Aquaculture 428–429 (2014) 150–157

ontents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Effects of hydraulic dredging on the benthic ecology and sediment chemistry on a cultivated bed of the Northern quahog, *Mercenaria mercenaria*

Ronald Goldberg *, Julie M. Rose, Renee Mercaldo-Allen, Shannon L. Meseck, Paul Clark, Catherine Kuropat, Jose J. Pereira

NOAA Fisheries, Northeast Fisheries Science Center, Milford Laboratory, 212 Rogers Avenue, Milford, CT 06460, USA

ARTICLE INFO

Article history:
Received 16 January 2014
Received in revised form 5 March 2014
Accepted 10 March 2014
Available online 19 March 2014

Keywords:
Hard clam aquaculture
Hydraulic clam dredging
Benthic community
Biogeochemistry
Sediment grain size

ABSTRACT

We examined the effects of hydraulic dredging on the benthic ecology and sediment biogeochemistry of a leased shellfish bed in Long Island Sound near Milford, Connecticut, where Northern quahog or hard clam, *Mercenaria mercenaria* (Linnaeus 1758), aquaculture is conducted. Six 1 ha plots were sampled at 1–2 week intervals from June through October of 2010. One-time hydraulic dredging to harvest hard clams was conducted on 3 dredged treatment plots in mid-June, while 3 control plots remained not dredged. Repeated measures analysis indicated no significant differences between dredged and not dredged plots for any of the ecological indices or sediment chemistry measurements. Numbers of newly settled hard clams were significantly higher on dredged plots. Cluster analysis indicated a strong seasonal influence on benthic community structure distinguishing between early and late season assemblages. Hydraulic shellfish harvesting as conducted on leased beds in Long Island Sound did not appear to significantly impact benthic assemblages or sediment biogeochemistry, while sediment grain size and sampling date had a greater influence on benthic community structure.

Published by Elsevier B.V.

1. Introduction

The increasing demand for fresh locally grown fish and shellfish underscores the importance of sound aquaculture practices in food production. Sustainable cultivation and harvest of hard clams, *Mercenaria mercenaria* (Linnaeus 1758), has been practiced in coastal Connecticut for decades. Annual clam production has increased steadily from a few thousand bushels in the early 1960s (Getchis, 2006) to more than 450,000 bushels harvested during 2010, valued at over $17 million dollars (Connecticut Department of Agriculture, 2013).

Aquaculture of hard clams in Long Island Sound has similarities to terrestrial farming practices. Clam beds are located primarily in nearshore shallow waters, less than 15 m in depth. In Connecticut, shellfish beds are leased to growers by the state's Department of Agriculture, Bureau of Aquaculture. Beds are left fallow for several years until natural sets of young clams attain marketable size and can be harvested with hydraulic dredges. These dredges rely on pressurized water to loosen surface sediments and efficiently remove clams from shellfish beds (MacKenzie et al., 2001). Dredging activity on Connecticut clam beds is generally of short duration, conducted intermittently, and harvest is restricted to the lease holder.

Composition of soft sediment communities in Long Island Sound varies from east to west and relates closely to the physical and biogenic structure and characteristics of the local seafloor (Zajac et al., 2000). Long Island Sound is dominated by unstructured benthic communities, composed of opportunistic organisms, which are well-adapted to periodic seafloor disturbance and are commonly associated with the inshore coastal zone (McCall, 1977). Benthic infauna impact sediment biogeochemistry through bioturbation and in turn, chemical processes at the sediment/water interface influence the composition of species assemblages (Widdicombe et al., 2004). Disturbance of the seafloor during dredging can release chemicals from deeper sediment, thereby altering conditions for benthic organisms. Dredging can also loosen and oxygenate compacted sediments, increasing porosity and potentially enhancing the quality of benthic habitat (Visel, 1990a,b).

Sediment grain size, biogeochemistry, hydrodynamics, biological assemblages, gear type and configuration, and many other factors can influence the effects of hydraulic dredging. Recent reviews have compiled information on the physical, biological, and chemical changes associated with shellfish harvesting to evaluate habitat impacts (e.g., Mercaldo-Allen and Goldberg, 2011; Stokesbury et al., 2011). These reviews suggest that effects of hydraulic dredging are difficult to generalize and therefore require experimental studies which evaluate specific harvesting activities.

Relatively few data exist that describe the effects of hydraulic dredging on benthic ecology and sediment biogeochemistry. Studies at

* Corresponding author. Tel.: +1 203 882 6546; fax: +1 203 882 6557.
E-mail address: ronald.goldberg@noaa.gov (R. Goldberg).

http://dx.doi.org/10.1016/j.aquaculture.2014.03.012
0044-8486/Published by Elsevier B.V.

different geographic locations and spatial scales are necessary to better understand the impact of hard clam cultivation on marine habitat. Previously, we described the limited biological (Goldberg et al., 2012) and chemical (Meseck et al., in press) effects of a July hydraulic dredging event on benthic infauna within a leased, cultivated clam bed. Our current study further examines the effects of shellfish cultivation on benthic assemblages and sediment biogeochemistry of nearshore habitat over a longer time period, post-dredging. For this experiment at a different site, dredging was conducted earlier in the season, at a larger spatial scale, more relevant to industry practices.

2. Materials and methods

2.1. Site characteristics and hydraulic dredging

Our study site, on a leased, cultivated clam bed, was located off Milford, Connecticut at approximately 41° 12.208′ N latitude and −73° 3.305′ W longitude, in the central basin of Long Island Sound (Fig. 1). We delineated 6, 1 ha plots, where 3 treatment plots (1, 3, 5) were to be dredged and 3 control plots (2, 4, 6) remained not dredged. The approximate distance from shore of the midpoints of plots 1 and 4 was 600 m, 700 m for plots 2 and 5, and 800 m for plots 3 and 6. These plots were further subdivided into 9 boxes to allow for spatially randomized sampling events within plots. Seawater depth at the study site varied over tidal cycles from 3.1 m to 4.9 m.

Hydraulic shellfish dredging was conducted on plots 1, 3, and 5 on June 14, 2010 by the G. & B. Shellfish Farm Inc. of Stratford, Connecticut with a 13.7 m clam boat, the F/V Stacie Frances. The hydraulic dredge weighed 408 kg, measured 1 m wide, and had 30, 1 cm hydraulic jets. The manifold was positioned 61 cm from the teeth which were set at a 45° angle, resulting in sediment penetration to a depth of about 2 cm. Each 1 ha test plot was dredged over a 1 hour period at a speed of about 2 nautical miles h^{-1} (3.7 km h^{-1}), covering approximately 50% of the area of each plot. Cage bars of the dredge were spaced 38.1 mm apart, allowing small sub-legal clams to pass through. During the experimental dredging approximately 7.9–19.9 bushels of marketable clams of varying sizes was removed from each of the dredged plots.

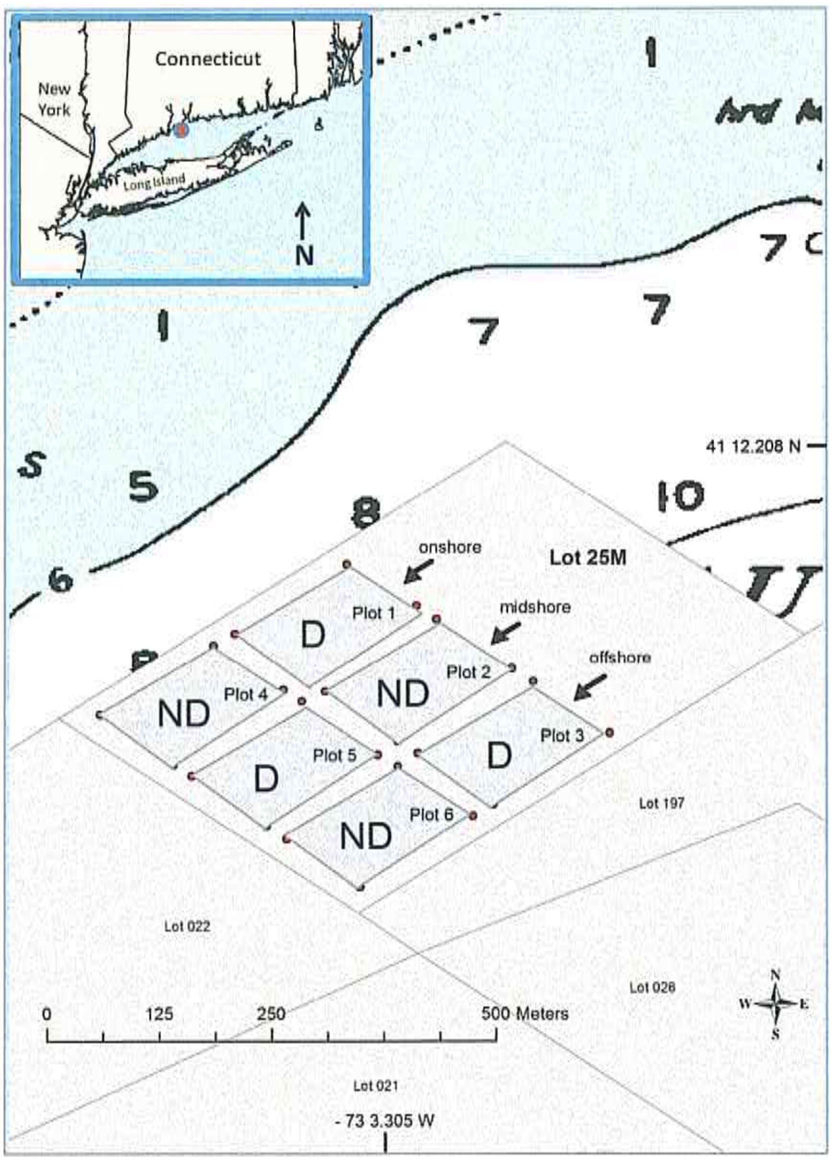

Fig. 1. Study site in Long Island Sound (inset) off the coast of Milford, CT. Projection shows a schematic of the 6 1 ha experimental plots indicating dredged (D) and not dredged (ND).

2.2. Benthic sampling

Benthic field sampling was conducted at 1–2 week intervals from aboard NOAA's R/V Victor Loosanoff. Seventeen sampling trips were conducted from June 1 until October 28, 2010. Environmental data (temperature, salinity and dissolved oxygen) were measured near the sediment–water interface at the beginning and end of each trip using handheld Yellow Springs Instrument Co. optical dissolved oxygen, temperature, and salinity meters.

Sediment was sampled from 3 randomly selected boxes within each of the 6 plots using a Smith–McIntyre grab, providing a total of 18 sediment samples, each with a surface area of 0.1 m^2. GPS coordinates were recorded for each individual grab. The sediment depth in each grab sample was measured in millimeters and a subsample of 50 g of sediment was removed for grain size analysis. Sediment samples were dried at 60 °C, acid washed with 1 M hydrochloric acid to remove shell matter, wet sieved to remove fine sediment (<63 μm) and dried again at 60 °C. Next, sediment was dry sieved for 20 min using a Meinzer II sieve shaker into the following size fractions: 1 mm, 500 μm, 250 μm, 125 μm, 63 μm, and <63 μm (from wet sieving) for classification according to Wentworth (1922).

Sediment collected in the grab was immediately washed through 4 mm and 1 mm sieves while aboard the boat. Live animals on the 4 mm screen and all the material retained on the 1 mm screen were transferred to storage jars for sorting at the laboratory. Samples were picked using 10× lighted magnifiers and all live organisms were removed and held in a refrigerator for 24–48 h. Organisms were then counted and identified to the lowest taxon possible (Gosner, 1978; Morris, 1947; Pollock, 1943; Smith, 1964; Weiss, 1995).

During most weeks that sediment was collected, epibenthic assemblages of mobile juvenile finfish and invertebrates on the plots were sampled using a 1-m wide beam trawl with a 3-mm mesh net. Three boxes were randomly selected from within each of the dredged and not dredged areas with two trawls conducted per box, for a total of 12 samples, 6 each from each treatment. Tows were made over the longest dimension of each plot, an approximate distance of 137 m, for 2–3 min at a speed of approximately 1 nautical mile h^{-1}. Juvenile fish were identified by species and counted.

2.3. Chemistry sampling and analytical procedures

Sediment cores were obtained from various locations in the study area using a sediment corer designed for this study and described by Alix et al. (2013). Two 45 mm diameter sediment cores were collected at each station. The first core was analyzed for hydrogen sulfide (not reported), and the second core was used to determine pH, oxygen, and total ammonia concentrations in sediments.

Measurements of pH and oxygen were determined in 1 mm increments from the top 10-mm of each core. For pH readings, a MI-414 pH electrode in a 16-gauge needle was attached to a micro-manipulator to attain millimeter-scale resolution for pH. For dissolved oxygen measurements, an oxygen micro-optical, 140-μm probe in a needle (Loligo Systems, Denmark) attached to a micro-manipulator provided millimeter-scale resolution of oxygen profiles. Probes were calibrated before each use according to the manufacturer's instructions. The cores were extruded and sectioned at 2-cm intervals; each section was placed in a 50-ml centrifuge tube and centrifuged at 1000 ×g for 20 min to obtain the porewater. The porewater was decanted, hand-filtered by syringe through a 0.45-μm filter, and the effluent collected in 15-ml centrifuge tubes that were placed immediately on ice in the dark for subsequent total ammonia determination. Sediment which remained in the centrifuge tube was sieved for analysis of particulate nitrogen, carbon, and sulfur.

Total ammonia was determined within 24-h of sample collection using a Quattro autoanalyzer (Seal Analytical, Wisconsin). Detailed descriptions for quantifying total ammonia can be found in Methods of Seawater Analysis (Hansen and Koroleff, 1999). Briefly, total ammonia was determined using the Berthelot reaction (detection limit, 0.05 μM; Hansen and Koroleff, 1999).

Particulate carbon, nitrogen, and sulfur were determined with a Costech ECS 4010 CHNS elemental analyzer (Valencia, California). All samples were dried in an oven at 60 °C, overnight. Sediments were ground using a Retsch PM 200 (Newton, Pennsylvania) grinder to a size of 63 μm. Approximately 3-μg subsamples of sediment were weighed into tin boats with 0.50 μg of vanadium oxide added for total carbon, nitrogen, and sulfur determination. A subsample of each sediment section was also acidified for determination of organic carbon and nitrogen using an elemental analyzer. A standard reference material (SRM 8704 Buffalo River Sediment) was analyzed along with the samples, with a reported total carbon value of 3.35%. The measured total carbon recovery, 3.15 ± 0.33% (n = 50), was within the reported value range

2.4. Flux calculations

Sediment ammonia, oxygen, and hydrogen fluxes were calculated with Fick's first law of diffusion (Berner, 1980), commonly used for shallow-water estuarine sediments (Emerson et al., 1984; Hammond et al., 1985). The assumption is that molecular diffusion represents the major component in exchange of dissolved substances between bottom sediments and overlying water and is expressed by the formula:

$$J = -\varphi^m D_s \frac{\partial C}{\partial z}$$

where J is the flux, φ is the porosity, m has a value of 3 for these surface sediments (Ullman and Aller, 1982), D_s is the effective diffusion coefficient, and $\frac{\partial C}{\partial z}$ is the observed concentration gradient of porewater. Molecular diffusion coefficients in seawater were corrected for the in situ, bottom-water temperature. Positive numbers indicate a net flux into the sediment while negative numbers indicate a net flux out of the sediments.

2.5. Data analysis and statistics

Repeated measures analysis was used to compare dredged versus not dredged plots over time, post-dredging, for a variety of environmental parameters. Results for dredged and not dredged plots were averaged for each time point. A bootstrap-t method for comparing 20% trimmed means of two dependent groups based on difference scores was used (Wilcox, 2003). The bootstrap method was selected for its robust nature and lack of assumptions about normality or homoscedasticity. The bootstrap-t method was chosen over a percentile bootstrap method due to the generally small sample sizes (i.e., n < 20). Familywise error rate was controlled using the method of Hochberg (1988) as described in Wilcox (2003). The statistical software program R version 2.13 was used to perform these comparisons (http://www.r-project.org). Differences in sediment grain size, with regard to plot position relative to the shoreline, were assessed using a percentile bootstrap-based multiple comparisons test (Wilcox, 2003).

Benthic assemblage data and chemistry data were analyzed separately using the statistical software program PRIMER version 6 with the PERMANOVA add-on (Anderson et al., 2008; Clarke and Gorley, 2006). A square root transformation was applied and the Bray–Curtis resemblance measure was used to generate similarity matrices across all plots and sampling dates. Agglomerative, hierarchical cluster analysis using group average linkage was combined with the SIMPROF permutation test to explore internal structure in the benthic assemblage data. Non-metric multidimensional scaling (MDS) was also used to visualize sample relationships in the benthic assemblage data. The canonical analysis of principal coordinates (CAP) routine was used to identify members of the benthic assemblage that were associated with the early- and late-season assemblages distinguished in the clustering and

MDS visualization. CAP was also used to visualize sample relationships associated with plot position relative to the shoreline (inshore vs. midshore vs. offshore). Early and late-season samples were examined separately to avoid masking of significant results for other parameters by the strong seasonal signal. The Analysis of Similarity (ANOSIM) test was used to look for effects of dredging treatment on benthic assemblage composition and effects of dredging treatment, sampling date, and shore position on chemistry data. The CAP routine was also used to perform a discriminant analysis to explore potential dredging effects on benthic assemblages, and the PERMANOVA routine was used, with mean grain size as a covariate, as another technique to try to identify dredging effects on the biology and chemistry of the experimental plots. The CAP routine was also used to look at the chemical parameters in relation to distance of the experimental plots from shore. Finfish assemblages on dredged and not dredged sites were also compared using Primer (version 6) software and the Bray–Curtis resemblance measure on the untransformed data followed by the ANOSIM procedure.

3. Results

3.1. Sediment grain size and environmental parameters

Sediment grain size analysis revealed a slight gradient of larger to smaller particle sizes from nearshore plots (lower ϕ values) toward offshore plots (greater ϕ values) while ϕ size of adjacent plots did not differ significantly and no dredging effect on grain size was detected. We assigned three groupings of paired plots (based on position relative to the shoreline) designated as inshore (plots 1 and 4), midshore (plots 2 and 5), and offshore (plots 3 and 6) for further statistical analysis. When grouped, ANOVA detected a significant difference ($p < 0.01$) in the mean ϕ size between each of these groupings (inshore vs. midshore, inshore vs. offshore and midshore vs. offshore) (Table 1). Based on mean values, all of the paired plots were categorized as very fine sand, as defined by the Wentworth scale. Seawater temperatures over the sampling period ranged from 16.7 to 24.3 °C. The mean salinity measured was 25.8 ± 0.75 and mean dissolved oxygen values remained above saturation at 7.24 ± 1.70 ppm.

3.2. Effects of dredge treatment, sampling date, and plot location on benthic and finfish assemblages

Repeated measures analyses indicated no significant differences between dredged and not dredged plots for the most abundant phyla, the most common bivalves, and for the most common polychaetes (Table 2). No significant differences were observed between dredged and not dredged plots over time for any of the ecological diversity measures including number of species, number of individuals, and Margalef, Pielou, Shannon, and Simpson indices (Table 3). No significant differences between dredged and not dredged plots by sampling date were detected for biovolumes of organisms collected in the sediment grabs.

A total of 110 species were identified in the sediment grab samples. Cluster analysis with SIMPROF indicated groupings of species by season, with a clear separation between early (June/July/early August) and late (late August/September/October) seasonal occurrence. This seasonal progression was apparent in the MDS plot of sample relationships (Fig. 2). The CAP routine was used to identify taxa that were correlated with early versus late season assemblages. Taxa comprising the early community include the amphipod *Ampelisca* spp., the polychaetes *Clymenella torquata* and *Leitoscoloplos fragilis*, the crustaceans *Caprella* spp., *Crangon septemspinosa*, *Mysidae*, *Ovalipes ocellatus*, and *Unicola irrorata*, the gastropod *Turbonilla*, the echinoderm *Leptosynapta* spp., and the bivalves *Ensis directus*, and *Mya arenaria*. Species dominating the late community include the gastropod *Haminoea solitaria*, the bivalves *Anadara transversa*, *M. mercenaria*, *Mulinia lateralis*, and *Petricolaria pholadiformis*, the echinoderm *Chirodata laevis*, the nemerteans *Amphiporus bioculatus* and *Lineus* spp., the polychaetes *Glycera* spp., *Lepidametria commensalis*, *Pectinaria gouldii*, *Phylodoce*, *Polydora* spp., and *Spiochaetopterus oculatus*, and the crustaceans *Cumacea* and *Hemigrapsus sanguineus*.

ANOSIM of early and late season assemblages examined separately found no significant difference in community structure between dredged and not dredged plots for either grouping (early summer $R = -0.01$, $p = 0.58$; late summer $R = -0.02$, $p = 0.66$). The PERMANOVA analysis, with grain size as a covariate, also yielded no significant difference between communities from dredged vs. not dredged plots ($p = 0.97$). Within the early and late season communities, organisms showed associations with position relative to shore location (inshore, midshore, and offshore), corresponding to minor differences in sediment ϕ size (Fig. 3).

Eighty-two beam trawls were conducted, and twenty-five species of finfish collected. Pipefish, *Syngnathus fuscus* (Storer 1839), were the most abundant fish species (975 individuals), followed by anchovy, *Anchoa mitchilli* (Linnaeus 1758) (874), cunner, *Tautogolabrus adspersus* (115) and porgy/scup, *Stenotomus chrysops* (49). All other species occurred at densities of <35 individuals. ANOSIM found no difference in finfish assemblages between dredged and not dredged plots ($p = 0.12$). MDS plot of the data indicates that composition of the trawls corresponded closely with season (not shown).

Table 1
Mean ϕ size and number of newly settled *M. mercenaria* sampled at 3 locations relative to shore. *M. mercenaria* abundance on each sampling date, for each plot, was summed over the entire season to obtain the total number. Superscript letters indicate a significant difference among grouped plots ($p < 0.05$).

Location	Mean ϕ size	Number of clams
Inshore (plots 1, 4)	$3.02^{a} \pm 0.36$	186^{ab}
Midshore (plots 2, 5)	$3.41^{b} \pm 0.39$	248^{a}
Offshore (plots 3, 6)	$3.63^{c} \pm 0.37$	109^{b}

Table 2
Repeated measures analysis for most abundant phyla, bivalve species, and polychaete taxa, comparing dredged to not dredged plots.

Phyla	Genus species	p
Annelid		0.26
	Clymenella torquata	0.69
	Glycera spp.	0.35
	Nepthys spp.	0.03
	Pectinaria gouldii	0.15
	Spiochaetopterus oculatus	0.58
Arthropoda		0.57
Echinodermata		0.14
Mollusca		0.49
	Mercenaria mercenaria	0.70
	Mulinia lateralis	0.38
	Mya arenaria	0.26
Nemertea		0.25

Table 3
Repeated measures analysis of ecological indices and biovolume for dredged versus not dredged plots.

Indices	p
Number of species	0.08
Number of individuals	0.41
Margalef richness	0.15
Pielou evenness	0.05
Shannon diversity	0.71
Simpson diversity	0.32
Biovolume	0.75

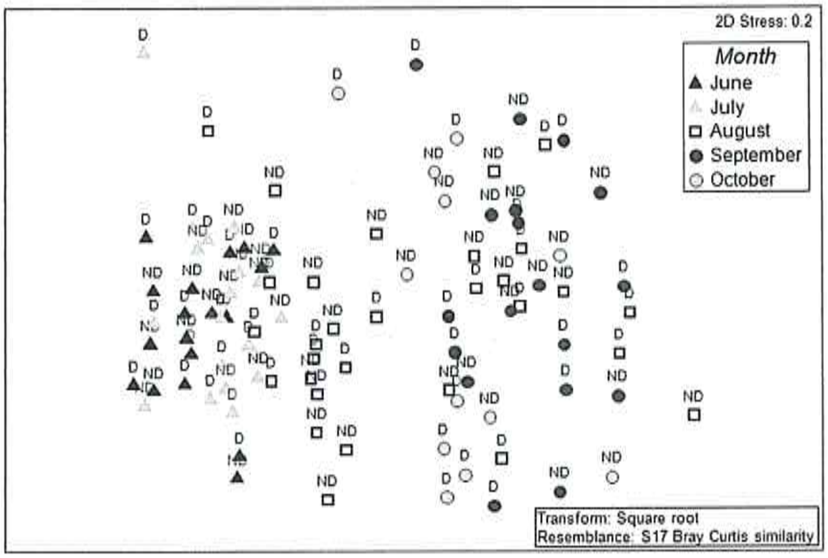

Fig. 2. Non-metric multidimensional scaling plot of benthic community samples. Symbols correspond to the month of sampling. Labels indicate treatment: dredged (D) or not dredged (ND).

3.3. Effects of dredge treatment, sampling date, and plot location on hard clam settlement

Repeated measures analysis indicated significantly more newly settled *M. mercenaria* in the 0.1 m^2 sediment samples ($n = 3$) on dredged versus not dredged plots for the last six sampling dates ($p = 0.03$; Fig. 4). Repeated measures analysis for these last six sampling dates, based on shore position, indicated no statistical difference in abundance of newly settled *M. mercenaria* between inshore and midshore plots, while the midshore plots had a significantly greater number of set compared to the offshore plots ($p = 0.01$) (Table 1). Hard clam set, recovered from samples during this time period, measured from 2 to 8 mm in shell length. Densities of hard clams were estimated to be 40–100 m^{-2} on the dredged plots, up to 10 times greater than on not dredged plots.

3.4. Effects of dredge treatment, sampling date, and plot location on sediment chemistry

Repeated measures analysis detected no significant difference between dredged and not dredged plots for any of the chemical parameters (Table 4). Generally for both dredged and not dredged plots, ammonia fluxed out of the sediments, oxygen fluxed in and hydrogen flux was variable (Table 5). Carbon and nitrogen ratios are typical of marine detritus and phytoplankton (i.e., Redfield ratio—6.625). Sulfur levels combined with organic carbon levels indicate that sulfur was deposited under a water column that was mostly oxic.

ANOSIM tests indicated some differences in the suite of chemical parameters related to shore position and/or sediment grain size (global

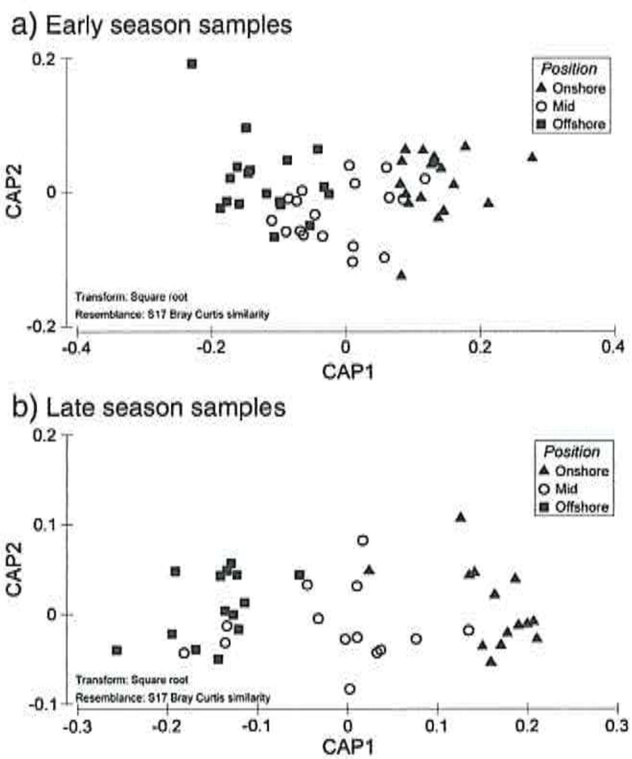

Fig. 3. Canonical analysis of principal coordinates (CAP) plots showing early season (A) and late season (B) benthic community assemblages in relation to distance from shore.

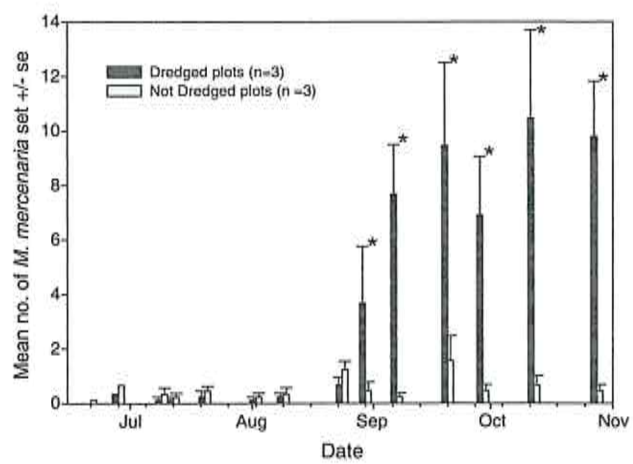

Fig. 4. Mean number of *M. mercenaria* set in the 0.1 m^2 sediment samples ($n = 3$) on dredged and not dredged plots over the sampling season. An asterisk above paired bars indicates a significant difference ($p = 0.03$).

Table 4
p-Values of repeated measures analysis for chemical parameters comparing dredged (D) to not dredged (ND) plots over the growing season.

Chemical parameter	p
Mean grain size	0.23
Total NH_4^+ flux	0.43
Oxygen flux	0.70
Hydrogen flux	0.73
Organic carbon	0.41
Total carbon	0.09
Nitrogen	0.15
Total sulfur	0.46
Organic C:N	0.39
Total C:N	0.89
Total C:S	0.82
Total N:S	0.72

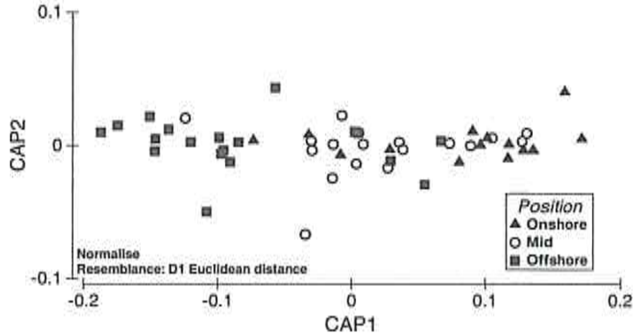

Fig. 5. Canonical analysis of principal coordinates (CAP) plots showing the association of chemical variables in relation to distance from shore.

test $p < 0.01$; inshore vs. midshore $p = 0.08$; inshore vs. offshore $p < 0.01$; midshore vs. offshore $p < 0.01$). There was no significant difference detected when comparing month of sampling ($p = 0.25$) or dredging treatment ($p = 0.67$).

CAP analysis was used to examine differences in chemical parameters based on distance of plots from shore (Fig. 5). All chemical parameters, except hydrogen flux, showed a high correlation with shore position, with a trend toward decreasing values moving away from shore (Table 6).

4. Discussion

4.1. Effects of dredge treatment, sampling date, and plot location on benthic and finfish assemblages

We found that a one-time hydraulic shellfish dredging event did not significantly affect the composition of benthic assemblages on a cultivated clam bed. Ecological indices showed no differences between dredged and not dredged plots in abundance or diversity of the benthic community over the course of the growing season. Disturbance of the benthos by clam dredging was either insufficient to disrupt benthic community structure or if changes occurred, they resolved quickly and could not be detected. The extent and duration of disturbance and the rate of recovery among benthic organisms may be influenced by the physical characteristics of the seabed, proximity of the clam beds to shore, and the suite of organisms inhabiting the benthos.

Benthic communities in coastal Connecticut are inhabited by resilient organisms which tolerate and recover quickly from dynamic environmental conditions found in shallow inshore waters (Dobbs and Vozarik, 1983; McCall, 1977). Natural physical disturbances, such as wave action, tidal currents, and wind and storm events (Stokesbury et al., 2011), are common in the coastal zone, continually disrupting bottom sediments (Falcão et al., 2003). In high energy environments where disturbance is frequent, the effects of shellfish dredging on bottom sediments and benthic assemblages may be indistinguishable from naturally occurring changes to the seabed (Constantino et al., 2009; Sciberras et al., 2013). In a study within Long Island Sound, McCall (1977) found rapid recolonization by opportunistic species after removal of benthic fauna by either natural or simulated disturbance. Abundant infaunal populations and diverse benthic species assemblages have been reported in areas historically subject to long-term, continual molluscan shellfish harvesting (Bigford, 1997).

Recruitment processes, driven by seasonal changes in water temperature, timing of spawning cycles, and patterns of larval settlement all influence the population dynamics of inshore benthic communities in the coastal zone of Long Island Sound (McCall, 1977) and likely account for the temporal variations in species abundance we observed. Sampling date strongly influenced community structure with observed differences in benthic assemblages between early and late season sampling. Shifts in benthic community structure, resulting from annual cycles of settlement and recruitment, can exceed short-term changes associated with shellfish harvesting (e.g., Alves et al., 2003; Goldberg et al., 2012; Sparsiset al., 1993). For example, although ecological differences were not detected in Cardigan Bay, UK between seafloor continually dredged for scallops and adjacent areas closed to scalloping, seasonal fluctuations in epifaunal diversity and benthic community composition were apparent (Sciberras et al., 2013). Commercial harvesting of clams from leased beds is generally completed within hours or days while temporal changes in population dynamics with regard to seasonal cycles are ongoing. Effects of discrete shellfish harvesting during our study appear minor when compared to natural fluctuations in the composition of benthic assemblages which occurred over the course of our sampling period.

Mobile macrofauna can avoid active dredge harvesting and studies have shown that finfish drawn to dredge tracks, following harvest, consume organisms exposed by disturbance of the sediments (Gilkinson et al., 2005). In our study, composition of finfish assemblages did not differ between dredged and not dredged plots at any time during sampling, but a seasonal trend was indicated as abundance and occurrence of species corresponded closely with sampling date. Results of this study are consistent with our previous study (Goldberg et al., 2012) and suggest little or no effect of one-time hydraulic dredging on fish populations inhabiting clam beds in Long Island Sound.

Benthic assemblages were also affected by plot location relative to the shoreline, a proxy for sediment grain size. Across our study area we observed a minor gradient, where sediment grain size decreased with distance from shore, but all plots were still classified as very fine sand. This typical size distribution of sediments, caused by wave and tidal energy, has been well described (Grasso et al., 2011; Silva et al., 2009; Wildish and Kristmanson, 1997). We found that relatively small differences in sediment grain size across the clam bed had a greater

Table 5
Range of values for chemical parameters on dredged and not dredged plots. Units for chemical parameters: mean grain size (ϕ), fluxes (mmol m^{-2} d^{-1}), and carbon (C), nitrogen (N) and sulfur (S) (mg g^{-1}).

Chemical parameter	Dredged (min)	Dredged (max)	Not dredged (min)	Not dredged (max)
Mean grain size	3.19	3.64	2.80	3.77
Total NH_4^+ flux	−68.26	−21.52	−79.25	−9.62
Oxygen flux	0.71	0.38	0.69	0.34
Hydrogen flux	−10.25	1.15	−10.35	0.61
Organic carbon	2.6	6.91	3.03	6.27
Total carbon	9.26	14.62	9.21	13.18
Nitrogen	0.62	1.28	0.62	1.27
Total sulfur	1.39	2.82	1.46	2.61
Organic C:N	3.81	7.53	4.26	7.42
Total C:N	12.61	18.45	11.76	19.21
Total C:S	13.68	20.91	11.78	20.96
Total N:S	0.79	1.43	0.91	1.38

Table 6
Canonical analysis of principal coordinates showing Spearman correlation coefficients and mean (±SE) values for chemical parameters by proximity from shore. Units for chemical parameters: mean grain size (ϕ), fluxes (mmol m^{-2} d^{-1}), and carbon, nitrogen and sulfur (mg g^{-1}). Units for chemical parameters: mean grain size (ϕ), fluxes (mmol m^{-2} d^{-1}), and carbon (C), nitrogen (N) and sulfur (S) (mg g^{-1}).

Chemical parameter	Inshore	Midshore	Offshore	Correlation coefficient
Mean grain size	3.65 (0.08)	3.37 (0.06)	3.03 (0.07)	−0.69
Total NH_4^+ flux	−56.48 (6.70)	−43.17 (5.23)	−27.95 (4.51)	0.70
Oxygen flux	0.64 (0.03)	0.56 (0.48)	0.41 (0.03)	−0.66
Hydrogen flux	−2.56 (1.13)	−1.29 (0.90)	−2.21 (1.52)	0.09
Organic carbon	6.70 (0.58)	3.97 (0.46)	2.84 (0.41)	−0.88
Total carbon	15.97 (0.77)	10.72 (0.60)	8.28 (0.75)	−0.89
Nitrogen	1.20 (0.07)	0.84 (0.05)	0.73 (0.6)	−0.86
Total sulfur	2.53 (0.20)	1.73 (0.14)	1.69 (0.18)	−0.78

influence on benthic community composition than one-time hydraulic shellfish dredging.

4.2. Effects of dredge treatment, sampling date, and plot location on sediment chemistry

In our study, no detectable changes to sediment chemistry resulted from clam dredging. No significant differences were observed for the measured suite of chemical parameters between dredged or not dredged plots or among sampling dates. In a study of clam dredging in southern Portugal, Falcão et al. (2003) found an immediate drop in porewater chemical parameters including ammonium, nitrates, organic nitrogen, phosphate, and silicate, just after dredging, which returned to initial values within minutes to hours. Meseck et al. (in press) found similar results on another Long Island Sound clam bed, where sediment chemistry was not significantly different between dredged and not dredged sites, but was more of a function of season and plot location. Other studies of clam harvesting found no measurable changes to biological oxygen demand, nitrogen, sulfide, phosphate (Goodwin, 1977; Goodwin and Shaul, 1978), or total organic carbon (Sparsiset al., 1993) measurements. Any changes to sediment chemistry related to dredging during our study may have been immediate and short-lived, resolving before our first post-dredge sampling on the following day. Nearshore coastal sediments, prone to frequent natural disruption, are likely to recover chemical equilibrium rapidly following brief, pulse disturbance events.

4.3. Effects of dredge treatment, sampling date, chemistry, and plot location on hard clam settlement and survival

Bivalve settlement involves larval and post larval site selection in response to biological, chemical, and/or physical cues (Rodriguez et al., 1993). Settlement and/or survival of juvenile hard clams during our study may have been enhanced by the effects of hydraulic dredging on habitat. For the last six weeks of sampling we found significantly greater numbers of newly settled hard clams on dredged, compared to not dredged plots, independent of sediment grain size. During this period, post-settlement clams, likely resulting from a spawning pulse several weeks earlier, had grown to a size where they were readily detectable in our samples.

Cultivated clam beds may have more diverse and productive ecological communities than undisturbed areas because of potentially beneficial effects of dredging on habitat (Stokesbury et al., 2011). Anecdotally, clam fishermen have reported increased hard clam settlement following major storm events, where the seafloor is disturbed. Enhanced settlement has been attributed to resuspension of organic material, increased oxygenation, and reduced acidity of sediments (Mercaldo-Allen and Goldberg, 2011; Visel, 1990a,b). Although clam density and settlement were not initially enhanced by hydraulic escalator dredging in Maryland, recruitment and/or survival of young soft shell clams (*M. arenaria* Linnaeus 1758) increased following the harvest of adult clams, and greater porosity of sediments was observed for a year post-dredging (Pfitzenmeyer, 1972a,b). Periodic clam harvesting may also increase settling or survival of young clams by removing larger clams, which reduces intraspecific competition (Goodwin and Shaul, 1980; Kyte and Chew, 1975; Rice et al., 1989). Alternatively, Keck et al. (1974) reported that coarser grained sediments and the presence of adult clam juices enhanced settlement, suggesting that occurrence of adult clams in proper numbers might act to increase numbers of settling clams.

Although not the focus of our study, we found that differences in sediment chemistry and grain size, related to the distance of plots relative to the shoreline, resulted in biotic effects. The relatively lower numbers of newly settled *M. mercenaria* found on the offshore sites may reflect less suitable habitat, based on subtle differences in sediment chemistry. Laboratory "still-water" experiments have investigated chemical settlement cues for bivalves, including ammonia and oxygen levels (Coon et al., 1990; Marinelli and Woodin, 2004), but dynamic field conditions introduce many more variables.

Sediment grain size has been reported to influence post-settlement survival of bivalve spat (Cardoso et al., 2006). We observed many newly settled hard clams at the plots closer to shore where sediment grain sizes were largest, ranging from 3.02 to 3.41 ϕ, which may indicate a preferential habitat selection. Hard clam density was positively associated with increasing sediment grain size in both Chesapeake (Mann et al., 2005) and Chincoteague (Wells, 1957) Bays. Conversely, we found the fewest newly settled *M. mercenaria* in the finer grain sediments on the offshore plots. Alternatively, the recently settled hard clams we observed in finer sediments may have been prone to erosional transport by currents and some may have been relocated to inshore areas with slightly coarser sediments (Hunt, 2004). These slightly coarser sediments may also have inhibited the activity of some predators, leading to greater hard clam survival (Kraeuter, 2001).

Enhanced settlement and survival of bivalves may relate to changes in sediment chemistry resulting from shellfish cultivation. Natural disturbance of nearshore coastal sediments from storm events may raise pH and/or calcium carbonate concentrations, beneficially altering biogeochemical parameters to favor post-set survival and recruitment of bivalves. In a laboratory study, hard clams increased burrowing activity at increasing carbonate saturation states and soft shell clam recruitment increased three-fold when crushed shell ($CaCO_3$) was applied to an intertidal mudflat, elevating the saturation state of surface sediments (Green et al., 2013). Our results suggest that the relationship between sediment biogeochemistry and bivalve settlement and survival merits further study.

5. Conclusion

We found that hydraulic clam dredging, as conducted for our experiment, did not cause measurable disturbance to the benthic community or sediment chemistry. Abundance of newly settled hard clams, however, was greater on plots that were hydraulically dredged as compared to adjacent plots that were not dredged. Sampling date and sediment grain size were shown to significantly influence the composition of benthic assemblages. Our experimental data suggest that a clam dredging event on a leased, cultivated bed had limited effects on benthic biota and that physical and chemical properties of sediment may have enhanced hard clam recruitment and post-set survival.

Acknowledgment

The authors thank Captains Robert Alix and Werner Schreiner for vessel operations; Mark Dixon, Kimberly Dickinson, Austin Hurst, Amanda Kardas, Dylan Redman, and James Reidy for technical support; our industry partners the Frank M. Flower & Sons Company and Gary Salce of G. & B. Shellfish Farm Inc. for allowing us to sample on their leased shellfish beds and for dredging our study site; and David Carey and Thomas Barrell of the State of Connecticut, Department of Agriculture, Bureau of Aquaculture, for assistance in selection and marking of study sites. The use of trade names does not imply endorsement.

References

Alix, R.J., Schreiner, W., Meseck, S.L., 2013. Construction of an inexpensive gravity sediment corer for micro-profiling O_2 and pH in marine sediments. NOAA Tech. Memo. NMFS NE, 224 (13 pp.).
Alves, F., Chícharo, L., Nogueira, A., Regala, J., 2003. Changes in benthic community due to clam dredging on the Algave coast and the importance of seasonal analysis. J. Mar. Biol. Assoc. UK 83 (4), 719–729.
Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. Primer-E Limited, Plymouth.
Berner, R.A., 1980. Early Diagenesis: A Theoretical Approach. Princeton University Press, Princeton.
Bigford, T.E., 1997. Environmental challenges facing the shellfish industry. In: MacKenzie Jr., C.L., Burrell Jr., V.G., Rosenfield, A., Hobart, W.L. (Eds.), The History, Present Condition, and Future of the Molluscan Fisheries of North and Central America and Europe. NOAA Tech. Rep. NMFS, 128, pp. 157–163.
Cardoso, J.F.M.F., van der Veer, H.W., Kooijman, S.A.L.M., 2006. Body-size scaling relationships in bivalve species: a comparison of field data with predictions by the Dynamic Energy Budget (DEB) theory. J. Sea Res. 56, 125–139.
Clarke, K.R., Gorley, R.N., 2006. Primer v6: User Manual/Tutorial. Primer-E Limited, Plymouth.
Connecticut Department of Agriculture, 2013. Shellfish industry profile and economic impact. http://www.ct.gov/doag/cwp/view.asp?a=3768&q=458588 (Accessed on July 18).
Constantino, R., Gaspar, M.B., Tata-Regala, J., Carvalho, S., Cúrdia, J., Drago, T., Taborda, R., Monteiro, C.C., 2009. Clam dredging effects and subsequent recovery of benthic communities at different depth ranges. Mar. Environ. Res. 67, 89–99.
Coon, S.L., Walch, M., Fitt, W.K., Weiner, R.M., Bonar, D.B., 1990. Ammonia induces settlement behavior in oyster larvae. Biol. Bull. 179, 297–303.
Dobbs, F.C., Vozarik, J.M., 1983. Immediate effects of a storm on coastal infauna. Mar. Ecol. Prog. Ser. 11, 273–279.
Emerson, S., Jahnke, R., Heggie, D., 1984. Sediment–water exchange in shallow water estuarine sediments. J. Mar. Res. 42 (3), 709–730.
Falcão, M., Gaspar, M.B., Caetano, M., Santos, M.N., Vale, C., 2003. Short-term environmental impact of clam dredging in coastal waters (south of Portugal): chemical disturbance and subsequent recovery of seabed. Mar. Environ. Res. 56, 649–664.
Getchis, T.S., 2006. Clam heaven: what summer brings to the Connecticut coast. Wrack Lines 6 (1), 3–6.
Gilkinson, K.D., Gordon Jr., D.C., MacIsaac, K.G., McKeown, D.L., Kenchington, E.L.R., Bourbonnais, C., Vass, W.P., 2005. Immediate impacts and recovery trajectories of macrofaunal communities following hydraulic clam dredging on Banquereau, eastern Canada. ICES J. Mar. Sci. 62, 925–947.
Goldberg, R., Mercaldo-Allen, R., Rose, J.M., Clark, P., Kuropat, C., Meseck, S., Pereira, J., 2012. Effects of hydraulic shellfish dredging on the ecology of a cultivated clam bed. Aquacult. Environ. Interact. 3, 11–21.
Goodwin, L., 1977. Some Environmental Impacts of Subtidal Hardshell Clam Harvest with Hydraulic Clam Harvesters in a Small Experimental Plot in Puget Sound. Washington Department of Fisheries, Washington (16 pp.).
Goodwin, L., Shaul, W., 1978. Some effects of the mechanical escalator shellfish harvester on a subtidal clam bed in Puget Sound, Washington. State of Washington, Dep. Fish. Prog. Rep., 53 (23 pp.).
Goodwin, L., Shaul, W., 1980. Studies of mechanical clam harvest on an intertidal beach near Port Townsend, Washington. State of Washington, Dep. Fish. Prog. Rep., 119 (26 pp.).
Gosner, K.L., 1978. Peterson Field Guide Atlantic Seashore. Houghton Mifflin Company, New York.
Grasso, F., Michallet, H., Barthélemy, E., 2011. Experimental simulation of shoreface nourishments under storm events: a morphological, hydrodynamic and sediment grain size analysis. Coast. Eng. 58 (2), 184–193.
Green, M.A., Waldbusser, G.G., Hubazc, L., Cathcart, E., Hall, J., 2013. Carbonate mineral saturation state as the recruitment cue for settling bivalves in marine muds. Estuar. Coasts 36, 18–27.
Hammond, D.E., Fuller, C., Harmon, D., Hartman, B., Korosec, M., Miller, L.G., Rea, R., Warren, S., Berelson, W., Hager, S.W., 1985. Benthic fluxes in San Francisco Bay. Hydrobiology 129, 69–90.
Hansen, H., Koroleff, F., 1999. Determination of nutrients. In: Grasshoff, K., Kremling, K., Ehrhardt, M. (Eds.), Methods of Seawater Analysis. Wiley-VCH, Germany.
Hochberg, Y., 1988. A sharper Bonferroni procedure for multiple tests of significance. Biometrika 75, 800–802.
Hunt, H.L., 2004. Transport of juvenile clams: effects of species and sediment grain size. J. Exp. Mar. Biol. Ecol. 312, 271–284.
Keck, R., Maurer, D., Malouf, R.E., 1974. Factors influencing the setting behavior of larval hard clams, *Mercenaria mercenaria*. Proceedings of the National Shellfisheries Association, 64, pp. 59–67.
Kraeuter, J.N., 2001. Predators and predation. In: Kraeuter, J.N., Castagna, M. (Eds.), Biology of the Hard Clam. Elsevier Scientific Press, New York, pp. 441–588.
Kyte, M.A., Chew, K.K., 1975. A Review of the Hydraulic Escalator Shellfish Harvester and Its Known Effects in Relation to the Soft-shell Clam, *Mya arenaria*. Washington Sea Grant Publication WSG (75-2, 32 pp.).
MacKenzie Jr., C.L., Taylor, D.L., Arnold, W.S., 2001. A history of hard clamming. In: Kraeuter, J.N., Castagna, M. (Eds.), Biology of the Hard Clam. Elsevier Scientific Press, New York, pp. 651–673.
Mann, R., Harding, J.M., Southworth, M.J., Wesson, J.A., 2005. Northern quahog (hard clam) *Mercenaria mercenaria* abundance and habitat use in Chesapeake Bay. J. Shellfish Res. 24 (2), 509–516.
Marinelli, R.L., Woodin, S.A., 2004. Disturbance and recruitment: a test of solute and substrate specificity using *Mercenaria mercenaria* and *Capitella* sp. 1. Mar. Ecol. Prog. Ser. 269, 209–221.
McCall, P.L., 1977. Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. J. Mar. Res. 35 (2), 221–266.
Mercaldo-Allen, R., Goldberg, R., 2011. Review of the ecological effects of dredging in the cultivation and harvest of molluscan shellfish. NOAA Tech. Memo. NMFS-NE, 220, pp. 1–78.
Meseck, S.L., Mercaldo-Allen, R., Rose, J.M., Clark, P., Kuropat, C., Pereira, J.J., Goldberg, R., 2014. Effects of hydraulic shellfish dredging on the sediment biogeochemistry of a cultivated clam bed. J. World Aquacult. (in press).
Morris, P.A., 1947. A Field Guide to Shells of the Atlantic and Gulf Coasts and the West Indies. Houghton Mifflin Company, Boston.
Pfitzenmeyer, H.T., 1972a. Hydraulic softshell clam dredge study completed. Commer. Fish. News 5 (4), 1–2.
Pfitzenmeyer, H.T., 1972b. The Effects of the Maryland Hydraulic Clam Dredge on Populations of the Soft-shell Clam, *Mya arenaria*. National Marine Fisheries Service, MD Dep. Nat. Resour 1–74 (COM-73-11006).
Pollock, L.W., 1943. A Practical Guide to the Marine Animals of Northeastern North America. Rutgers University Press, New Brunswick.
Rice, M.A., Hickox, C., Zekra, I., 1989. Effects of intensive fishing effort on the population structure of quahogs, *Mercenaria mercenaria* (Linnaeus 1758), in Narragansett Bay. J. Shellfish Res. 8 (2), 345–354.
Rodriguez, S.R., Ojeda, F.P., Inestrosa, N.C., 1993. Settlement of benthic marine invertebrates. Mar. Ecol. Prog. Ser. 97, 193–207.
Sciberras, M., Hinz, H., Bennell, J.D., Jenkins, S.R., Hawkins, S.J., Kaiser, M.J., 2013. Benthic community response to a scallop dredging closure within a dynamic seabed habitat. Mar. Ecol. Prog. Ser. 480, 83–98.
Silva, R., Baptista, P., Veloso-Gomes, F., Coelho, C., Taveira-Pinto, F., 2009. Sediment grain size variation on a coastal stretch facing the North Atlantic (NW Portugal). J. Coast. Res. 56, 762–766.
Smith, R.I., 1964. Keys to Marine Invertebrates of the Woods Hole Region. Marine Biological Laboratory, Woods Hole.
Sparsis, M., DeAlteris, J.T., Rice, M.A., 1993. Effects of bottom cultivation on quahogs and other bottom invertebrates in Narragansett Bay. In: Rice, M.A., Grossman-Garber, D. (Eds.), Proceedings of the Second Rhode Island Shellfish Industry Conference, August 4, 1992, University of Rhode Island, Narragansett Bay Campus. Report No. RIU-W-92-002. Rhode Island Sea Grant, University of Rhode Island, Narragansett, pp. 63–78.
Stokesbury, K.D.E., Baker, E.P., Harris, B.P., Rheault, R.B., 2011. Environmental impacts related to mechanical harvest of cultured shellfish. In: Shumway, S.E. (Ed.), Aquaculture and the Environment. John Wiley and Sons, Inc, Oxford, pp. 319–338 (Chapter 11).
Ullman, W.J., Aller, R.C., 1982. Diffusion coefficients in near-shore marine sediments. Limnol. Oceanogr. 27, 552–556.
Visel, T.C., 1990a. The hydraulic cultivation of marine soils to enhance clam production. September 20, 1990 Special Meeting Madison Town Hall, Madison CT. The Sound School Adult Education Outreach Program, New Haven (10 pp.).
Visel, T.C., 1990b. The Cultivation of Marine Soils: The Hydraulic Cultivation of the Hard Shell Clam *Mercenaria mercenaria*. The Sound School, Adult Education Outreach Program, New Haven (23 pp.).
Weiss, H.M., 1995. Marine animals of southern New England and New York. Identification Keys to Common Nearshore and Shallow Water Macrofauna. Bulletin, 115. State Geological and Natural History Survey of Connecticut, Hartford.
Wells, H.W., 1957. Abundance of the hard clam *Mercenaria mercenaria* in relation to environmental factors. Ecology 38 (1), 123–128.
Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. J. Geol. 30, 377–392.
Widdicombe, S., Austen, M.C., Kendall, M.A., Olsgard, F., Schaanning, M.T., Dashfield, D.L., Needham, H.R., 2004. Importance of bioturbators for biodiversity maintenance: indirect effects of fishing disturbance. Mar. Ecol. Prog. Ser. 275, 1–10.
Wilcox, R.R., 2003. Applying Contemporary Statistical Techniques. Academic Press, New York.
Wildish, D.J., Kristmanson, D.D., 1997. Benthic Suspension Feeders and Flow. Cambridge University Press, Cambridge.
Zajac, R.N., Lewis, R.S., Poppe, L.J., Twichell, D.C., Vozarik, J., DiGiacomo-Cohen, M.L., 2000. Relationships among sea-floor structure and benthic communities in Long Island Sound at regional and benthoscape scales. J. Coast. Res. 16 (3), 627–640.