scale(SweptArea)	0.495184
MusselpClumps	-2.13378
SeasonSpring	1.241721
SeasonSummer	21.22351
SeasonFall	20.88411
DayNightNight	1.908476

Table A5. Model fixed coefficients for flatfish

	fixef(flatfish.model)
(Intercept)	-2.12754
scale(SweptArea)	0.423827
Boulders	0.011184
SeasonSpring	1.088475
SeasonSummer	1.52691
SeasonFall	1.312117

Table A6. Significance values generated by the GLMM.

	numDF	denDF	F-value	p-value
(Intercept)	1	132	504.4808	0
SweptArea	1	132	37.8214	**8.60E-09**
Coverage	1	132	10.8381	**0.001276**
SurveyYear	1	76	3.719616	0.057511
Season	3	76	3.477549	**0.019983**
DayNight	1	132	2.703738	0.102493
GP_TidalStage	1	132	4.957623	**0.027671**
WSPD_m.s	1	132	0.771862	0.381238

Appendix B: Tow Tracks, Clam Catch and Habitat Features by Season

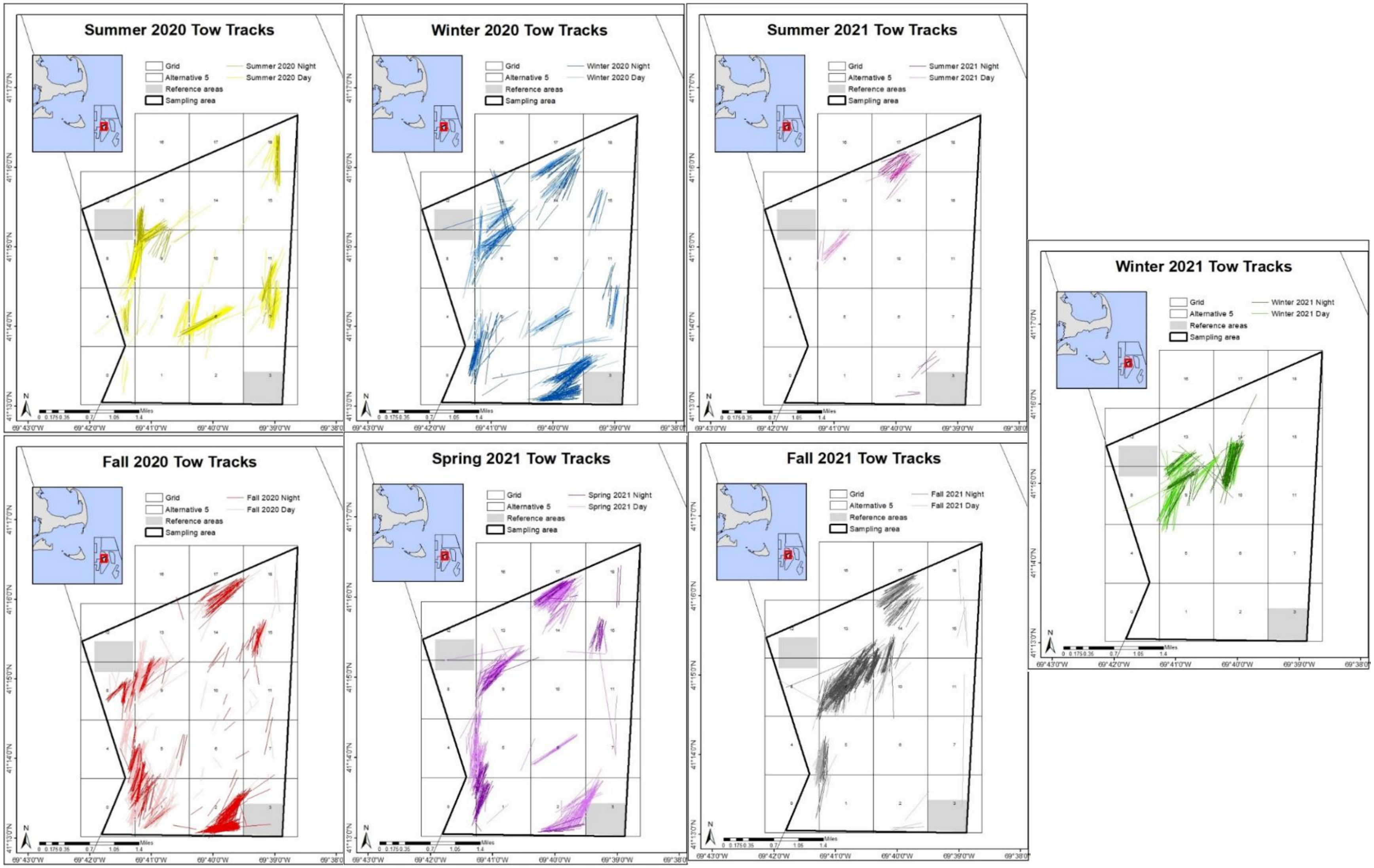


Figure B1. Tow tracks by season.

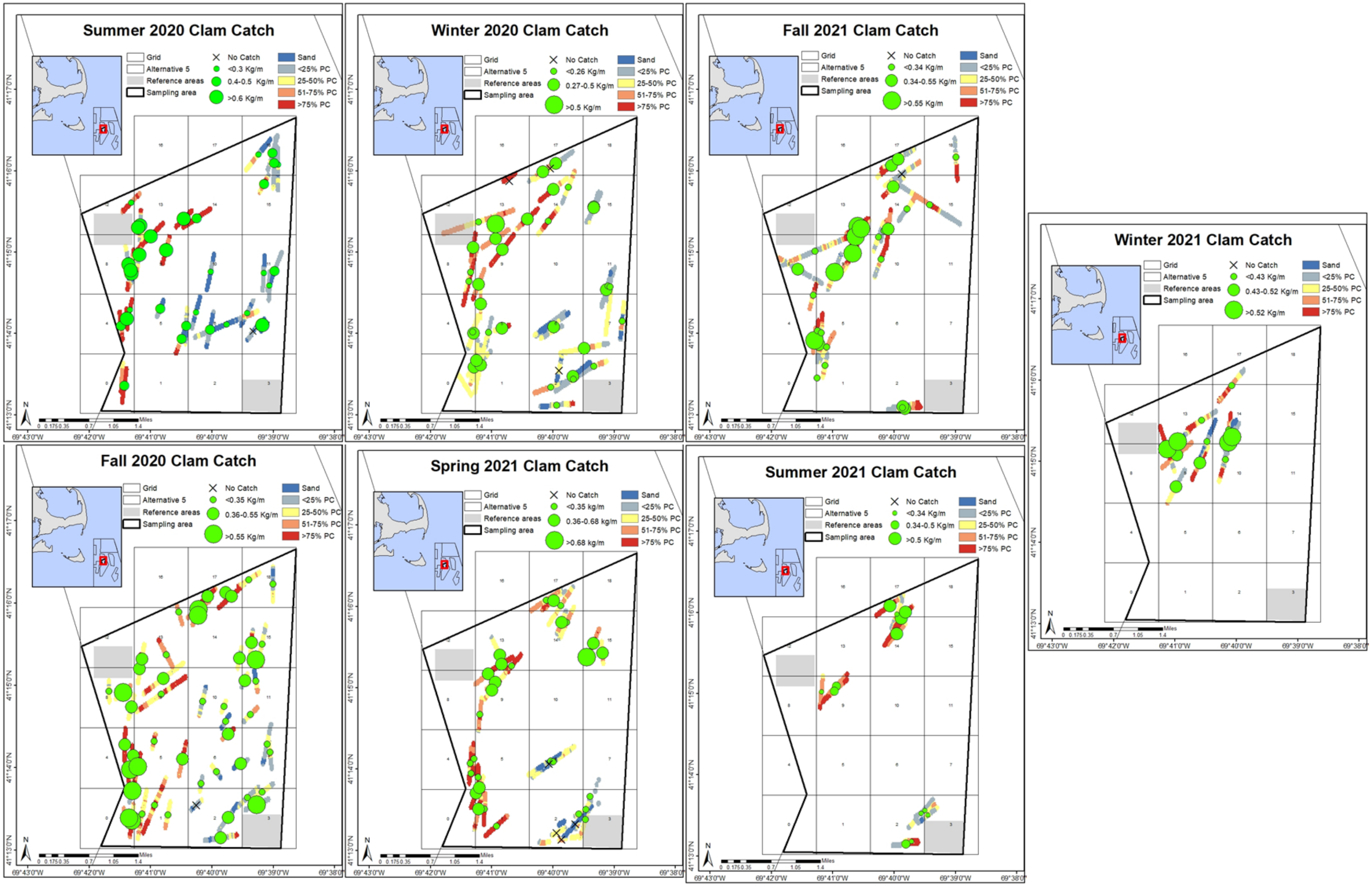


Figure B2. Surfclam harvested in the research area overlayed on the substrate coverage distribution map by season.

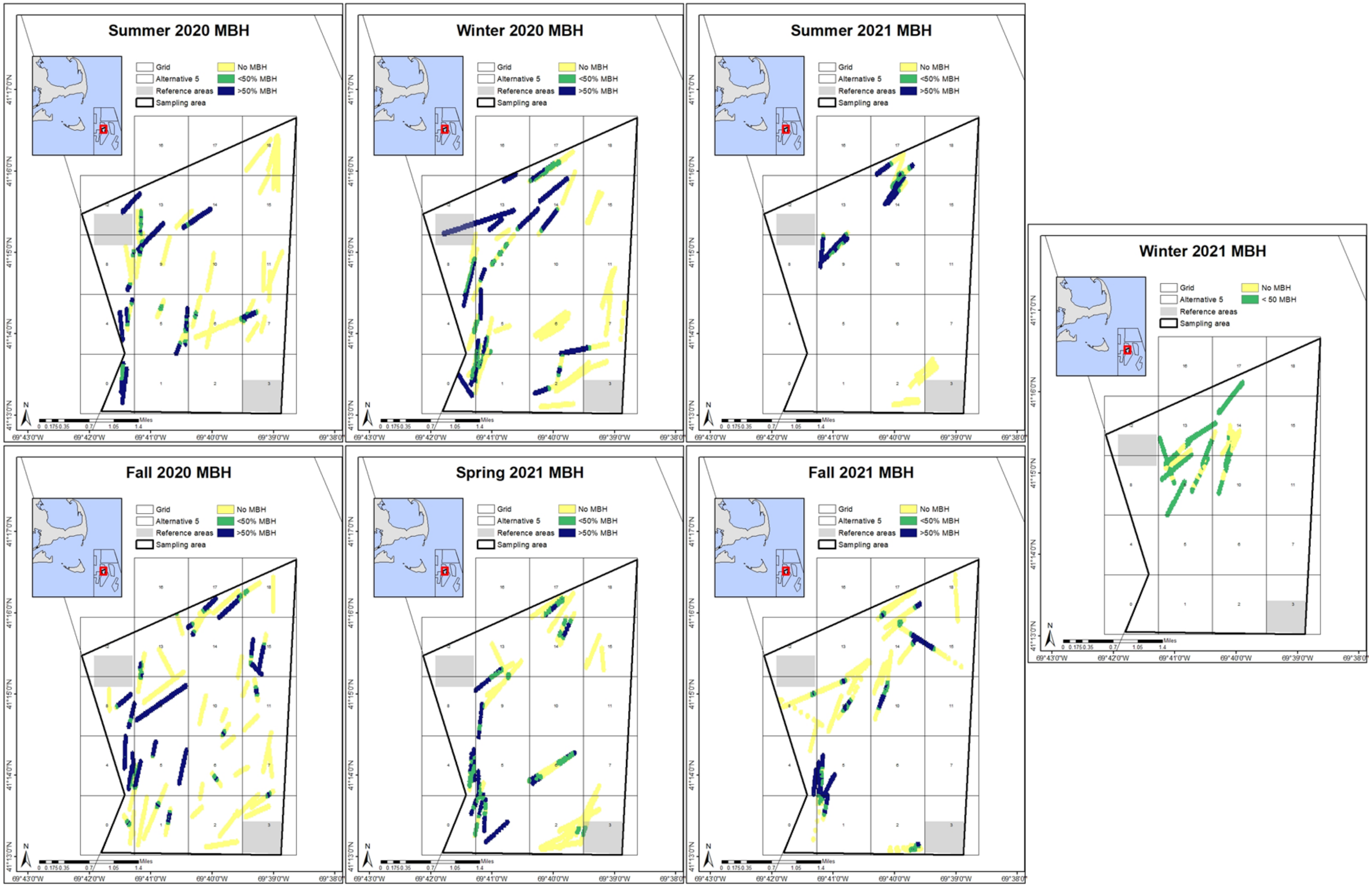


Figure B2. Macroalgae/bryozoan/hydrozoan (MBH) coverage found in the research area by season.

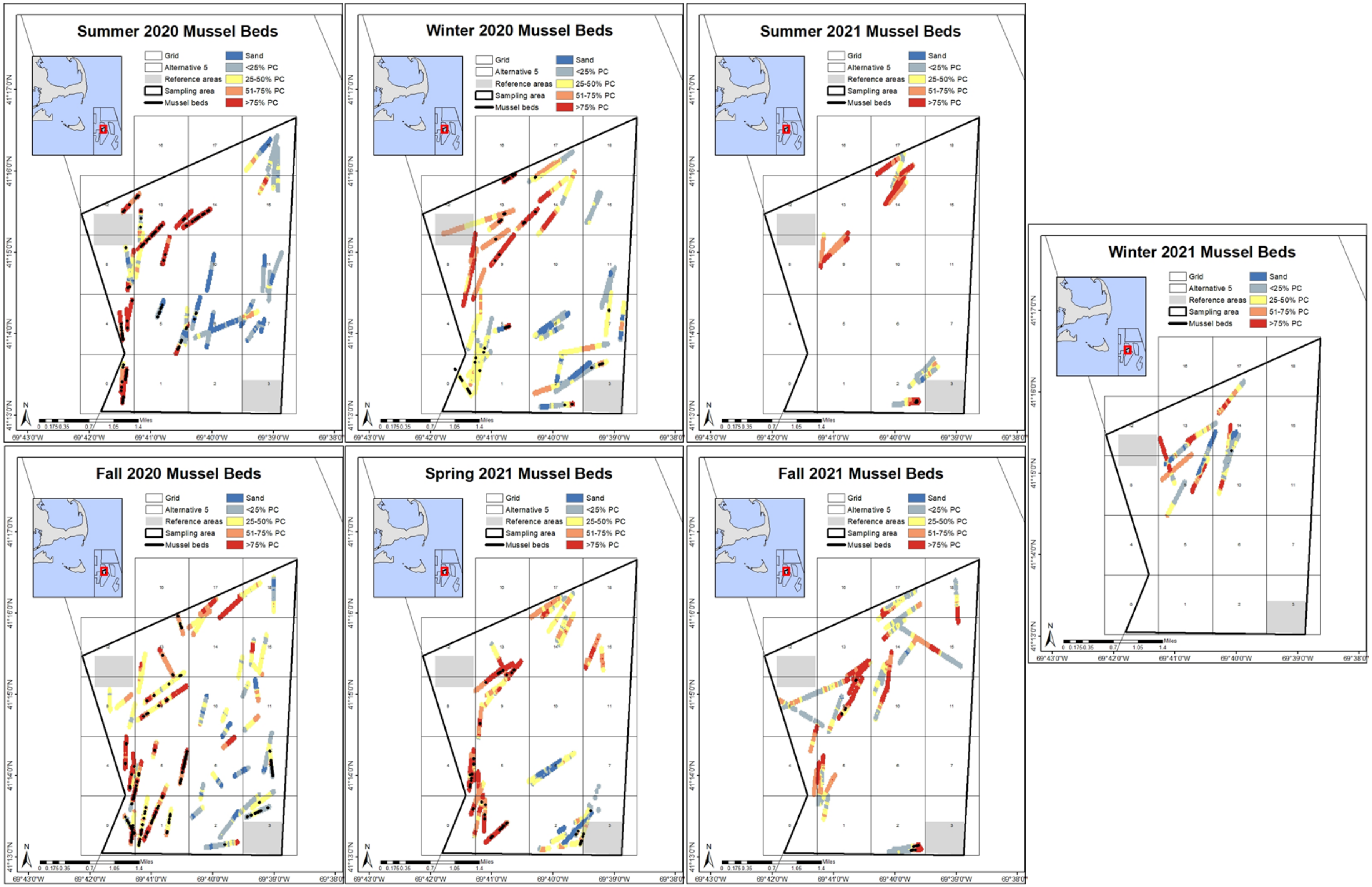


Figure B3. Mussel beds found in the research area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

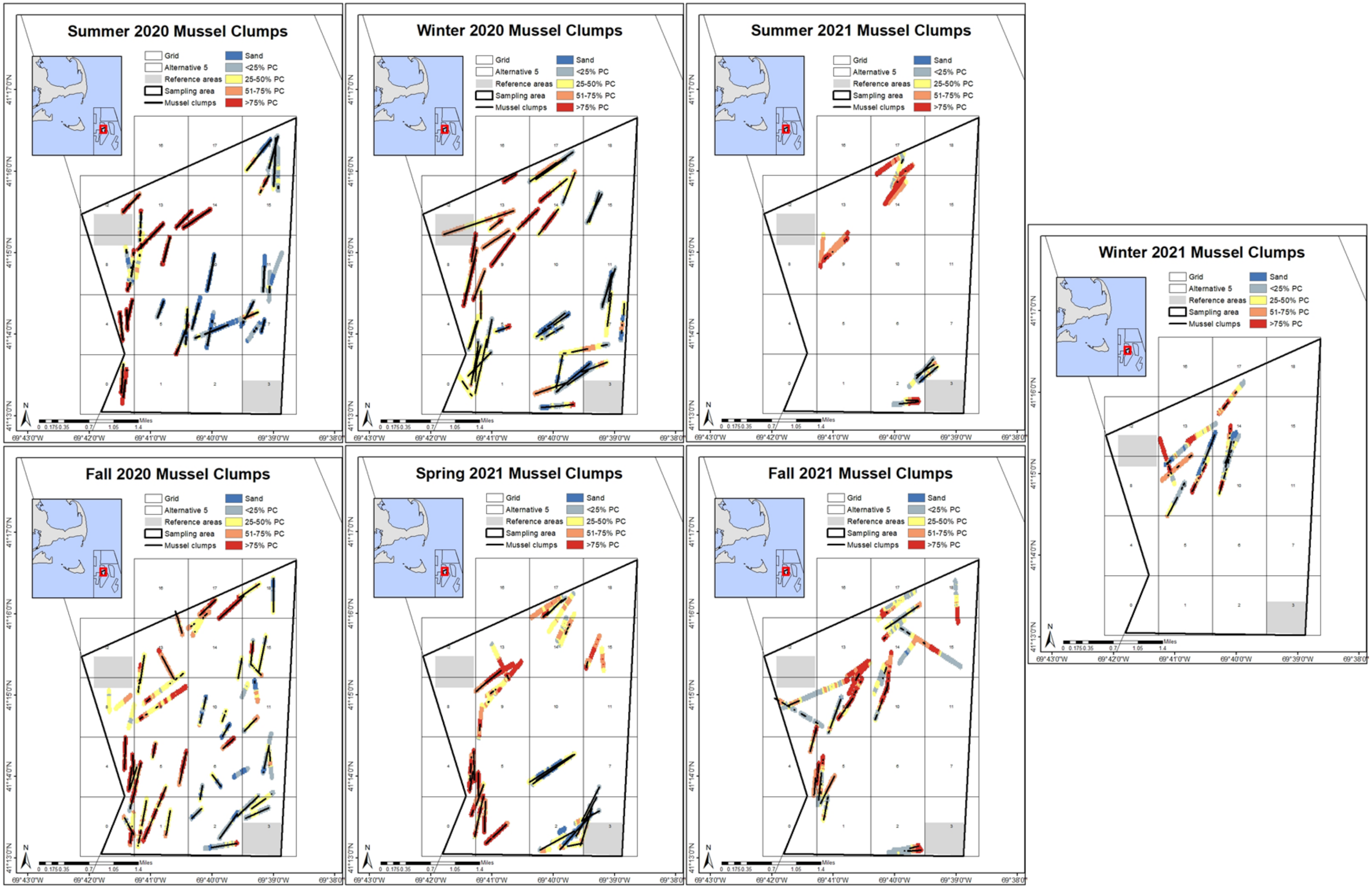


Figure B4. Mussel clumps found in the research area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

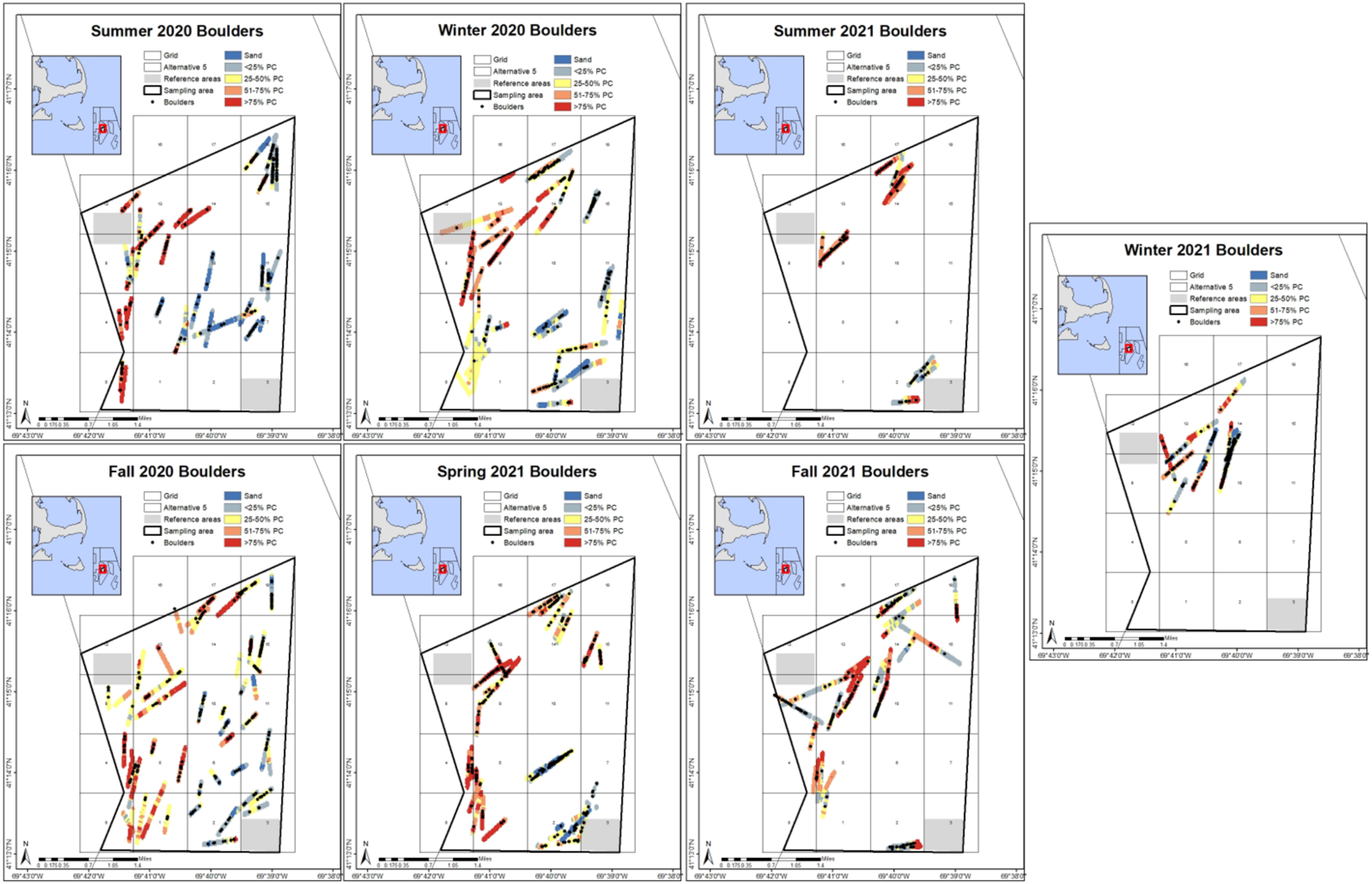


Figure B5. Boulders found in the research area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

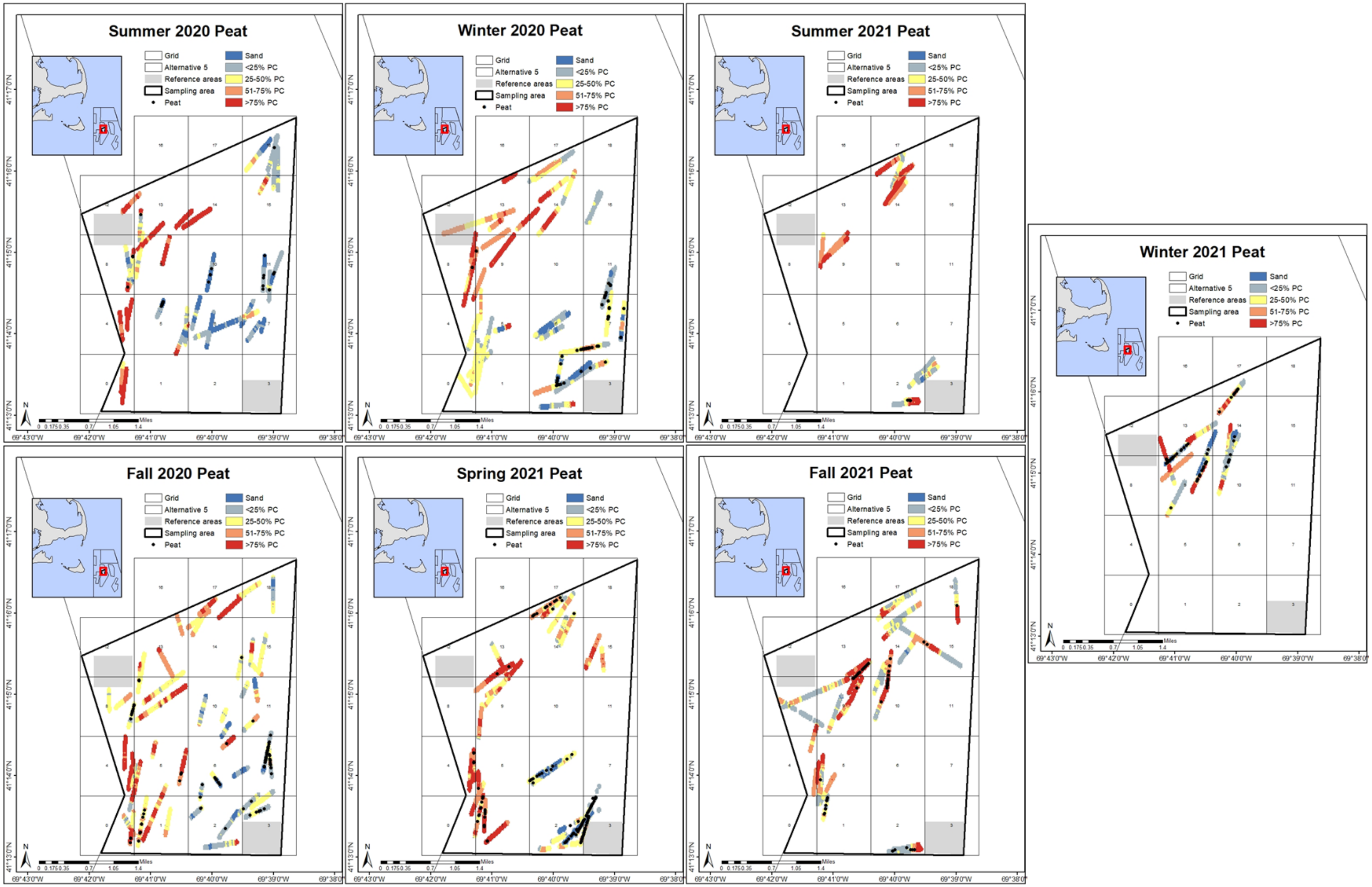


Figure B6. Peat found in the research area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

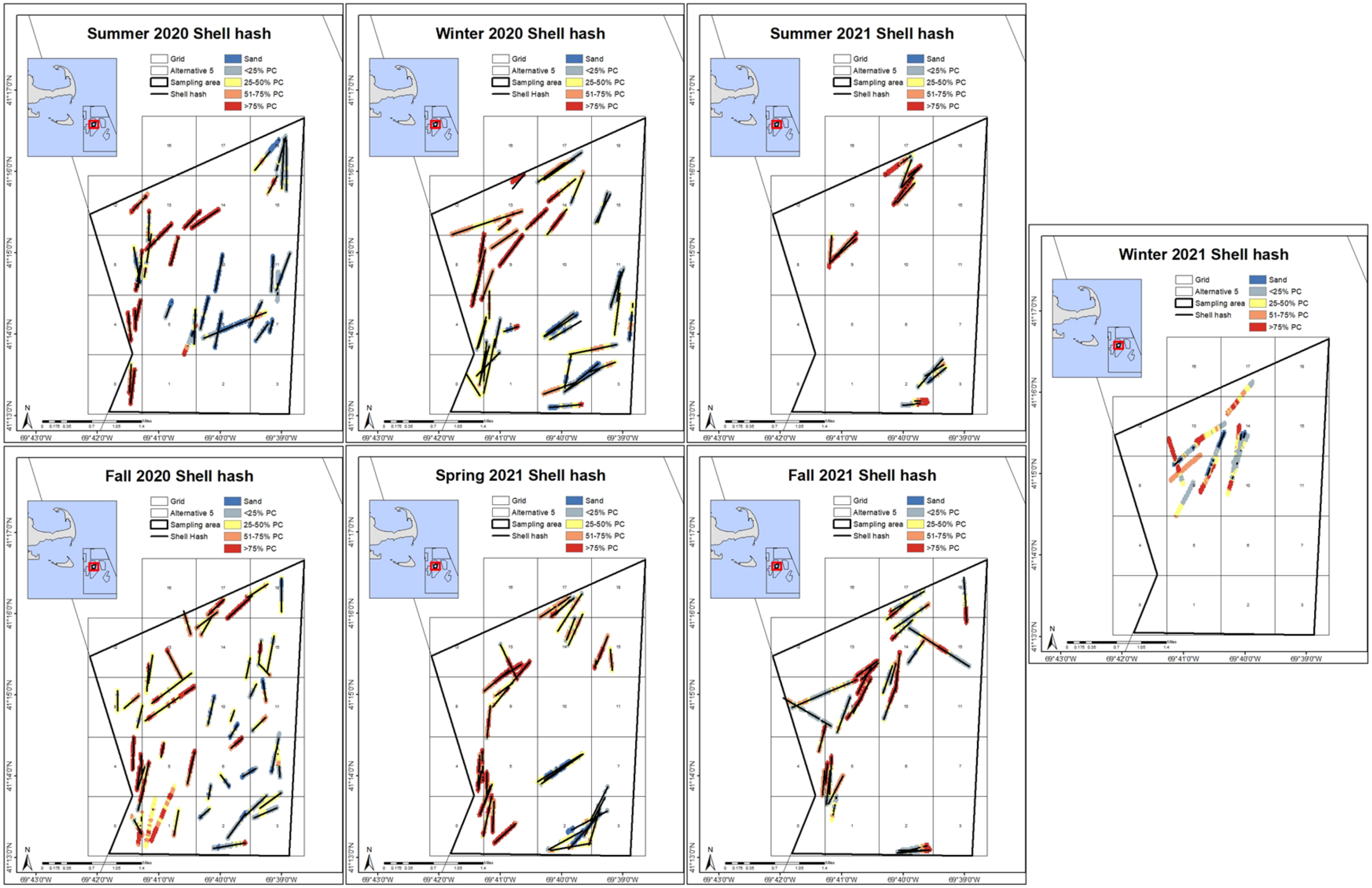


Figure B7. Shell hash found in the research area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

Appendix C: Heavily Fished Area Habitat Features by Season

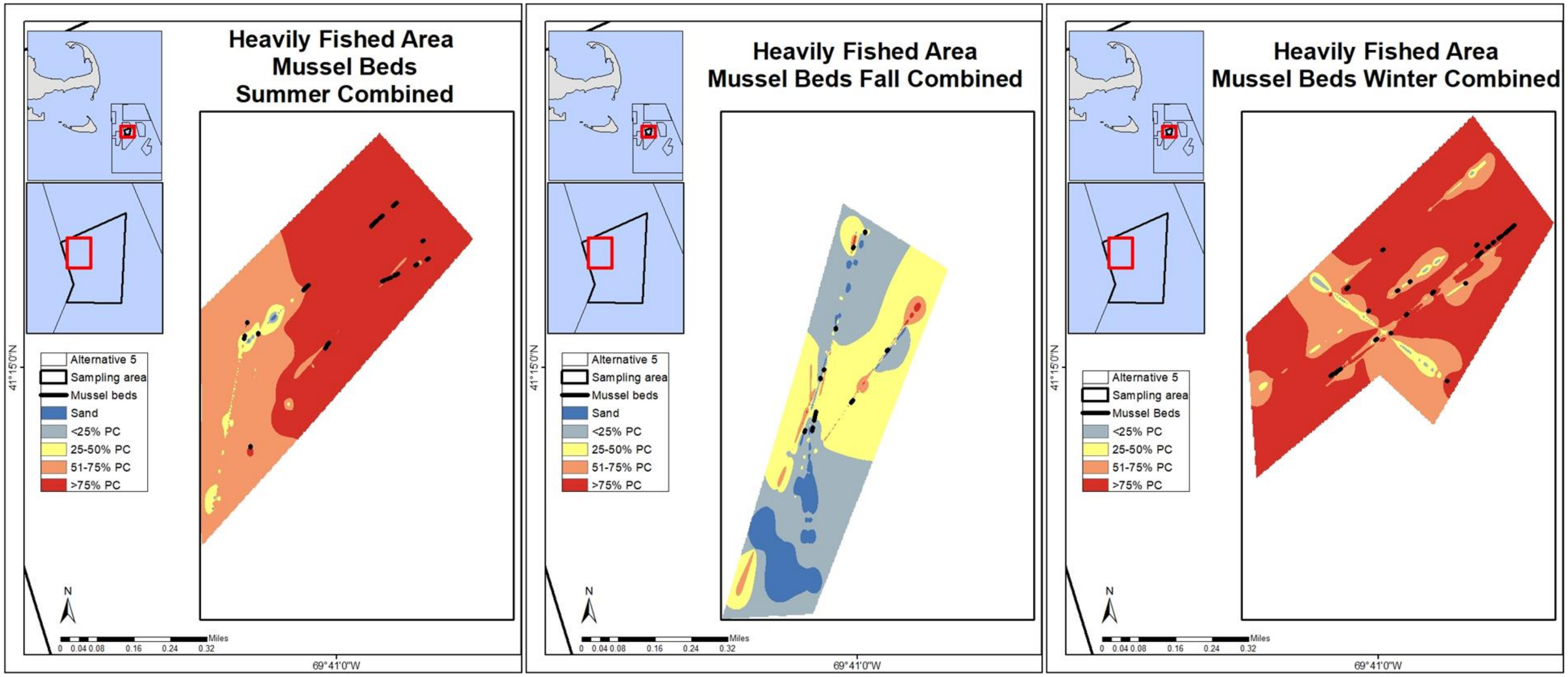


Figure C1. Mussel beds found in the heavily fished area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

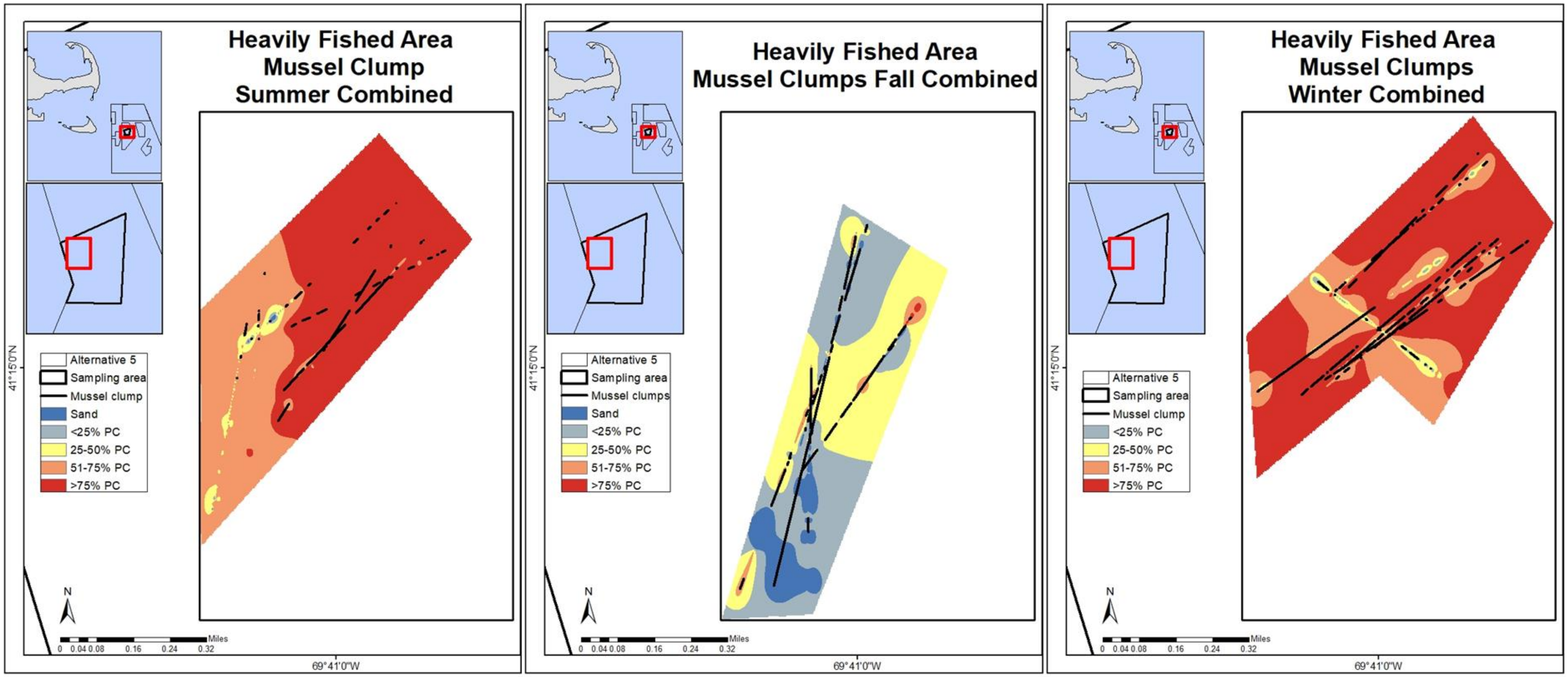


Figure C2. Mussel clumps found in the heavily fished area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

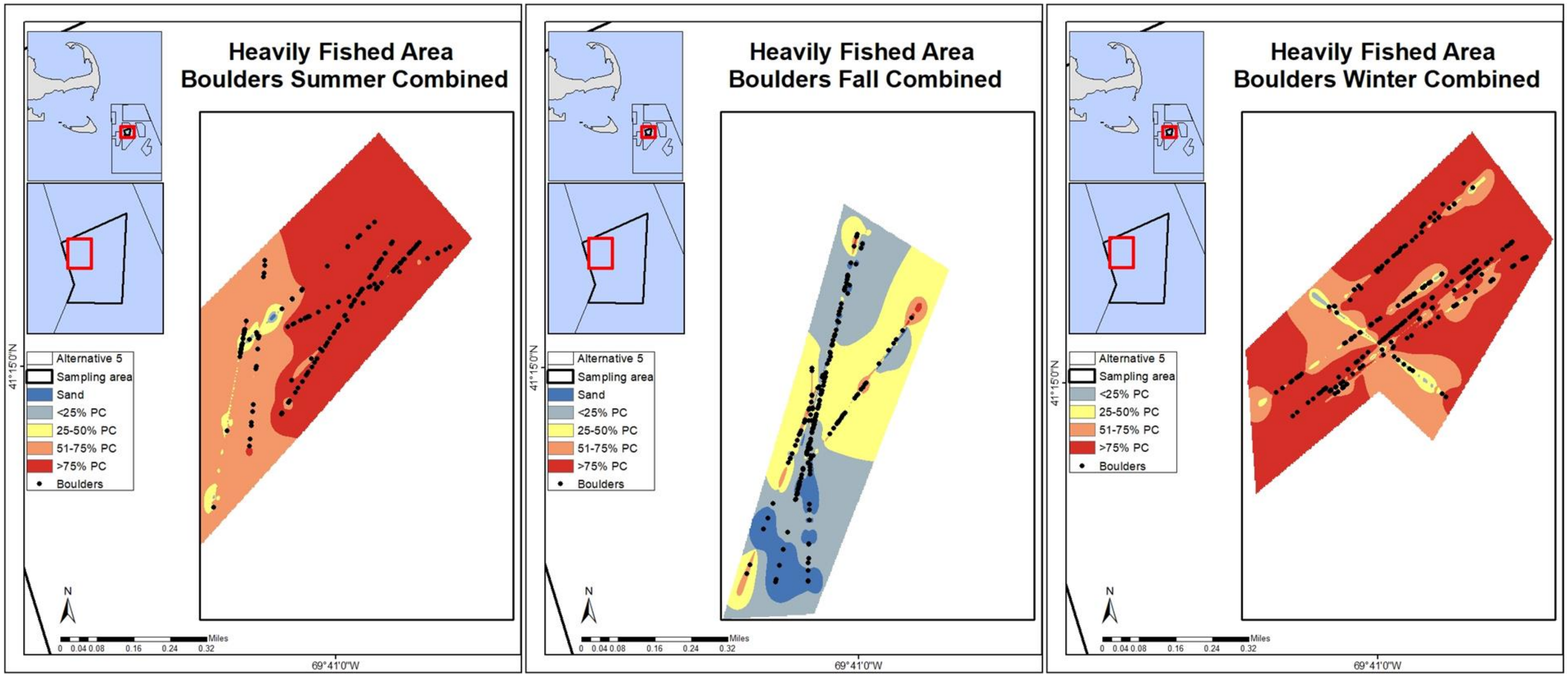


Figure C3. Boulders found in the heavily fished area overlayed on the substrate coverage distribution map by season. PC=Pebble/cobble.

Appendix D: Finfish Observations

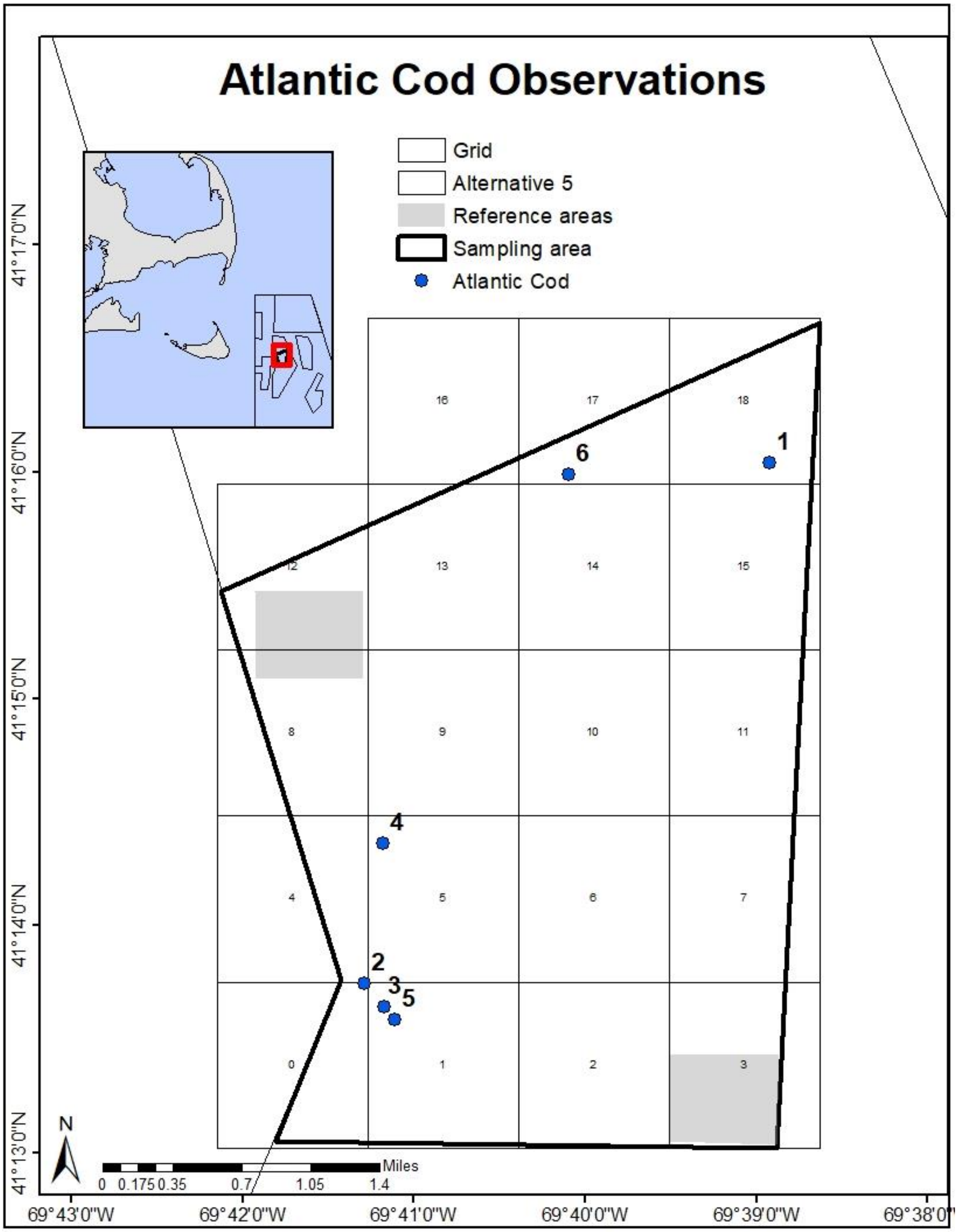


Figure D1. Atlantic cod observations in the research area. 2020 and 2021 are combined.

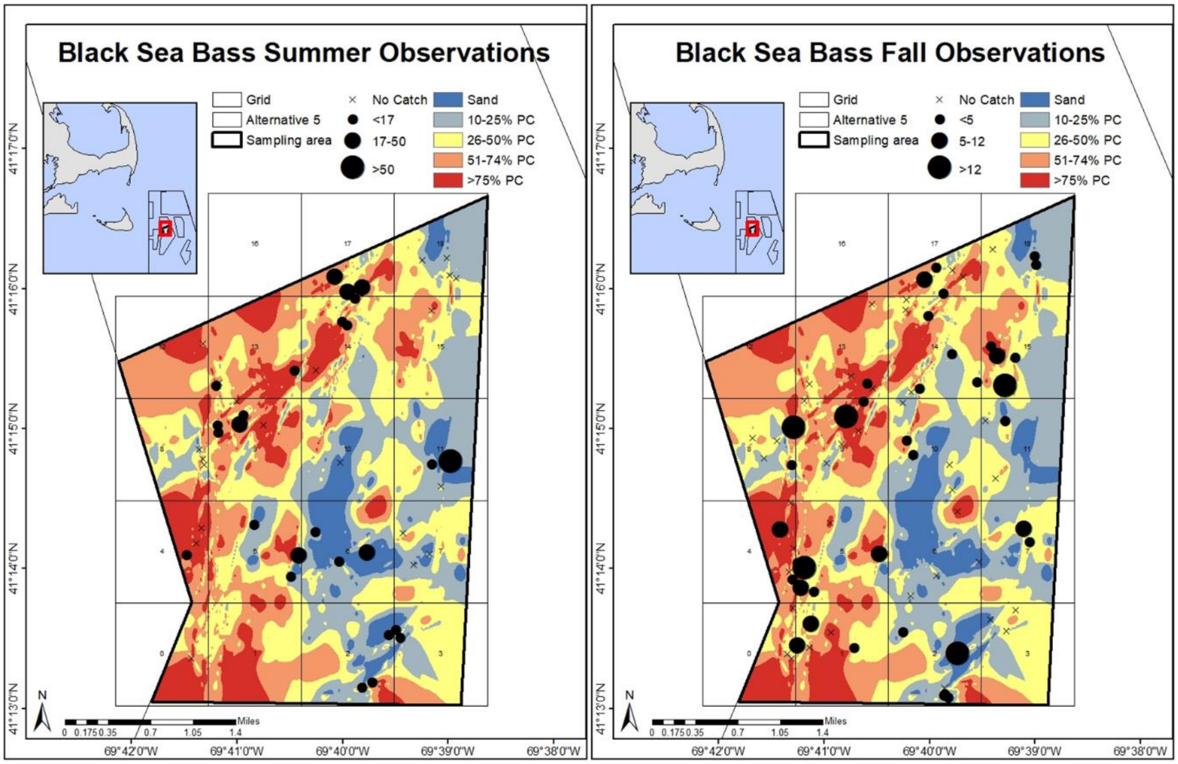


Figure D2. Black sea bass observations in the research area. 2020 and 2021 are combined. No individuals were observed in spring or winter.

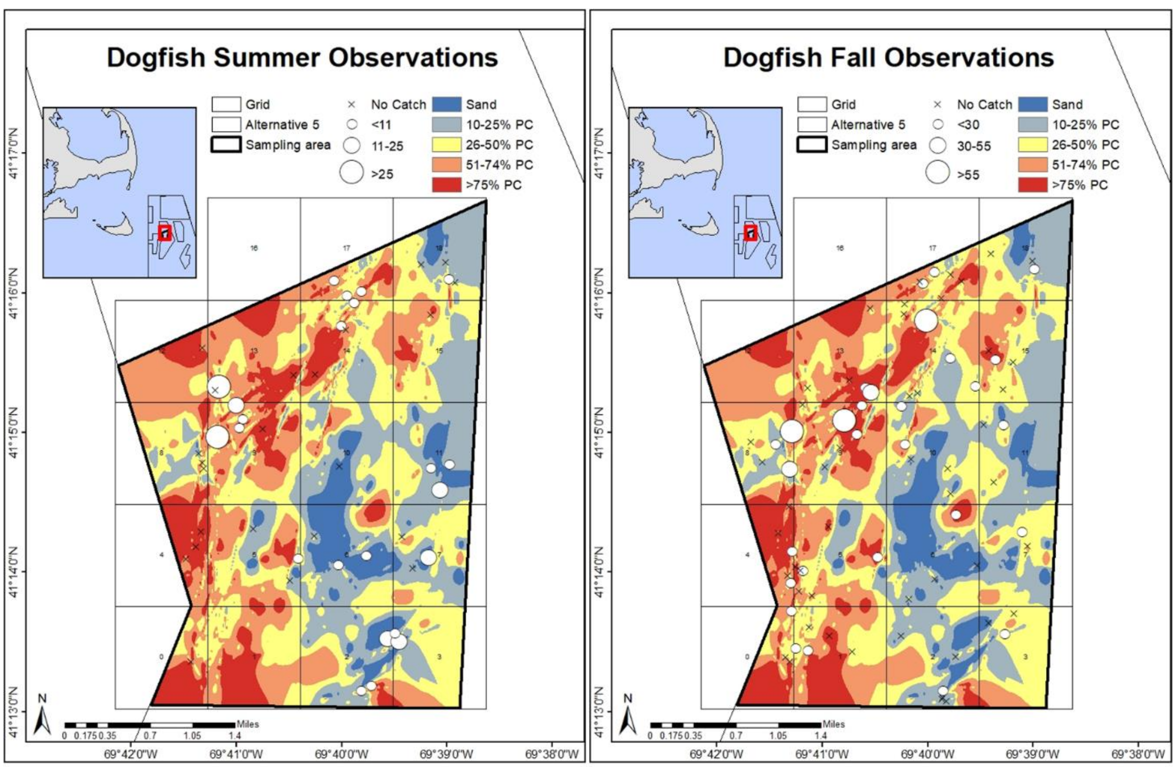


Figure D3. Dogfish observations in the research area. 2020 and 2021 are combined. No individuals were observed in spring or winter.

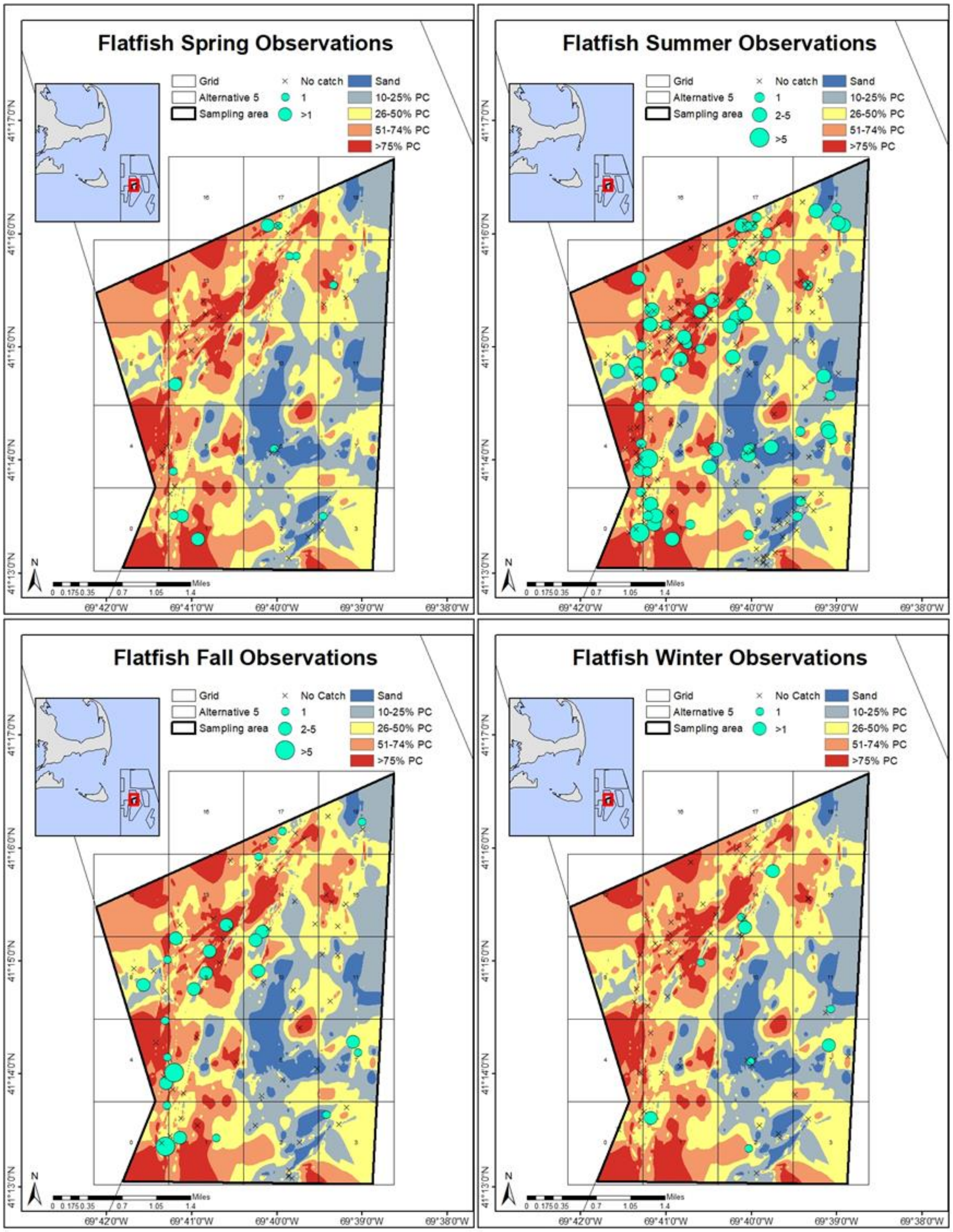


Figure D4. Flatfish observations in the research area. 2020 and 2021 are combined.