Estimating dredge catch efficiencies for the northern quahog (*Mercenaria mercenaria*) population of Narragansett Bay

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ABSTRACT

The catch efficiency of a hydraulic dredge was tested on a population of the northern quahog (*Mercenaria mercenaria*) in Narragansett Bay, RI, USA to understand gear limitations and correct relative abundance time series data. In 2017 and 2018, 45 hydraulic dredge tows were conducted following a longstanding fisheries-independent survey protocol, with the dredge transects inspected on SCUBA to assess dredge catch efficiency. Bull raking and quadrat samples taken on SCUBA were also conducted alongside the transects to compare sampling methods. Average dredge catch efficiency across samples was 0.64 (±0.29 standard deviation). Bottom type was the most significant determinant of dredge catch efficiency, with higher catch efficiency on hard bottom (0.73 efficiency) than on soft bottom (0.48 efficiency). The quadrat and bull rake samples reflected higher catch rates than the dredge, but relationships between relative abundance estimates from the alternate methods and the dredge were either weak or insignificant. Bottom type, sediment classification, depth, and observed abundance were used to model dredge catch efficiencies and predict fisheries-independent abundance indices to more accurate estimates. Applying corrections using a generalized linear model scaled abundances through time, with trends generally the same between time series both with and without the corrections applied. This work provides an example of addressing gear efficiency concerns through diverse collaborations and improving the science and management for a commercially and recreationally significant marine resource.

Short Title: Dredge catch efficiency for northern quahog
Key Words: northern quahog, hydraulic dredge, catch efficiency, bottom type

INTRODUCTION

Fisheries-independent surveys are conducted to infer marine species population trends. Such information is used as input data for stock assessment models and to inform fisheries management regulations (Pennington and Stromme 1998, Rotherham et al. 2007). Within statistical stock assessment models, fisheries-independent relative abundance indices are used to estimate population sizes (Hilborn and Walters 1992). In its simplest form, the relationship between a fisheries-independent survey abundance index (I) in a given year (t) and population size (N) for a species is proportional, with a scaling factor incorporating time-invariant catchability considerations (q) of the survey (Quinn and Deriso 1999, Hilborn 2001):

$$N_t = \frac{I_t}{q}$$

The catchability parameter is often estimated within stock assessment models (Miller et al. 2018) yet comprises both the efficiency of the sampling gear and the availability of the population to the survey (Cadrin et al. 2016), making it difficult to discern what the catchability parameter alone represents. Catchability parameters can be further described as:

$$q = k\ \frac{a}{A}$$

where k represents fishing gear efficiency, and A the total resource area that is vulnerable to the fishery or survey, a (Cadrin et al. 2016). To minimize the gear efficiency component of catchability, testing gear configurations and sampling strategies to identify the most suitable fishing gear to sample the target species is imperative (Rotherham et al. 2007).

The gear efficiency is often assessed using a paired or multi-geared experimental design (Cadigan and Dowden 2010, Miller 2013). This approach utilizes multiple gears surveying within nearly the same time and space, allowing other spatio-temporal confounding factors on catch efficiency estimates to remain constant. In the fisheries-independent survey context, the traditional sampling gear is typically one of the survey methods tested to understand the uncertainty in survey trends used for science and management. Quantified catch efficiency data can then be used to address gear efficiency concerns through correcting relative abundance estimates *a priori* to stock assessment modeling.

Hydraulic dredges are a common fisheries-independent sampling gear used to monitor soft bottom marine shellfish populations (Myer et al. 1981, Ganz et al. 1999, Thorarinsdottir et al. 2010). Dredge configuration, water depth and sediment type have been found to influence catch efficiency and can lead to inaccuracies in estimating local relative abundances (Thorarinsdottir et al. 2010). Visual inspection of the dredge tracks with cameras or SCUBA are optimal methods for estimating dredge catch efficiencies (Meyer et al. 1981) but can be challenging to implement depending on the depth of sampling and turbidity caused by the hydraulic dredge. Other gear types are also routinely used for assessing shellfish populations, including diver or snorkel-based transects (Arnold et al. 1998), drop cameras (Bethoney et al. 2019), and hydraulic paten tongs (Southworth et al. 2010); similarly, these gears can also have efficiency or selectivity concerns based on the species and gear.

The northern quahog (*Mercenaria mercenaria*) in Narragansett Bay, Rhode Island, USA serves important roles in the ecosystem, as well as the economy and cultural heritage of Rhode Island (Doering et al. 1986, Schuman 2015, McManus et al. 2019). In 1993, the Rhode Island Department of Environmental Management Division of Marine Fisheries (RIDEM DMF) began a hydraulic dredge survey to assess northern quahog population changes over time and inform management measures. Proper estimates of gear efficiency for the dredge are paramount for the fishery management decisions. A hydraulic dredge was chosen based of the sediment features of Narragansett Bay and the sessile nature of the species; however, concerns have been raised, particularly by the commercial quahog fishing industry, regarding the catch efficiency of the dredge and the accuracy of derived relative abundance estimates used for fisheries management.

This study implemented multiple methods to quantify the relative abundance of quahogs and to estimate the dredge catch efficiency. Methods used include hydraulic dredge sampling with diver-based assessment of quahogs missed during dredge tows, diver-based quadrat sampling, and commercial bull rake sampling. The objectives of this work were to (1) estimate catch efficiency of the hydraulic dredge by market class of quahogs and environmental covariates, (2) understand the relative catch efficiency between the various sampling methods, and (3) compare traditional fisheries-independent relative abundance indices from the dredge to those corrected based on the catch efficiency estimates. This work aimed to improve estimates of quahog populations and fisheries management through collaboration with the quahog fishing industry.

METHODS

Hydraulic Quahog Dredge Survey

The hydraulic dredge is equipped with 0.45-m (18-inch) width and 2.5-cm (1-inch) spacings to target legal sized (≥ 1-inch hinge width) quahogs. The basal and rear ends of the dredge have 1-inch bar spacing, with side and top panels containing 1-inch^2 wired mesh. Sublegal quahogs are sporadically caught in the survey, but their sizes are not considered to be selected by the gear. During sampling, the dredge is towed at a speed < one knot over a target transect length of 30.5-m (100-ft) for a swept area of approximately 13.9-m^2. All quahogs are counted and measured (hinge width), and bycatch species identified and enumerated. In addition to dredge catch and effort information, the day, year, position (latitude, longitude), bottom type (hard/soft), depth, and finer sediment type classification are also recorded. The dredge blade angle is adjustable and changing it could improve the efficiency depending on sediment; however, it has been held constant at 15° across sites and years to maintain consistency in the sampling.

The quahog dredge survey is conducted to monitor the quahog population of Narragansett Bay using a fixed-rotational sampling design. The survey area is comprised of several strata, each including individual stations. The strata were constructed to describe areas useful in addressing several topics regarding quahogs, including their biology and life history, population units and historical abundance gradients, spatial structure of the commercial quahog fishery, and water quality considerations. The sampling frequency of each stratum has varied through time; since 2010, a given stratum is targeted for sampling at minimum biannually, with all stations within that stratum to be sampled.

Multi-Gear Sampling

Concurrently with hydraulic dredge tows, three additional sampling methods were used to evaluate the sampling ability of the dredge. The first method estimated the dredge catch efficiency by deploying divers on SCUBA to follow the towed dredge paths and collect quahogs missed by the dredge laying in the dredge scars. Quahogs seen during the transect inspections outside of the dredge scar were not considered to be missed by the dredge. Diver-based sampling with quadrats and commercial bull raking were also used to compare quahog sampling methods across varying gear types. Quadrat samples often covers a smaller swath of area than other sampling methods but often rely on fewer gear efficiency issues. Up to three 1-m^2 quadrat samples were collected at each dredge station via SCUBA, with their specific location adjacent to the track chosen randomly. Divers manually sifted and dug through the upper six inches of sediment within each quadrat and collected quahogs by hand. Bull rake pulls were taken alongside the dredge tracks to compare a traditional scientific sampling method to that used by the commercial fishery. The bull rake has been the preferred method of commercial quahog digging after commercial harvest with dredges was prohibited in Narragansett Bay in 1956 (Mackenzie 1997). All bull rakes are comprised of a metal basket (or purse) with one open side lined with protruding metal teeth (spaced at slightly less than 1 inch) used to dig into the substrate. The basket is connected to a long, often telescopic pole (termed the stale) with handles on the opposite end which the fishers hold and "rake" the benthos from the surface. Raking is done onboard a fishing vessel which is typically freely drifting with the wind and currents. Commercial fishers raked their bull rakes up to two times at a given station to provide insight on catch variability within a site using this method. Bull rake pulls were conducted over typical rake durations conducted by the fishery until the basket felt full, at which point the fishers halted digging. Area swept for the bull rake tows were calculated using the width of the rake basket and the distance towed, as measured using start and end points from handheld GPS or tablet systems. The commercial diggers changed the specifications of their rake (e.g. basket width, weights, stale length, and tooth length) at each site, based on their best judgement to optimize the efficiency of the raking. Thus, with rake specification changes between sites, each bull rake tow was treated as the most efficient sampling version of the bull rake. Quahogs sampled using each method were enumerated by market size using their corresponding size classes: sublegal (< 25.4-mm width at the hinge), littlenecks (25.4 to 34.9mm), topnecks (35 to 39.9 mm), cherrystones (40 to 43.9mm) and chowders (≥ 44mm).

The multi-geared sampling was conducted at 45 stations throughout Narragansett Bay over 2017 and 2018 (Figure 1). The stations were selected to cover a range of sediment types, depths, local abundances of quahogs, and fisheries and water quality management areas. Each sampling station had dredge tows conducted with corresponding dredge transect inspections and quadrat sample collections using SCUBA. Bull rake sampling was done opportunistically, with only some of the sampling dates and stations having pairwise bull rake data available (Table 1).

Hydraulic Dredge Catch Efficiency

Dredge catch efficiency was evaluated by comparing relative abundance estimates with and without quahogs missed by the dredge included. Observed dredge relative abundance estimates were corrected by summing the count of quahogs found lying in the dredge transect during the inspection on SCUBA (N_T) to the number retained in the dredge (N_D):

$$\text{Observed Dredge Relative Abundance} = \frac{\mathrm{N_D}}{\text{Dredge Swept Area (m}^2\text{)}}$$

$$\text{Corrected Dredge Relative Abundance} = \frac{\mathrm{N_D} + \mathrm{N_T}}{\text{Dredge Swept Area (m}^2\text{)}}$$

Corrected estimates were then compared to relative abundances obtained from the quadrat and bull rake samples using linear regression and Wilcoxon Rank Sum Tests. Dredge catch efficiency was estimated as the ratio of the observed dredge relative abundance to the corrected estimate, ranging from 0 to 1:

$$\text{Dredge Catch Efficiency} = \frac{\text{Observed Dredge Relative Abundance}}{\text{Corrected Dredge Relative Abundance}}$$

Samples where quahogs were not found in the dredge nor on SCUBA inspection were excluded from catch efficiency analyses. Catch efficiency was compared to covariates that were believed to either influence local quahog abundance and/or influence the fishing ability of the dredge. Significant differences in dredge catch efficiency within categorical variables were tested using Kruskal-Wallis Rank Sum and post-hoc Nemenyi Tests, and continuous variables were tested using linear regression.

The influence of these factors on dredge catch efficiency were further examined using generalized linear models (Venables and Dichmont 2004). The models were constructed using R package ‘glmmTMB’ (Brooks et al. 2017) with a beta error distribution. Given beta distributions only apply to values within (and not inclusive of) 0 and 1, dredge efficiencies were transformed to account for these observations using the sample size of the dataset following Smithson and Verkuilen (2006):

$$\text{Dredge Efficiency}_{\text{Transformed}} = \frac{\text{Dredge Efficiency}_{\text{Observed}} * (\mathrm{n}-1) + 0.5}{\mathrm{n}}$$

Covariates assessed in modeling dredge efficiency included bottom type (hard vs. soft bottom), sediment type, depth of sampling, and observed relative abundance. Bottom type, sediment, and depth were included to standardize benthic characteristics that influence quahog abundance (Pratt 1953, Pratt et al. 1992, Rice 1992) and may influence dredge efficiency. The observed relative abundance was included in the modeling to better understand if the dredge efficiency varies depending on the local density of quahogs in the dredge track (Ganz et al. 1994). Model variants using different combinations of these covariates were evaluated and compared through minimization of the Akaike information criterion (AIC; Akaike 1973.) The performance of the final model variant selected for use was evaluated by comparing the predicted efficiencies for the samples of this study to those observed.

The selected model variant was then used to predict catch efficiencies for historical RIDEM DMF hydraulic dredge survey tows. Samples with missing field data needed as covariates in the model (e.g. bottom type, sediment, depth) could not produce efficiency predictions and were excluded from the analysis. Each observed quahog relative abundance estimate from the fisheries-independent survey through time was then divided by its corresponding predicted efficiency to estimate corrected abundances. Annual average observed and corrected relative abundance indices were produced to compare the differences in the trends. The relative abundance indices were derived by averaging the observed and corrected relative abundances by year and region. Time series were constructed for the spatial regions used in the RIDEM DMF quahog stock assessment model: Greenwich Bay, Providence River, and Narragansett Bay proper (Figure 1). The abundance time series generated represented relative indices from the survey data; these indices did not represent the total population sizes nor swept area abundances for spatial domains.

RESULTS

Dredge Catch Efficiency and Comparison of Sampling Methods

Of the 45 dredge tows with diver-based transect inspections, three tows had zero quahogs caught in the dredge or found in the dredge scar on SCUBA. Of the 42 tows with positive catches in either the dredge or dredge scar, the average quahog catch efficiency was 0.61 (0.28 standard deviation). Dredge efficiency did not vary statistically across market size classes (Figure 2). The dredge exhibited a significantly greater catch efficiency for total quahog catch on hard bottoms than soft bottoms (Figure 3; Kruskal-Wallis χ^2 = 7.95, p-value=0.02), but not for sediments where the bottom type was undiscernible or likely a mix. Dredge catch efficiency varied greatly across and within sediment types, with mean efficiencies by sediment type ranging from 0.44 to 1 (Figure 3, Table 2.) Generally, mud sediments had lower catch efficiency than sand, but catch efficiencies by individual sediment type were not statistically different. Dredge catch efficiency did not indicate a significant relationship with either depth or observed relative abundance; catch efficiency was highly variable over depth and relative abundance, particularly at the lower spectrums of these variables (Figure 3).

On average, chowders represented the most abundant size class caught in the dredge, quadrat, and bull rake samples (Figure 4). The proportion of sublegal quahogs was often very small (≤5%), with those of littlenecks, cherrystones, and topnecks often comparable. Relative abundances observed using the hydraulic dredge and those corrected based on quahogs found in the transect were significantly correlated (Figure 5; $R^2=0.95$, p-value<0.001). Abundance estimates from sampling with a quadrat were higher than corrected estimates from the dredge (Figure 5; Wilcoxon Rank Sum Test $p<0.001$), with a mean abundance of 3.84 (± 6.44) quahogs m^{-2} from quadrat samples compared to the corresponding dredge observed abundances of 1.91 (± 2.10) quahogs m^{-2}. The correlation between these paired samples was significant, but weak ($R^2=0.12$, p-value<0.001). A similar comparison between corrected abundances from dredge and bull rake sampling indicated a similar finding; bull rake abundances were on average greater than those from the dredge, with a mean abundance of 5.60 (± 6.81) quahogs m^{-2} compared to the corresponding corrected dredge abundances of 1.84 (± 2.07) quahogs m^{-2} (Figure 5; Wilcoxon Rank Sum Test $p=0.006$). Linear regression indicated there was not a significant relationship between the corrected dredge abundance estimates and bullrake sampling. Average abundance estimates from quadrat sampling (3.26 ± 3.41 quahogs m^{-2}) and bull rake sampling (4.69 ± 7.72 quahogs m^{-2}) were not significantly different from each other (Wilcoxon Rank Sum Test > 0.05).

Modeling Dredge Efficiency and Time Series Predictions

When testing all prospective covariates within the models, only bottom type was a significant covariate in predicting dredge catch efficiency, and the model variant using only bottom type had the lowest AIC score (Table 3). For predictive purposes of incorporating variability from both continuous and discrete variables on dredge catch efficiency, the model variant with all covariates was used for dredge efficiency predictions. The correlation between the final model predictions and observed efficiencies was significant (Figure 6; R^2= 0.46, p-value < 0.001).

With corrections applied to the quahog abundance time series data, average annual relative abundance indices increased for all years except for 2003 in Greenwich Bay (Figure 7.) This instance is likely attributed to a low number of tows with required covariate data for predictions, thus excluding many samples from the corrected annual 2003 abundance estimate. Increases in relative abundances through time and region varied based on the sampling that occurred in the given year but reached up to 1.98 times that of the original annual relative abundance indices (Figure 7). Despite increased relative abundances from the model corrections, the abundance trends for each region were similar when applying the dredge efficiency corrections to samples. The Providence River remained the most abundant region, with Greenwich Bay and Narragansett Bay proper indices still similar in magnitude (Figure 7).

DISCUSSION

Catch efficiency information for a hydraulic dredge is presented for the commercially and recreationally significant northern quahog. The hydraulic dredge exhibited less than optimal catch efficiency, with an average efficiency across the samples of 0.61. The measured dredge efficiency in the present study is aligned with those reported for other fisheries incorporating a hydraulic dredge to monitor infaunal bivalves (Medcof and Caddy 1971, Meyer et al. 1981, Smolowitz and Nulk 1982, Michael et al. 1990, Thorarininsdottir et al. 2010). More specifically, earlier work evaluating the quahog catch efficiency of hydraulic dredge sampling in Narragansett Bay was 0.57 (Ganz et al. 1999).

Catch efficiencies were most strongly correlated with bottom type, with hard bottoms having a higher efficiency on average than soft sediments (Table 2). These results indicated there was a stronger difference in catch efficiency between hard and soft bottoms than previously reported by Ganz et al. (1999); however, their work grouped bottom and sediment types together, whereas this research analyzed bottom and sediment types separately. While sediment type did not indicate there was a significant difference in catch efficiency between mud and sand, this difference was likely manifested in the hard and soft bottom classification. Ganz et al. (1999) noted that the hard bottoms in Narragansett Bay usually represent packed sand, and soft bottoms are typically mud. Previous work suggested quahog catch efficiency varies with local quahog density (Ganz et al. 1994), yet this study did not.

Dredge catch efficiency estimates by legal market classes of quahogs indicated that the dredge sampled these classes equally well. In the absence of other gear data for comparison, possible hypotheses for low relative abundance of sublegal quahogs could be gear selectivity or small individuals being displaced from the sampling area due to the hydraulics of the dredge. The similar market class catch compositions by gear type and lack of sublegal quahogs found in the dredge scar during transect inspections suggest that the mesh gear selectivity hypothesis may not hold. While the quadrat and bull rake samples had more sublegal quahogs than the dredge, these gears also had fewer sublegal quahogs than older, legal market-sized, individuals. The lack of capture of sublegal quahogs across the gears draws further questions regarding the settlement, growth, mortality, and survey selectivity of the early life stages of quahogs, justifying future research needs.

The paired diver sampling with quadrats and bull rake sampling caught more quahogs than the dredge. It is possible that some quahogs were missed during the SCUBA inspections of the dredge scar due to visibility or that quahogs observed outside the dredge scar were displaced by the dredge and thus missed catch. These observer error hypotheses seem unlikely, as the diligent SCUBA inspections likely led to minimal or negligible inspection error, and it is improbable that the quahogs observed outside the dredge scar originated in the dredge path based on their distance from the dredge scars. The disparity between the alternative methods and the corrected dredge relative abundances may be attributed to the differing swept areas of the gear types. Quahog distribution has often been described as super-dispersed or contagious, following a negative binomial distribution (Saila and Gaucher 1996, Russell 1972.) The larger swept area of the dredge (~14-m^2) compared to that of the quadrats sampled (1-m^2 segments) may explain this discrepancy, with the dredge representing a more integrated sample of the local standing stock with a larger swept area. Bull rake swept areas were much more variable, as they were conducted until the rake felt full to the fisher. This approach may lend itself to more efficient sampling and ensure that either a rake head or rear cage of a hydraulic dredge does not overfill before the end of a tow and cause quahog spillage (Meyer et al. 1981). The benefits of using an industry fleet to sample with bull rakes include prospective improved efficiency, ability to sample shallower and deeper depths based on boat outfitting the stale length changes, and including industry members in the scientific process of data collection for management. Current bull rake sampling drawbacks include the gear variability that quahoggers use between sites and loss of standardization (e.g. changes in rake head width, rake tooth length, stale length, weights), and the ability to ensure accurate distance or swept area calculations. Continued comparative work with the hydraulic dredge, quadrats, and bull rakes would improve these inferences, as the sample size for some of these comparisons was small and variability in quadrat and bull rake replicates were large. An alternative solution may be to change the blade angle of the hydraulic dredge by site to increase efficiency and not standardize the blade angle, which has been found to improve dredge efficiency for sampling other shellfish (Meyer et al. 1981).

The adjustments in time series abundances from the dredge using this efficiency information have more appropriately quantified northern quahog relative abundances in Narragansett Bay. Improving these estimates aids in addressing longstanding concerns that the hydraulic dredge survey does not accurately depict the local standing stock of legal sized quahogs. While this work has improved relative abundance estimates, the overall trends in the fisheries-independent abundance indices largely remained the same. This finding suggests that, annually, the sample breakdown by environmental factors used to infer dredge efficiency have largely been stable through time. The dredge efficiency corrections will improve estimates of the Narragansett Bay quahog population size in stock assessment models, but may not affect conclusions on population trajectories.

This work serves as an example of scientists, managers, and industry members collaboratively addressing questions that improve fisheries science and management. The pair-wise sampling provided dredge efficiency estimates and insight into the accuracy of a longstanding hydraulic dredge survey. Further, other gear types that may be suitable for use in the future were evaluated via supplementary fisheries-independent and industry-based sampling. By incorporating commercial quahoggers into the sampling procedures and data collection, this research improved both their understanding of how survey data are used by scientists and the working relationship between industry and managers. The findings of this research have direct applications, as they can be used to correct dredge gear efficiency issues prior to stock assessment modeling.

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Table 1. Dates and the number of stations sampled for each of the gear efficiency methods.

Date	Dredge Samples	Dredge Transect Inspection	Bull rake Samples	Quadrat Samples
10-Oct-2017	3	3	3	3
11-Oct-2017	5	5	-	5
18-Oct-2017	3	3	-	3
19-Oct-2017	4	4	3	4
27-Oct-2017	5	5	5	5
30-Jul-2018	5	5	-	5
1-Aug-2018	5	5	2	5
17-Sep-2018	5	5	-	5
5-Oct-2018	5	5	-	5
19-Oct-2018	5	5	2	5

Table 2. Descriptive statistics of mean dredge efficiency across bottom and sediment types. Sample sizes (n) and standard deviations around the means (sd) are presented by category. The categories with samples sizes of one do not have associated standard deviations. Significant differences between categories within a variable are denoted with lettered subscripts, as tested using Kruskal-Wallis Rank Sum and Nemenyi Tests.

Variable (n)	Dredge Efficiency (sd)
Bottom Type	
Hard (20)^{A}	0.73 (0.23)
Soft (19)^{B}	0.48 (0.28)
Unknown (3)^{A,B}	0.69 (0.16)
Sediment	
Mud (14)	0.50 (0.28)
Mud, Shell (11)	0.67 (0.29)
Sand (1)	1.00
Sand, Mud (8)	0.73 (0.28)
Sand, Mud, Shell (3)	0.56 (0.20)
Sand, Rock, Shell (1)	0.44
Sand, Shell (4)	0.58 (0.22)

Table 3. Generalized linear model variants tested for predicting dredge catch efficiency, with ‘x’ denoting variable inclusion in the model. Model variant in bold signifies the final model chosen for predictions.

Model	Covariate				ΔAIC	Degrees of Freedom
	Bottom Type	Sediment	Depth	Observed Abundance		
1	x				0	4
2	x	x			6.4	10
3	x	x	x		3.3	11
4	**x**	**x**	**x**	**x**	**3.9**	**12**

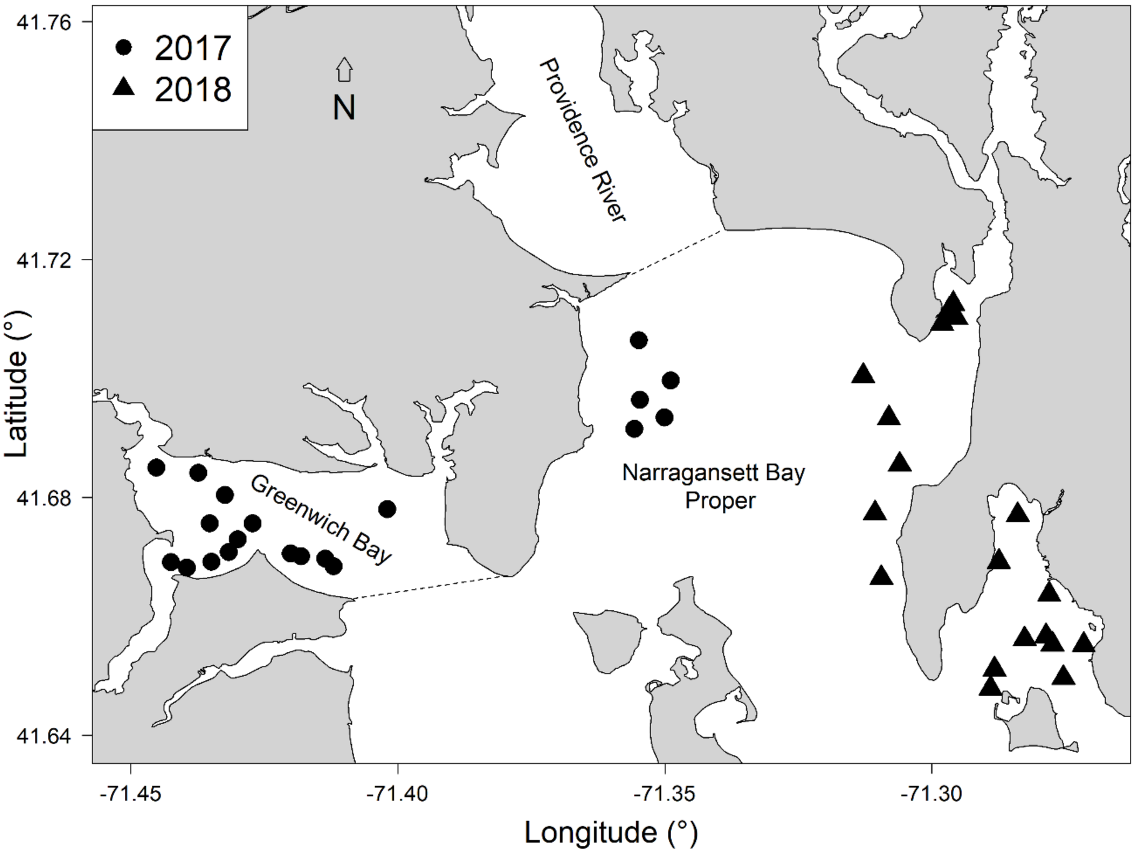

Figure 1. Station locations in Narragansett Bay for the multi-gear sampling in 2017 (circles) and 2018 (triangles). Regions modeled for the quahog stock assessment are labeled, with dashed lines delineating the regions.

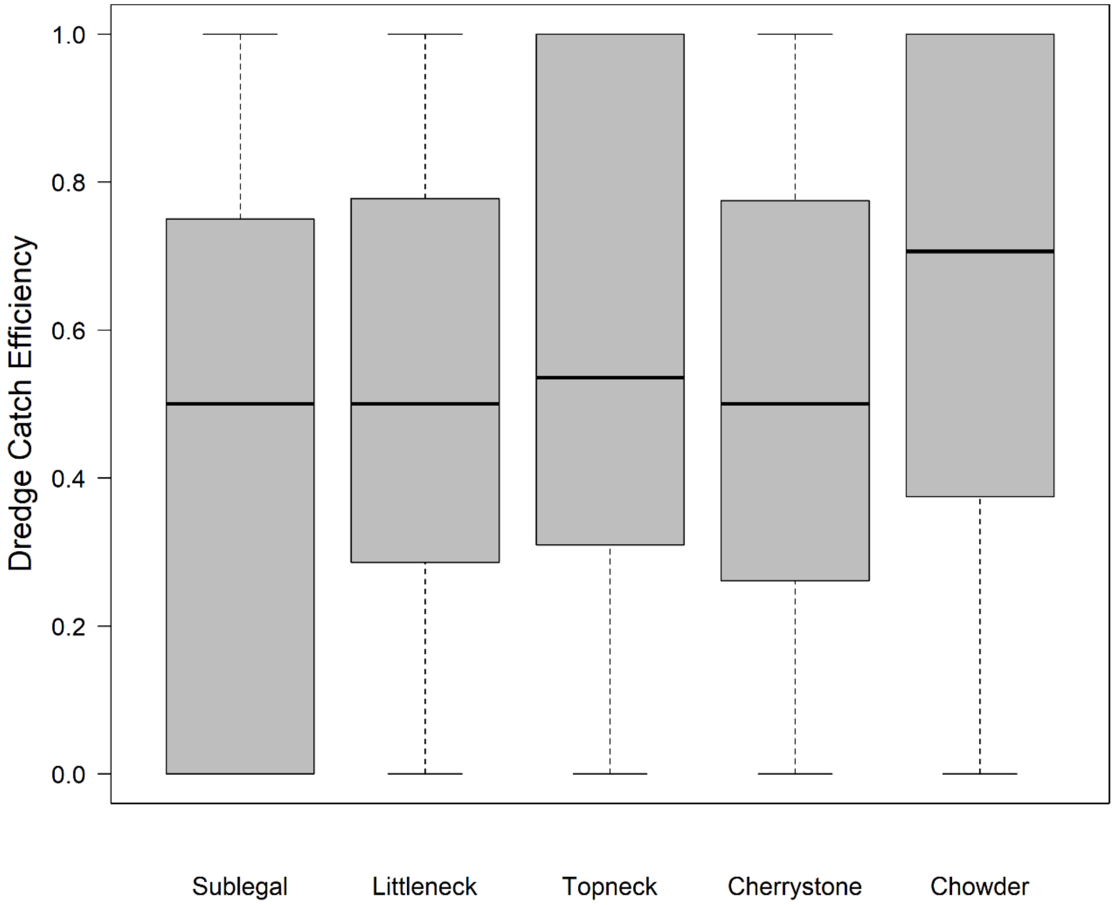

Figure 2. Dredge catch efficiencies for quahogs by market class. Dark lines, box heights, and tick marks indicate 50th, 25-75th, and 0-100th percentiles, respectively.

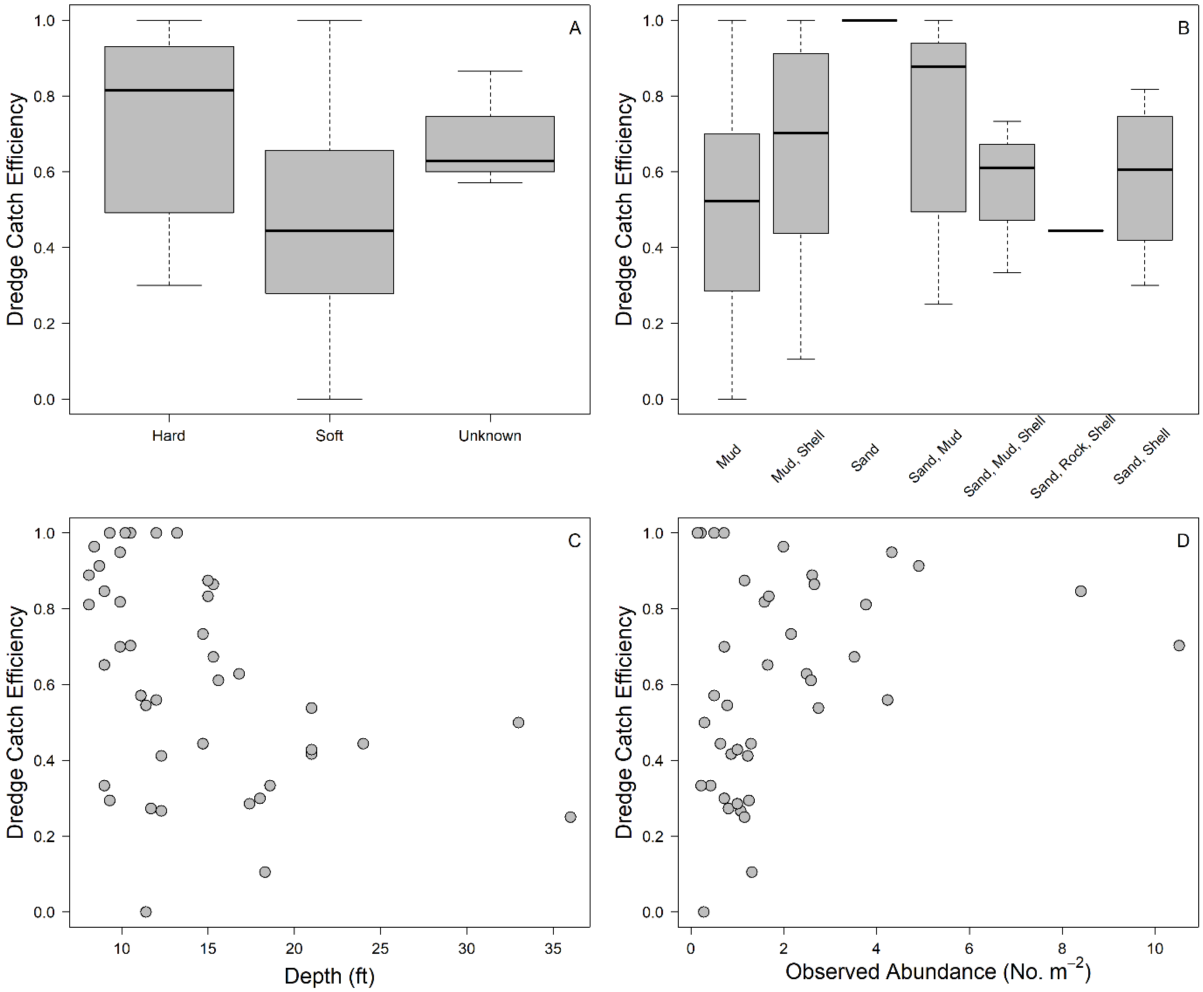

Figure 3. Dredge catch efficiencies for total quahog catch by (A) bottom type, (B) sediment type, (C) depth, and (D) total observed relative abundance. Dark lines, box heights, and tick marks for bottom and sediment types indicate 50th, 25-75th, and 0-100th percentiles, respectively.

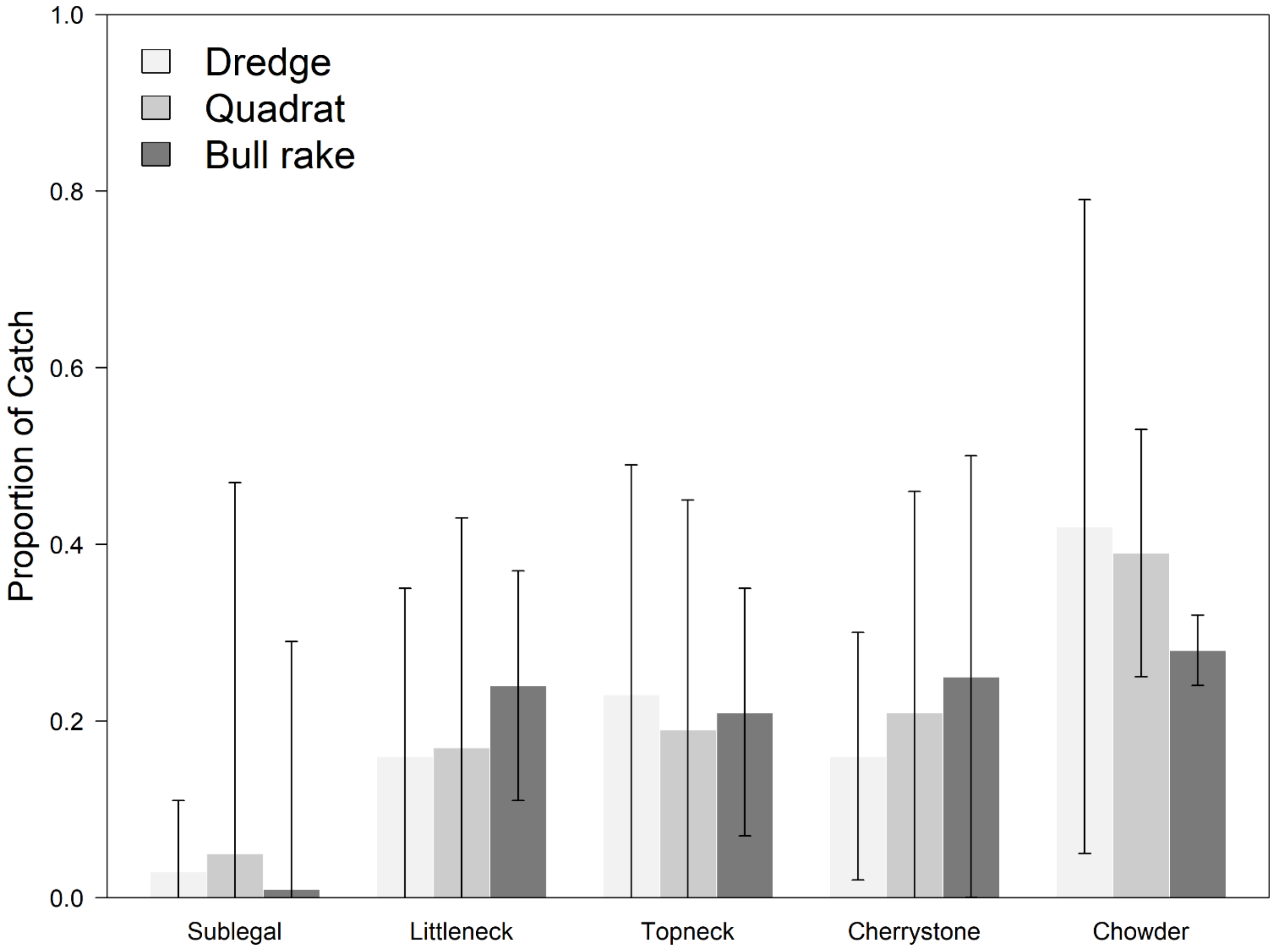

Figure 4. Average proportion of market classes within the samples of each sampling type: the hydraulic dredge, sampling with quadrats on SCUBA, and bull rake sampling. Proportions for quadrat and bull rake sampling include the replicates within a station. Bars are average proportions over all data within a sampling type, and bars represent the standard deviation range around the means.

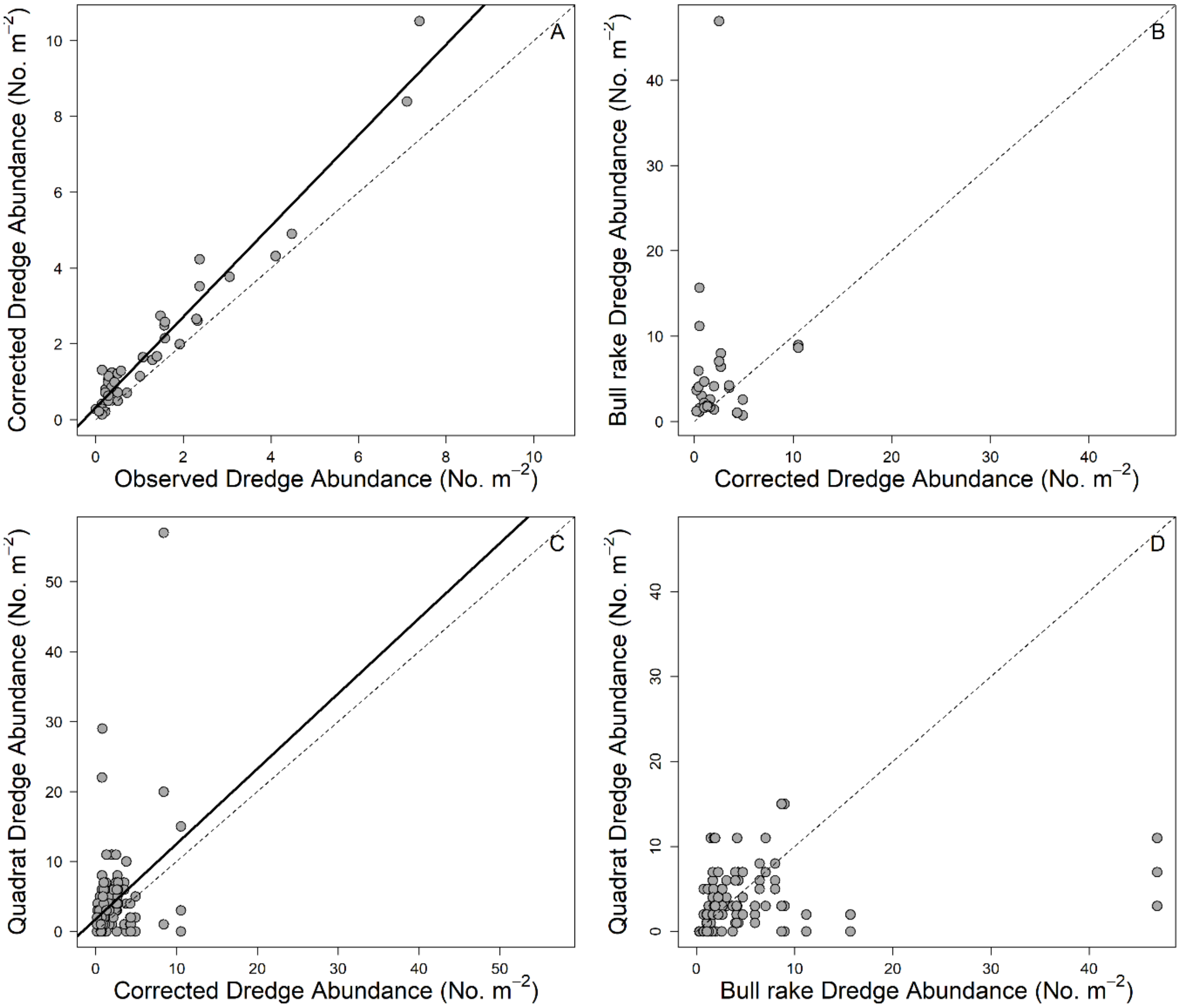

Figure 5. Relative abundance comparisons across gears and corrections. Observed quahog relative abundance from the hydraulic dredge compared to corrected abundances based on the transect inspections on SCUBA (A). Corrected quahog relative abundance from the hydraulic dredge compared to abundances collected using (B) bull rakes (n=32) and (C) quadrats on SCUBA (n=144), as well as (D) a comparison of bull rake and quadrat relative abundance estimates (n=114). Comparisons using bull rake and quadrat data were done at the replicate level. Solid lines represent linear fits for significant correlations. Dashed lines represent the 1:1 line, where abundances between the two estimates would be equal.

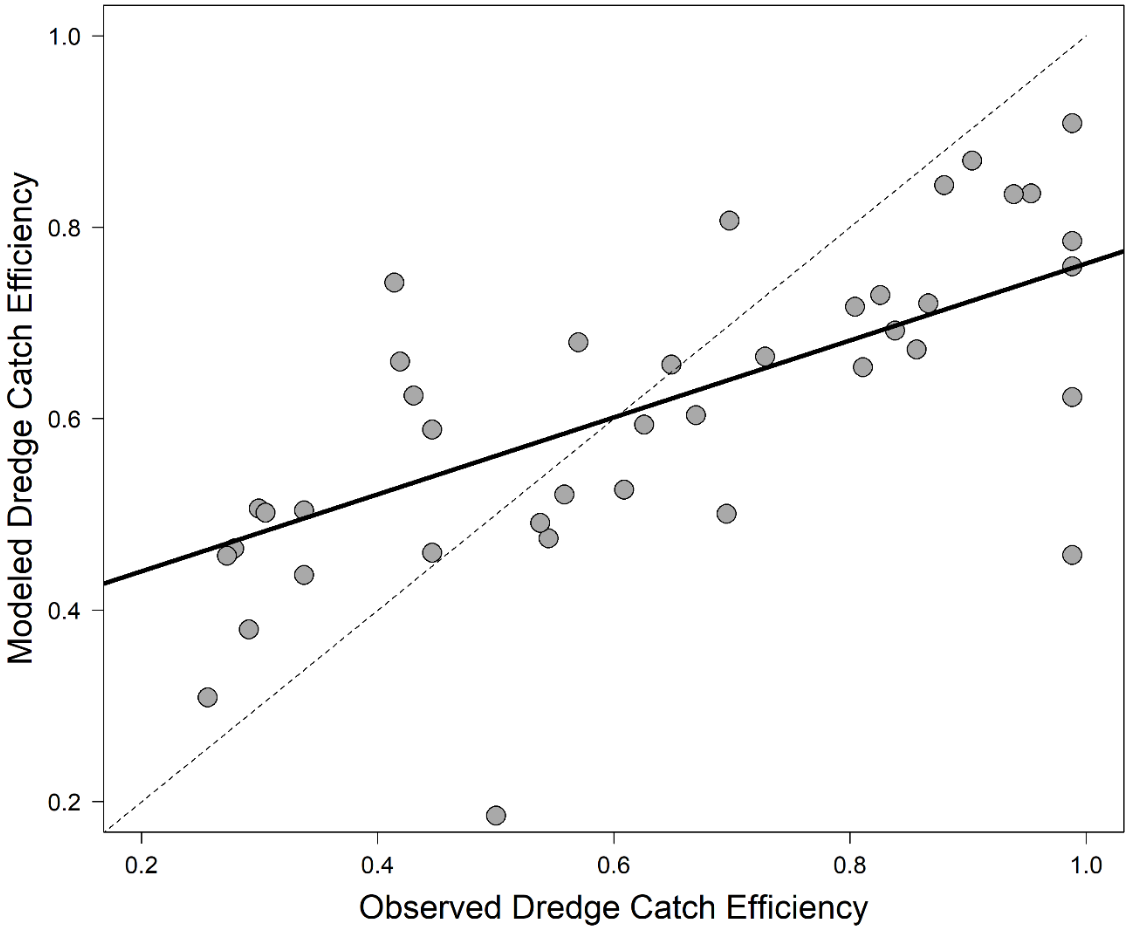

Figure 6. Observed dredge catch efficiency compared to that predicted from the model. The solid line represents the linear fit between the two datasets (R^2=0.46), and the dashed line represents a 1:1 line.

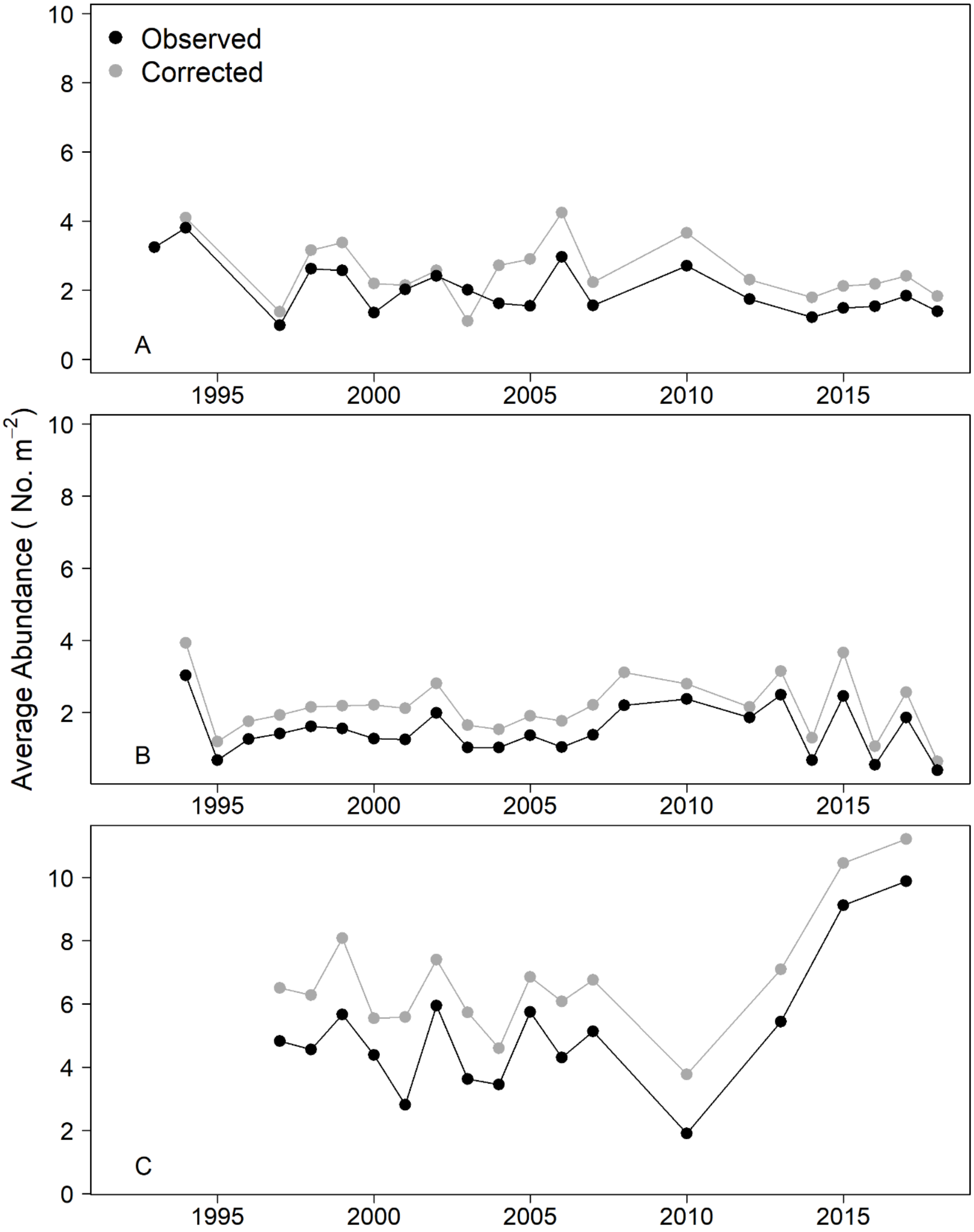

Figure 7. Quahog annual relative abundance indices from the RIDEM DMF quahog hydraulic dredge survey. Indices are presented for the three regions currently modeled for stock assessment: Greenwich Bay (A), Narragansett Bay proper (B), and the Providence River (C). Relative abundance time series are presented for those currently used (‘Observed’) and those corrected based on the dredge efficiency model (‘Corrected’).