

ENVIRONMENTAL AND ECOLOGICAL BENEFITS AND IMPACTS OF OYSTER AQUACULTURE



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Environmental and ecological benefits and impacts of oyster aquaculture

CHESAPEAKE BAY, VIRGINIA, USA

Award Information

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Abstract

To better quantify the ecological benefits and impacts of oyster aquaculture, we sampled water quality, sediment quality, benthic macrofaunal communities and oysters at four oyster aquaculture sites located on the western shore of Chesapeake Bay in Virginia, USA. At each site, samples were collected from within the footprint of the aquaculture cages and from nearby areas with similar physical and environmental conditions but far enough away to be minimally influenced by aquaculture operations. Data collected from the water column included chlorophyll concentrations, turbidity, pH, dissolved oxygen concentrations, light attenuation, particle concentration, median particle size, total suspended solids and their organic content, and dissolved nutrient concentrations. Sediment and macrofauna community data collected included sediment grain size and organic content and macrofauna identity, abundance, biomass and species richness. In addition to assessing the potential impacts of oyster aquaculture on the water column and benthos, we also assessed differences in the dimensions dry mass and nitrogen (N) and phosphorus (P) content of the oysters harvested at each site.

Differences in water quality, sediment quality, and macrofauna community structure between areas within and outside the farm footprint at each site were rare. Where differences existed, they were of small magnitude and varying direction (i.e. negative versus positive impact). Aquaculture sites varied by an order of magnitude in size, annual harvest and harvest per unit area. They also varied by an order of magnitude in the total amount of N and P harvested per unit. In contrast to the negative environmental impacts associated with other forms of animal protein production for human consumption, oyster harvest from the sites in the present study results in the removal of 21-372 lbs. of N and 3-49lbs of P per farm per year.

Rationale

Oyster populations in Chesapeake Bay have declined to ~0.3% of their historic levels (Wilberg et al. 2011). With the decline in oyster populations has come a growing recognition of the ecosystem services that can be provided by high densities of oysters (Coen et al. 2007; Grabowski et al. 2012, Kellogg et al. 2014). As a result, tens of millions of dollars have been invested in oyster reef restoration in Chesapeake Bay in recent decades in an attempt to regain the ecosystem services and functions that have been lost or diminished. While oyster aquaculture does not provide exactly the same ecosystem services and functions as oyster reefs, oysters in aquaculture settings do provide some of the same benefits without significant investment of public funds. However, aquaculture can also have negative impacts that likely vary depending upon the culture method used (Newell 2004). To date, there have been few studies in Chesapeake Bay that quantify both the benefits and impacts of commercial aquaculture operations using different culture approaches.

In the Virginia portion of Chesapeake Bay, oyster aquaculture has expanded rapidly in recent years (Hudson 2017, Fig. 1). Gear-intensive culture methods are commonly used and controversial. In this type of aquaculture, oysters are grown in cages that are either attached to floats that keep them near the surface (hereafter “floating cages”) or are placed on racks that keep them just above the sediments at the bottom of the water column (hereafter “bottom cages”). Aquaculture operations using floating or bottom cages have the potential to concentrate organic matter on the sediment surface, potentially creating hypoxic or anoxic conditions that negatively impact macrofaunal

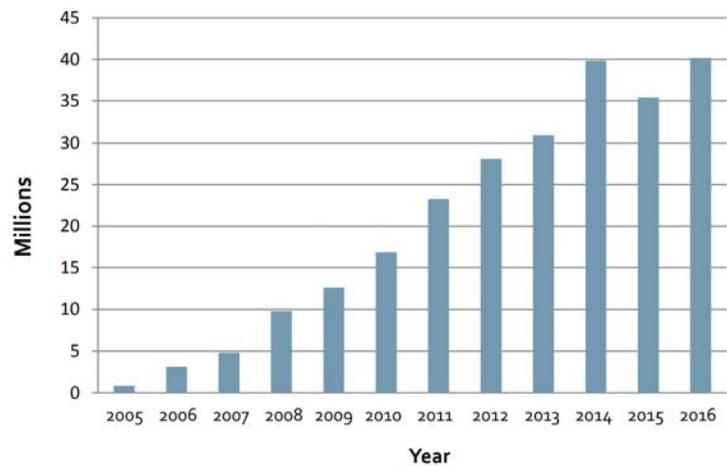


Fig. 1. Annual aquacultured oysters (in millions) sold by Virginia growers from 2005 through 2016 (Hudson 2017).

communities living in those sediments. However, these effects likely vary significantly in both space and time depending upon a variety of factors including gear type, stocking density, local hydrodynamic regime, and season. Of course, these potential concentrations of organic matter are a byproduct of oysters filtering phytoplankton, detritus and sediments from the water column which can improve water quality (Newell et al. 2005).

Project Narrative

To better understand the influences of gear-type and season on environmental and ecological benefits and impacts of oyster aquaculture, we sampled water quality, sediment quality, benthic macrofaunal communities and oysters at oyster aquaculture sites and compared those data to data from nearby reference sites. In fall 2016, two floating aquaculture sites and two near-bottom aquaculture sites were selected for study. The original sampling plan included sampling one site of each type in spring, summer and fall and the remaining two sites only in summer. However, all oysters were removed from the near-bottom site selected for seasonal sampling and there were no similar sites nearby, so this site was sampled in only two seasons. At the floating aquaculture site selected for seasonal sampling, all oysters were also removed before the completion of the study, however, a similar site was available nearby for sampling. A summary of farm types and sampling seasons is given in Table 1.

Methods

Study sites: Sites were selected along the western shore of Chesapeake Bay in Virginia and chosen to represent a range in environmental conditions as well as a range of gear types and spatial extents (Fig. 2). White Stone Oyster Company (WS) and Big Island Aquaculture (BI) both use floating cages to grow oysters but the type of cage used differs between sites (Fig. 3a,c). Chapel Creek Oyster Company (CC) and Lynnhaven River Oyster Company grow oysters in bottom cages that have similar designs (Fig. 3b, d). Sites also differed in wave exposure. WS has the greatest exposure followed by CC and LR. The site at BI was very sheltered.

Within each of the aquaculture sites, we selected a section of the farm on which to focus our studies (hereafter “farm footprint”, Fig 4). At LR and CC, our study site was the entire footprint of the cages at that site. At WS, we also studied the entire footprint of the cages at the site but different sites were

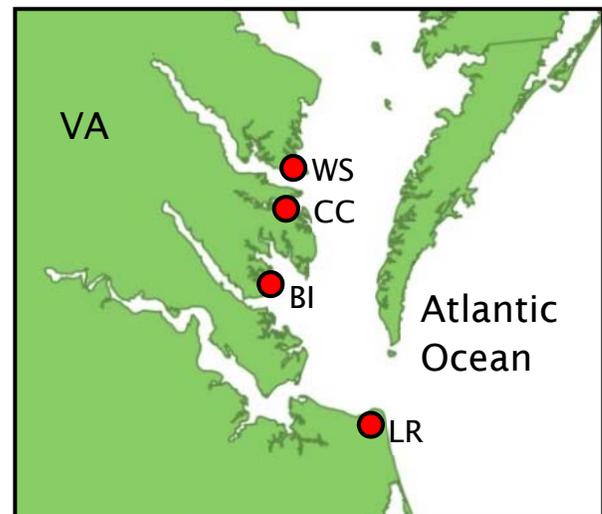


Fig. 2. Location of study sites in the Virginia portion of Chesapeake Bay: White Stone Oyster Company (WS), Chapel Creek Oyster Company (CC), Big Island Aquaculture (BI) and Lynnhaven River Oyster Company (LR)

studied in 2017 and 2018. At BI, the cages were distributed on either side of a point. Because flow characteristics were likely to differ on either side of the point, we focused our studies on the eastern side of the point.

a) White Stone



b) Chapel Creek



c) Big Island



d) Lynnhaven



Fig. 3. Aquaculture gear types used at each site. Floating gear types at White Stone Oyster Company (WS) and Big Island Aquaculture (BI) differed in design while those at Chapel Creek Oyster Company (CC) and Lynnhaven River Oyster Company (LR) were similar. The near-bottom gear at Chapel Creek and Lynnhaven are shown on the deck of the harvest vessel because water clarity precluded taking photos of cages while they were submerged.

Sampling periods: All four farms were sampled in Spring 2017 to gather information on general site characteristics (Table 1). In Summer 2017, all four sites were sampled to determine water quality, sediment quality, and macrofaunal community structure. In Fall 2017, additional samples of each type were taken at WS and LR. Original sampling plans also included collecting these same data at the same WS and LR locations in Spring 2018. However, the owners of LR chose to abandon their growing site in the Lynnhaven River in Winter 2017/2018 and removed all oysters from that site. Over the same time period, WS shifted production from the Windmill Point location previously sampled to a nearby location at North Point. The North Point location was 3.7 km to the north west of the Windmill Point site, used the same type of gear with similar densities and distributions within the footprint of the farm and had similar sediment and environmental characteristics. Water quality and sediment characteristics were assessed at the North Point site in Spring 2018.

Table 1. General characteristics of sampling sites and seasons sampled. Note that Spring 2017 sampling periods were for site characterization only.

| Site | Gear | Wave Exposure | Years - Seasons Sampled |
|------------------------------|-------------|---------------|-----------------------------|
| White Stone – Windmill Point | Floating | Very high | 2017 – Spring, Summer, Fall |
| White Stone – North Point | Floating | Very high | 2018 - Spring |
| Chapel Creek | Near-bottom | Moderate | 2017 - Spring, Summer |
| Big Island | Floating | Very low | 2017 - Spring, Summer |
| Lynnhaven | Near-bottom | Low | 2017 - Spring, Summer, Fall |

a) White Stone



b) Chapel Creek



c) Big Island



d) Lynnhaven



Fig. 4. Aerial images of aquaculture cages at each site showing differences in distribution of cages at each site. Lynnhaven aerial image has been edited to make cages more visible. Cages at Chapel Creek are difficult to distinguish from submerged aquatic vegetation in the vicinity of the cages. Dashed red lines indicate the extent of the farm footprint studied at each site. Samples collected inside these boxes were considered to be representative of conditions inside the farm. Sampling locations outside the farm were selected to have similar physical and environmental characteristics but to be sufficiently far away from aquaculture operations to be considered to be outside their influence.

Preliminary site characterization: To assess the general characteristics of each site, preliminary site surveys were conducted in Spring 2017. Salinity and water column depth data were collected using a CastAway CTD (Sontek). Surface sediment samples were collected from within and outside each site using a petite ponar grab to sample a 216 cm² area of the sediment surface. A minimum of 25 samples were collected at each site with actual sample numbers scaling with the footprint area of the farm. Samples were analyzed to determine grain size and organic content. Grain sizes were determined using wet sieve and pipette analysis. Separated size classes were dried at

103-105°C and >550°C and weighed to determine fixed and volatilized components by mass, with volatilized mass used a proxy for organic mass. Percent organic content was calculated dividing volatilized mass by total dry mass.

Farm characterization: To determine the scale of each aquaculture operation, we used a combination of aerial imagery and grower surveys to determine the area of the farm footprint at each site, annual oyster production, and annual oyster production per unit area at each farm. ArcGIS was used to measure the maximum length and width of the area covered by oyster cages visible in publicly available VBPM imagery. The maximum lengths and widths were multiplied to determine the area of the farm footprint. Growers were then asked to provide an estimate of the production from the footprint area using the 12 month period for which they thought they could provide the most accurate estimate. Growers were also asked to estimate the proportion of their harvest that occurred in each season of the year.

Oyster characteristics and nutrient content: To determine whether oysters grown at each site were similar in size and nutrient content, a sample of 100 oysters was collected from each site in late winter/early spring 2018. The length, width and depth of each oyster shell was measured to the nearest 0.01 mm. Oysters were then carefully shucked and both shells and meats were dried to a constant weight in an oven at 60°C. From each farm, five oysters were randomly selected for nutrient analyses. All samples selected for nutrient analyses were ground to a fine powder and a subsample was sent to VIMS Analytical Services Center to determine the percentage of NP by weight for oysters from each farm. By combining annual harvest data, dry weight data and nutrient content data, we were able to estimate the amount of N and P harvested per year from the farm footprint at each site.

Benthic macrofaunal community: To assess benthic macrofaunal communities inside and outside the farm at each site, divers used hand cores to collect samples from a 62.2cm² area to a depth of ~10cm at all four sites in Summer 2017. Samples were sieved immediately after collection and all material retained on a 1-mm mesh was fixed in Normalin for later analysis in the laboratory. In the laboratory, all organisms in each sample were identified to the lowest practical taxon and counted. Because individual biomasses were small and abundances were generally low, organisms were pooled by major faunal groups within each sample prior to drying and weighing. All samples were dried to a constant weight at 60°C. After dry weight data were collected, all samples were placed in a muffle furnace at 500°C and burned to determine ash weight. Ash-free dry weight was determined by subtracting ash weights from dry weights.

Sediment impacts: To determine whether farms had negative impacts on sediment quality we collected and compared sediment samples from inside and outside the farm footprint at each site. At all four sites in Summer 2017 and at WS and LR in Fall 2017, sediment samples were collected by divers using methods identical to those used to collect macrofauna samples. Additional rectangular core samples were collected to allow us to record sediment features and visualize vertical transitions between sediment

types using photographs and x-radiographs. Because we were sampling a new location at White Stone in spring 2018, we chose to again use the petite ponar grab to collect surface samples instead of using divers to collect cores because this approach allowed us to increase our sample size to better characterize this site. Sediment organic content and grain size were determined for all sample types using the same methods as those used for sampling in spring 2017.

Water quality benefits and impacts: Water quality data were collected at all four sites in summer 2017, at WS and LR in fall 2017, and at the North Point site at WS in spring 2018. During each sampling period, data were collected at a minimum of six stations inside and six stations outside the farm footprint at each site using a water quality sonde and a current profiler. All samples were collected within the three to four hours surrounding maximum tidal current. To increase the likelihood of detecting the influence of oyster aquaculture on water quality, data were collected from the upper portion of the water column at sites with floating cages and from the lower portion of the water column at sites utilizing bottom cages. At each station, an acoustic Doppler current profiler (ADCP) was used to measure current velocity and a YSI 6600-series sonde was used to measure temperature, salinity, dissolved oxygen concentration, chlorophyll-a fluorescence, pH and turbidity. At each sampling site, data were collected for two minutes. Simultaneous with each two-minute burst, water samples were collected using a small handheld submersible pump and retained for later laboratory analysis of nutrient and chlorophyll concentrations. In fall 2017 and spring 2018, these samples were also analyzed to determine total suspended solids (TSS) and the organic content of those solids.

Additional data were collected at all four sites in summer 2017 to characterize particle concentrations, median particles sizes and light penetration. At each aquaculture site, measurements were collected at five stations in a transect along the central line of the aquaculture field, including three interior stations within the extent of the cages and two exterior stations outside the influence of the cages. Sampling was conducted within the two hours bracketing maximum tidal current. At each station, light attenuation was measured using a Li-COR photosynthetically-active-radiation (PAR) sensor package including an upward-facing deck sensor mounted to the vessel cabin roof, a spherical quantum underwater sensor, and a downward-facing underwater sensor. The spherical and downward sensors were mounted to a small handheld frame along with an ONSET Hobo depth meter and held at a minimum of three depth intervals for 10 seconds each. Particle concentrations and size distributions were measured using a Laser In Situ Scattering and Transmissometer (LISST) at these same sampling stations.

Laboratory analyses were performed following field sampling to measure total suspended solid (TSS) concentrations, Chlorophyll-a (Chl a) concentrations, and dissolved nutrient concentrations in water samples collected at field sampling sites. All TSS and Chl a samples were filtered onto 0.7 μm GFF filters using vacuum filtration. To determine TSS concentrations, filters were dried at 103°C, weighed, burned at 555°C and weighed again to determine fixed (TFS) and volatile (TVS) portions resulting in

estimates of the percent organic content of suspended solids filtered from water samples. Chl-a concentrations were determined based on triplicate filters from each sample collected. All filters were extracted in an acetone solution for ≥24 hours then measured using a benchtop Turner fluorimeter. Dissolved nitrogen (ammonium, nitrate and nitrite) and phosphorus concentrations in water samples were determined by the Virginia Institute of Marine Sciences Analytical Services Center.

Statistical analyses: One and two-way ANOVA were used as appropriate to assess to compare data between areas inside and outside the farm footprint and to assess differences between sites. For all tests, significance the level for significance was set at $p = 0.05$. For benthic macrofauna data, principal coordinate analysis (PCO) was used to visualize differences in community structure between samples.

Results

Preliminary site characterization:

Data collected in Spring 2017 indicated that salinity across the four sites spanned a relatively narrow range with the lowest mean salinity (15.1) found at WS and the highest (22.0) found at LR. Comparison of mean depths between sites also varied little between sites. WS was the deepest site on average (1.8 m) and LR was the shallowest (1.2 m). Sediments at all sites were dominated by the sand and gravel fraction. Sediments at BI were finer and had a greater organic content than sediments at the other three sites. This finding is consistent with the sheltered location of the farm at BI.

Table 2. General characteristics of each sampling site. Salinity and depth data are means of samples collected over a minimum of four hours at each site in Spring 2017.

| Site | Salinity (psu) | Depth (m) | % Sand and Gravel | % Organic |
|------|----------------|-----------|-------------------|-----------|
| WS | 15.1 | 1.8 | 97.2 | 0.8 |
| CC | 16.5 | 1.6 | 95.1 | 0.9 |
| BI | 20.3 | 1.4 | 57.1 | 6.1 |
| LR | 22.0 | 1.2 | 94.0 | 1.3 |

Farm characteristics: The footprint of the farm area at study sites varied by an order of magnitude in area. CC had the smallest footprint at 0.28 acres and LR had the largest at 9.78 acres. Annual harvest varied by two orders of magnitude across sites and did not scale linearly with area occupied. WS had the highest annual harvest of all sites followed by LR, CC, and BI. CC had the highest harvest per unit area followed by WS, BI and LR. Given that there was an order of magnitude difference in production per unit area between farms using the same gear type, there was no discernable pattern in production per unit area associated with the type of gear used for oyster grow out. Farms also showed differing patterns of harvest with season. Both farms using floating cages (WS and BI) reported harvests that were largely similar across all seasons. The two farms using on-bottom cages reported greater variation in harvests across seasons. CC reported that half of its harvest occurred in summer, a quarter in spring and the rest divided evenly between fall and winter. LR reported that only 6% of its harvest occurred in summer and the majority of its harvest occurred in spring (58%).

Table 3. Farm area and annual harvest reported by growers for each farm along with their assessment of distribution of harvest across seasons.

| Farm | Area (acres) | Harvest Year | Annual Harvest (# oys.) | Harvest (# oys. per acre) | Harvest by Season | | |
|------|--------------|--------------|-------------------------|---------------------------|-------------------|------------------|------------------|
| | | | | | Season | % of Total Sales | Seasonal Harvest |
| WS | 4.01 | 2016 | 1,000,000 | 249,377 | Spring | 27.5% | 275,000 |
| | | | | | Summer | 22.5% | 225,000 |
| | | | | | Fall | 22.5% | 225,000 |
| | | | | | Winter | 27.5% | 275,000 |
| CC | 0.28 | 2017 | 99,593 | 355,689 | Spring | 25.0% | 24,898 |
| | | | | | Summer | 50.0% | 49,797 |
| | | | | | Fall | 12.5% | 12,449 |
| | | | | | Winter | 12.5% | 12,449 |
| BI | 1.35 | 2017 | 76,000 | 56,296 | Spring | 25.0% | 19,000 |
| | | | | | Summer | 25.0% | 19,000 |
| | | | | | Fall | 25.0% | 19,000 |
| | | | | | Winter | 25.0% | 19,000 |
| LR | 9.78 | 2017 | 236,000 | 24,131 | Spring | 58.0% | 136,880 |
| | | | | | Summer | 6.0% | 14,160 |
| | | | | | Fall | 16.0% | 37,760 |
| | | | | | Winter | 20.0% | 47,200 |

Oyster characteristics and nutrient

content: Oysters harvested at each site varied significantly in shell dimensions, tissue and shell dry weights, and nutrient content. All oyster dimension and dry weight data violated ANOVA assumptions of normality and equal variance and were resistant to transformation. However, because ANOVA is robust to these violations when sample sizes are large, we have chosen to report results of one-way ANOVAs rather than using ANOVAs on ranks to determine significant differences. Results were largely similar regardless of which statistical approach was used. An additional factor complicating interpretation of results is the fact that, due to circumstances beyond our control, oyster samples were collected across a timespan of more than two months. Regression of shell dimension and dry weight data against time did not produce consistent linear trends, so we are confident that reported patterns and significant differences are a function of differences between sites. However, there were consistent patterns in nutrient content data that prevent us from teasing apart the effects of farm and sampling date.

Oysters harvested from bottom cages were significantly larger than those harvested from floating cages (Fig. 5). Within each gear type, there were also significant differences in shell height between farms but these differences were small compared to differences between farms using different gear types. Shell width did not differ significantly between farms using the same gear type but did differ significantly between farms using different gear types, with shell width being greater at farms using bottom cages. Shell depth differed significantly between all sites. Greatest shell depths were associated with oysters harvested from bottom cages and differences between sites using the same gear type were smaller than between those using different gear types.

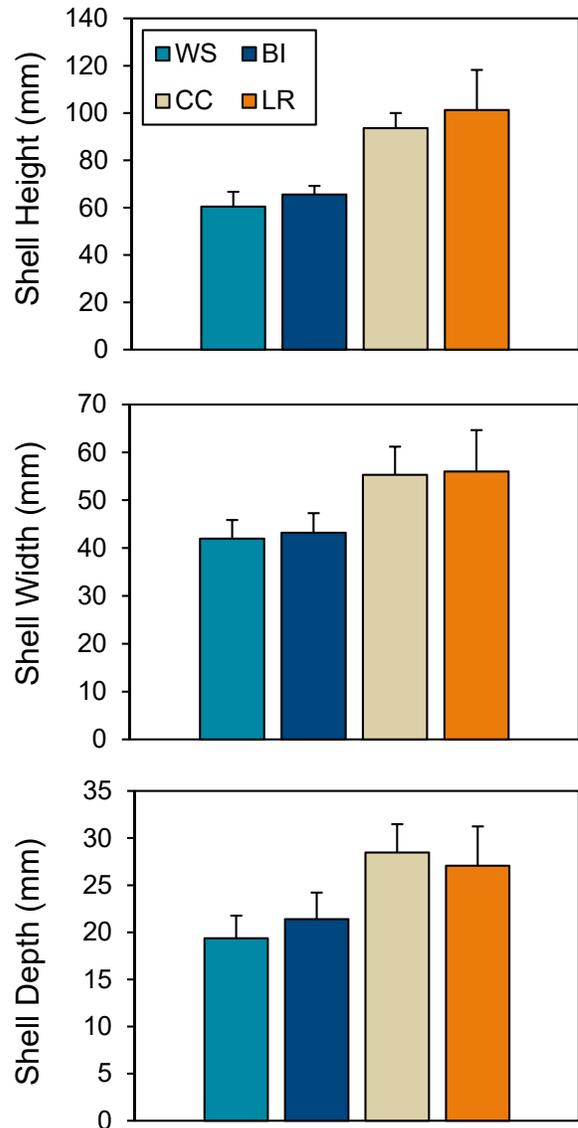


Fig. 5. Mean shell heights, widths and depths for harvested oysters from each farm. Error bars represent one standard deviation here and throughout. Significant differences between sites are described in text.

Both tissue and shell dry weights differed significantly between sites (Fig. 6). Tissue dry weights were similar for the two sites using bottom cages (CC and LR) and were significantly higher than the tissue dry weights for either of the floating aquaculture sites. Tissue dry weights at WS were significantly higher than those at BI. For shell dry weights, this pattern was reversed with higher shell dry weights at BI than at WS. As seen for shell height, shell weights were significantly different at each site but differences between sites using the same type of gear were smaller than differences between sites using different types of gear.

The N and P content of oyster tissue and shell differed between samples, however, as noted above, there were consistent temporal trends in these data. Therefore, significant differences represent the combined effects of site and sampling date. Samples from BI were collected later in the year than other samples and had significantly higher concentrations of nitrogen in their tissues than oysters from CC or WS (Table 4). There were no significant differences between any of the samples in the percentage of nitrogen in oyster shell. The amount of phosphorus in oyster tissue from WS was significantly higher than samples from CC but similar to the other two sites. The amount of phosphorus in oyster shell was significantly higher in shells from oysters harvested at WS than those harvested at CC but similar to all other sites. The amount of nitrogen and phosphorus in oyster tissue tended to increase over time while the amount of these nutrients in shell showed a tendency to decrease over time (Fig. 7).

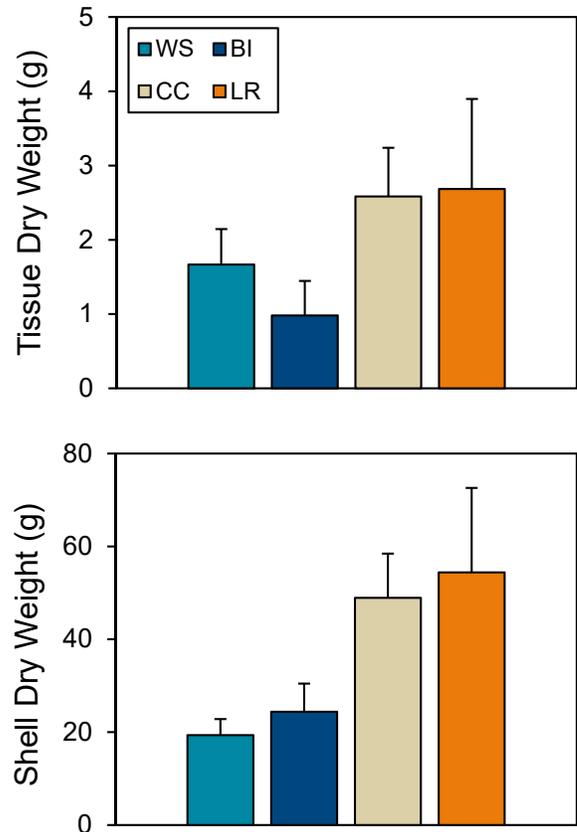


Fig. 6. Mean tissue and shell dry weights for harvested oysters from each farm. Error bars represent one standard deviation. Significant differences between sites are described in text.

Table 4. Concentrations of nitrogen and phosphorus in oyster tissue and shell as a percentage based on grams of each nutrient per gram dry weight of oyster tissue or shell.

| Farm | Sample Date | % N | | | | % P | | | |
|------|-------------|-------------|-------------|-------------|-------------|--------|--|-------|--|
| | | Tissue | | Shell | | Tissue | | Shell | |
| WS | 02/21/18 | 6.42 ± 0.65 | 0.32 ± 0.08 | 0.69 ± 0.03 | 0.06 ± 0.01 | | | | |
| CC | 03/13/18 | 6.31 ± 0.11 | 0.29 ± 0.09 | 0.82 ± 0.12 | 0.04 ± 0.00 | | | | |
| BI | 04/25/18 | 7.80 ± 0.68 | 0.20 ± 0.05 | 0.78 ± 0.03 | 0.05 ± 0.00 | | | | |
| LR | 03/27/18 | 6.93 ± 0.55 | 0.30 ± 0.07 | 0.72 ± 0.05 | 0.05 ± 0.01 | | | | |

Annual nutrient sequestration: To estimate the amount of nitrogen and phosphorus harvested at each aquaculture site, we combined oyster tissue and shell dry weight data with site-specific measures of nitrogen and phosphorus in oyster tissue and shell. Because oyster samples were collected once at each site, our estimates do not incorporate changes in the amount of oyster tissue and shell per oyster or changes in the percentages of nitrogen and phosphorus contained in oyster tissues and shells that are likely to occur throughout the year. Of these sources of variation, changes in the oyster tissue and shell dry weights per oyster at the time of harvest are likely to result in the greatest changes in estimates of the total amount of nitrogen and phosphorus harvested.

To determine the total mass of oyster tissue and shell harvested each year, we first summed the total tissue mass and the total shell mass from each site and divided by the number of oysters in the sample to determine the mean tissue dry weight and the mean shell dry weight for each site. Although we sampled 100 oysters from each farm, the number of oysters included in analyses was sometimes lower than 100 because samples contained oysters that had died or were of a size smaller than the growers reported that they typically harvested.

Once we had the mean shell and tissue dry weight per oyster for each site, we multiplied this by the percentages of nitrogen and phosphorus measured in oysters at that farm. Values were then multiplied by annual harvest estimates to determine total nitrogen and phosphorus harvested annually from the farm footprint at each site. Totals were then divided by the farm area to determine the N and P harvested per unit area at each farm. Resulting data (Table 5), show that variation in nitrogen and phosphorus harvested at each site is driven primarily by the total number of oysters harvested.

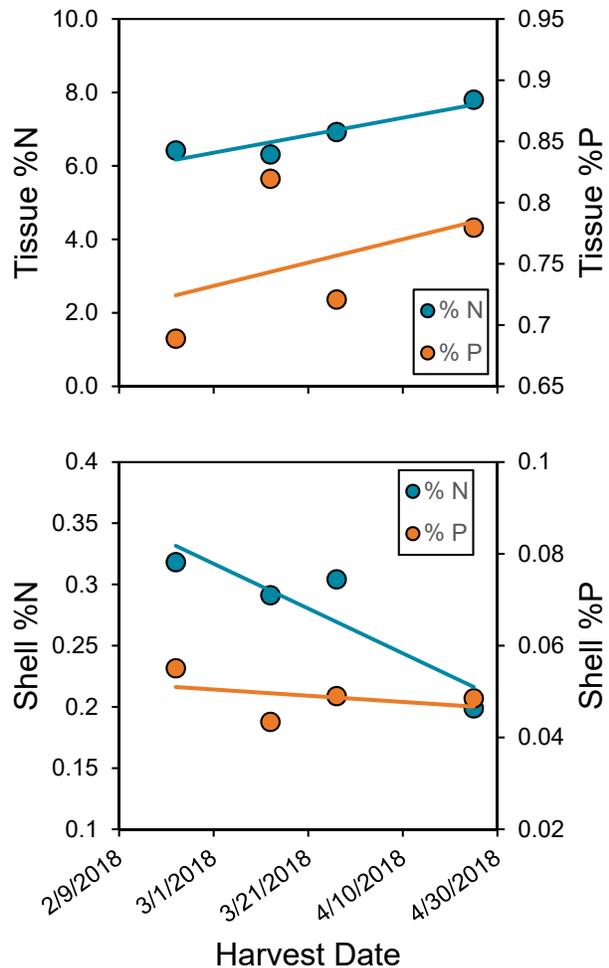


Fig. 7. Temporal trends in oyster tissue and shell nitrogen and phosphorus content. Correlations between time and nutrient content are not significant but the power to detect significant correlations is low because of low sample numbers. Significant differences between samples should be interpreted as resulting from the combined effects of site and harvest date.

Table 5. Number of oysters sampled at each site (n), mean nitrogen and phosphorus content per oyster, and amounts of nitrogen and phosphorus harvested annually from the farm footprint at each site.

| Site | n | N per Oyster (g) | P per Oyster (g) | Annual N Harvest (lbs) | Annual P Harvest (lbs) | Annual N Harvest (lbs/acre) | Annual P Harvest (lbs/acre) |
|------|-----|------------------|------------------|------------------------|------------------------|-----------------------------|-----------------------------|
| WS | 96 | 0.17 | 0.02 | 371.6 | 48.8 | 92.6 | 12.2 |
| CC | 100 | 0.31 | 0.04 | 67.1 | 9.3 | 241.4 | 33.5 |
| BI | 100 | 0.13 | 0.02 | 21.0 | 3.3 | 15.5 | 2.4 |
| LR | 88 | 0.35 | 0.05 | 182.9 | 24.0 | 18.7 | 2.4 |

Benthic macrofaunal community:

No evidence was found for significant negative impacts of oyster aquaculture farms on benthic macrofauna communities. Data on species richness, macrofauna abundance and total biomass were analyzed using two-way ANOVAs with site and location relative to farm footprint as factors. There was not a significant difference in species richness between areas inside and outside the farm footprint (Fig. 8; $p = 0.934$).

Differences in the number of species between sites were marginally significant ($p=0.051$).

Because analysis of abundance data revealed a marginally significant interaction between site and location with respect to farm footprint (Fig. 9, left; $p = 0.054$), we ran additional one-way ANOVAs to determine if there were significant differences in the number of individuals inside and outside of the farm at each site. The number of individuals inside the farm was significantly higher at LR than outside the farm ($p = 0.037$). No other sites had significant differences in the number of individuals inside and outside the farm footprint. In addition to ANOVA analyses, we also performed principal coordinates analysis using data on both species identity and abundance (Fig, 9, right panel). The resulting PCO plot shows that differences between sites had greater influence on macrofauna community structure than location with respect to farm footprint. Differences in the community structure inside and outside the farm at WS are far more apparent than at any of the other sites. The total biomass of benthic macrofauna was not significantly different between sites or seasons. PCO analyses show that three of the four samples

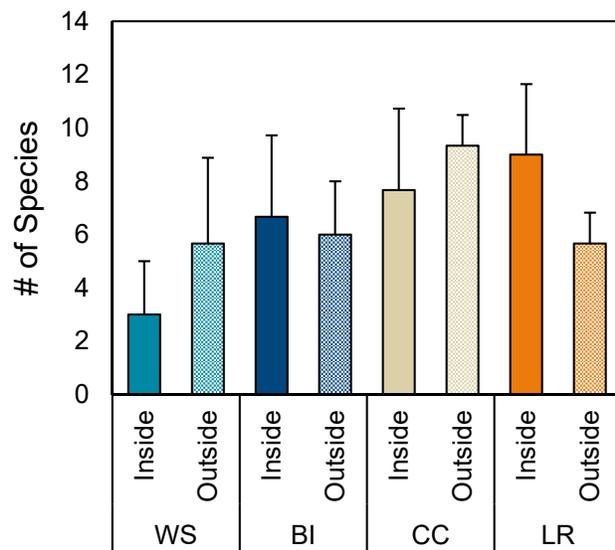


Fig. 8. Species richness in samples taken from inside and outside the farm footprint at each study site. Significance of differences is discussed in accompanying text.

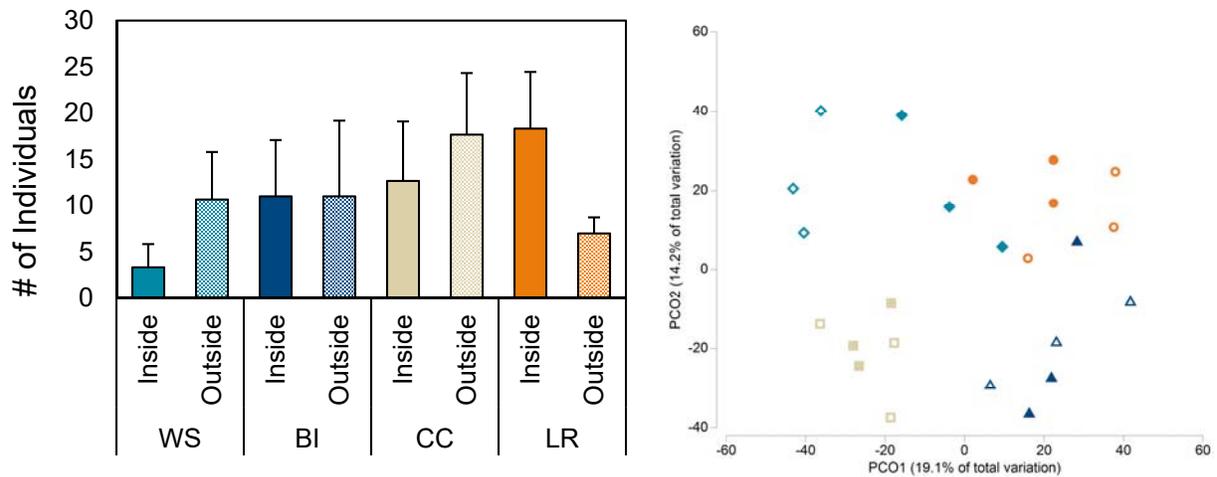


Fig. 9. Mean abundance of individuals (left panel) at each sampling site and results of principal coordinates analysis of species identity and abundance data (right panel). Colors in PCO plot correspond to the same sites as shown in the mean abundance graph. Filled markers indicate samples taken from inside the footprint of the farm. Open markers indicate samples taken from outside the farm footprint.

from WS are very different substantially from other samples but they are a mix of samples from inside and outside the farm footprint. Other samples also show no distinct differences between community structure inside and outside the farm footprints. However, there does appear to be a gradient in community structure across the sites that follows the same pattern as percentage of sand across these sites.

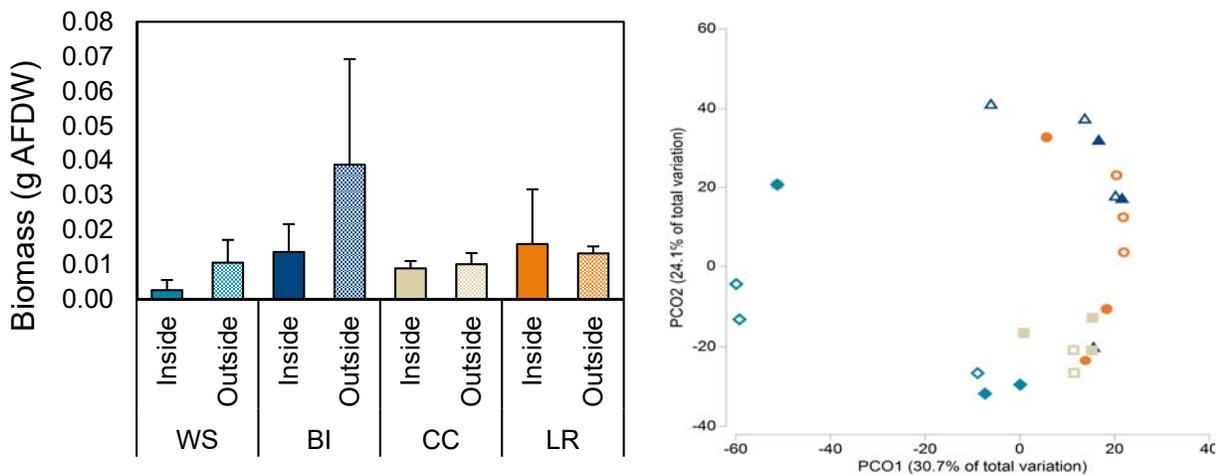


Fig. 10. Mean total macrofauna biomass (left panel) at each sampling site and results of principal coordinates analysis of species identity and biomass data (right panel). Colors in PCO plot correspond to the same sites as shown in the mean abundance graph. Filled markers indicate samples taken from inside the footprint of the farm. Open markers indicate samples taken from outside the farm footprint.

Sediment quality: We found no evidence for significant negative impacts of oyster aquaculture on sediment quality. All sediment cores and grab samples collected as part of this project showed evidence of oxic conditions at the sediment-water interface (Fig. 11). Although both LR and BI showed a trend towards higher organic content in sediments within the footprint of the farm in Summer 2017, differences were not significant. During this same sampling period, the organic content of sediments at BI was significantly higher than at any other site. In Fall 2017, organic content in sediments at WP was significantly higher ($p = 0.034$) outside the farm footprint than inside. In Spring 2018, samples collected from within the farm at the WS North Point site tended to have higher organic content but these differences were only marginally significant ($p = 0.053$). The lower overall organic content of sediments at WS in Spring is most likely attributable to differences in sample collection technique between this sampling period and the 2017 sampling periods. In 2017, diver-collected core samples were carefully extruded and only the top centimeter was included in the sample. Collection of samples by petite ponar grab is much less precise and likely included significant amounts of material from >1 cm below the sediment surface.

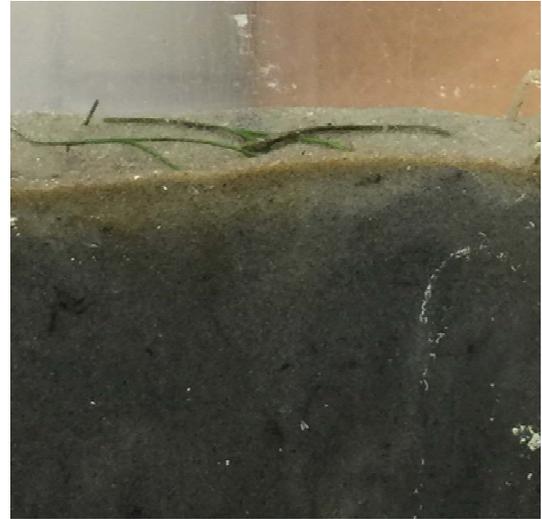


Fig. 11. Photograph of core sample from CC showing oxic surface sediments typical of samples taken at all sites.

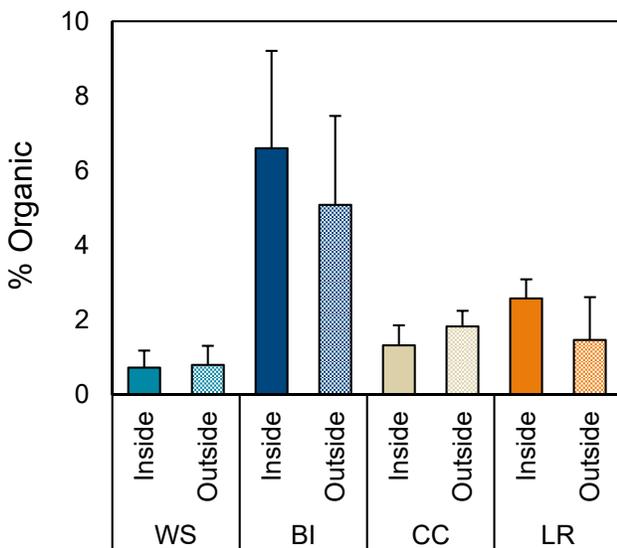


Fig. 12. Sediment organic content for samples collected in Summer 2017 at each site.

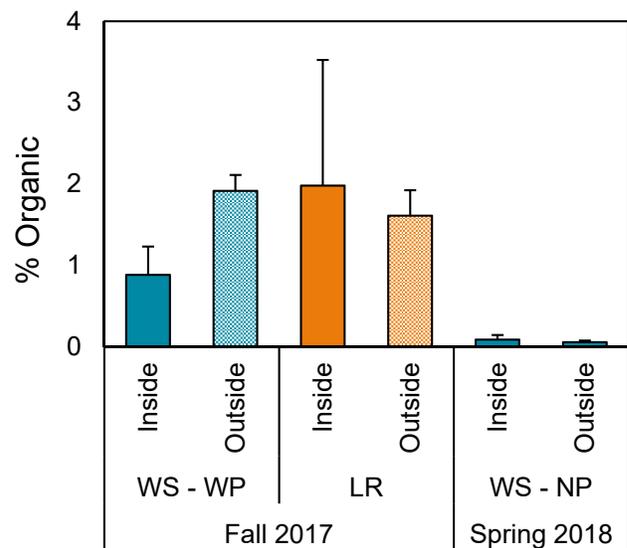


Fig. 13. Sediment organic content for samples collected at the Windmill Point site at WS and at LR in Fall 2017 and for samples collected in Spring 2018 at the North Point site at WS.

Water quality: Data collected as part of this project found little evidence to support the existence of consistent impacts, positive or negative, of oyster aquaculture operations on surrounding water quality. We used a series of one-way ANOVAs to compare data from inside the farm to data collected outside the farm. Where data violated assumptions of normality and/or equal variance, we also ran an ANOVA on ranks. After finding that results were in agreement with those of the original ANOVAs, we assumed that original analyses were robust to violations of normality and equal variance and report the p-values associated with those analyses (Table 6).

Table 6. Mean values and standard deviations for data on percent saturation of dissolved oxygen (DO), pH, chlorophyll-a (Chl-a), and turbidity collected using a YSI 6600 water quality sonde. Reported p-values are the result of one-way ANOVAs testing for differences between each parameter measured inside and outside the farm footprint during each sampling period. Significant p-values are indicated by bold italics.

| Parameter | Season | Farm | Inside | Out side | p-value | |
|--------------------------------|--------------------|-------------|---------------|---------------|--------------|--------------|
| DO (%) | Summer 2017 | WS | 116.40 ± 2.60 | 112.21 ± 8.74 | 0.191 | |
| | | BI | 92.48 ± 5.69 | 85.14 ± 1.52 | 0.004 | |
| | | CC | 99.54 ± 3.96 | 95.59 ± 6.21 | 0.160 | |
| | | LR | 97.92 ± 3.23 | 97.52 ± 9.07 | 0.915 | |
| | Fall 2017 | WS | 102.50 ± 1.38 | 102.16 ± 0.83 | 0.581 | |
| | | LR | 80.11 ± 1.65 | 80.17 ± 2.53 | 0.954 | |
| | Spring 2018 | WS | 115.71 ± 0.49 | 116.59 ± 1.94 | 0.238 | |
| | pH | Summer 2017 | WS | 8.20 ± 0.02 | 8.15 ± 0.07 | 0.035 |
| BI | | | 7.91 ± 0.06 | 7.82 ± 0.02 | 0.002 | |
| CC | | | 8.09 ± 0.03 | 8.06 ± 0.05 | 0.171 | |
| LR | | | 7.91 ± 0.02 | 7.90 ± 0.06 | 0.848 | |
| Fall 2017 | | WS | 8.07 ± 0.02 | 8.07 ± 0.01 | 0.809 | |
| | | LR | 7.63 ± 0.02 | 7.63 ± 0.02 | 0.550 | |
| Spring 2018 | | WS | 8.37 ± 0.01 | 8.38 ± 0.01 | 0.015 | |
| Chl a (µg L ⁻¹) | | Summer 2017 | WS | 1.89 ± 0.23 | 1.82 ± 0.35 | 0.653 |
| | | | BI | 9.31 ± 0.96 | 8.88 ± 1.10 | 0.459 |
| | | | CC | 3.44 ± 0.52 | 3.85 ± 0.62 | 0.185 |
| | LR | | 13.65 ± 0.61 | 13.85 ± 0.84 | 0.621 | |
| | Fall 2017 | WS | 2.39 ± 0.17 | 2.00 ± 0.26 | 0.004 | |
| | | LR | 5.37 ± 0.68 | 5.69 ± 0.42 | 0.301 | |
| | Spring 2018 | WS | 2.62 ± 0.42 | 2.76 ± 0.27 | 0.514 | |
| | Turbidity (NTU) | Summer 2017 | WS | 1.55 ± 0.07 | 1.71 ± 0.20 | 0.030 |
| BI | | | 7.43 ± 1.85 | 7.22 ± 0.23 | 0.753 | |
| CC | | | 1.69 ± 0.11 | 1.71 ± 0.04 | 0.587 | |
| LR | | | 8.70 ± 1.42 | 7.88 ± 0.92 | 0.222 | |
| Fall 2017 | | WS | 0.99 ± 0.09 | 0.94 ± 0.11 | 0.362 | |
| | | LR | 5.14 ± 0.67 | 4.75 ± 0.40 | 0.206 | |
| Spring 2018 | | WS | 0.18 ± 0.16 | 0.14 ± 0.14 | 0.603 | |

Although most differences were not significant, dissolved oxygen concentrations tended to be higher within the footprint of the aquaculture sites. In Summer 2017, dissolved oxygen concentrations were significantly higher inside the aquaculture site than outside. This pattern is the opposite of what would be expected if oyster biodeposition was overloading the local environment with organic material. Levels of pH were generally similar inside and outside the farm footprint. In two instances (Summer 2017 samples from WS and BI) pH levels were significantly higher (i.e. more alkaline) inside the farm and in one instance (Spring 2018 at WS) they were higher outside the farm.

Through their feeding activities, oysters are expected to reduce chlorophyll concentrations in the water column because they filter and consume phytoplankton. Although the production of oysters for harvest at these sites makes it clear that oysters are consuming phytoplankton, we did not find a consistent pattern of lowered chlorophyll concentrations inside the farm footprint. The one instance in which differences in chlorophyll concentrations were significantly different, levels were higher inside the farm than outside the farm. Turbidity is a measure of the amount of light scattered by particles in the water column and, like chlorophyll concentrations, is expected to decrease as a result of oyster filter feeding activities. In Summer 2017, turbidity was significantly lower inside the farm at WS than outside the farm but differences were not significant at any of the other sites or during any other sampling period. In Summer 2017, light attenuation, particle volume concentrations and particle sizes were also measured inside and outside the farm footprint at all four sites (Table 7). With the exception of median particle size at LR, no significant differences were detected in any of these parameters for water within versus outside the farm footprint for any of the sites.

Table 7. Mean values and standard deviations for light attenuation, particle volume and median particle size for data collected in Summer 2017 at all four sites. Reported p-values are the result of one-way ANOVAs testing for differences between each parameter measured inside and outside the farm footprint during each sampling period. Significant p-values are indicated by bold italics.

| Parameter | Season | Farm | Inside | Out side | p-value |
|--|-------------|------|----------------|---------------|--------------|
| Light attenuation (K_d) | Summer 2017 | WS | 0.60 ± 0.16 | 0.53 ± 0.04 | 0.631 |
| | | BI | 1.56 ± 0.80 | 1.97 ± 0.38 | 0.430 |
| | | CC | 0.80 ± 0.10 | 0.84 ± 0.23 | 0.782 |
| | | LR | 1.74 ± 0.59 | 2.23 ± 0.39 | 0.220 |
| Particle Volume ($\mu\text{L/L}$) | Summer 2017 | WS | 8.05 ± 0.33 | 7.69 ± 0.24 | 0.283 |
| | | BI | 30.72 ± 4.12 | 41.84 ± 17.33 | 0.156 |
| | | CC | 21.43 ± 0.75 | 16.53 ± 4.20 | 0.121 |
| | | LR | 57.25 ± 7.35 | 63.66 ± 27.56 | 0.460 |
| Median Particle Size (μm) | Summer 2017 | WS | 32.35 ± 6.52 | 34.63 ± 10.65 | 0.778 |
| | | BI | 36.95 ± 3.55 | 44.63 ± 7.72 | 0.071 |
| | | CC | 140.70 ± 14.33 | 96.64 ± 50.94 | 0.225 |
| | | LR | 49.54 ± 4.74 | 41.58 ± 7.74 | 0.011 |

In Fall 2017 and Spring 2018, water samples were collected and analyzed to determine total suspended solid concentrations and the organic content of those solids. Comparison of samples collected inside and outside the farm footprint detected no significant differences in any of these parameters during any of that sampling periods at any of the sites.

Table 8. Mean values and standard deviations for total suspended solids (TSS) and their organic content for sample collected in Fall 2017 and Spring 2018. Reported p-values are the result of one-way ANOVAs testing for differences between each parameter measured inside and outside the farm footprint during each sampling period.

| Parameter | Season | Farm | Inside | Outside | p-value |
|-------------|-------------|-------|--------------|--------------|---------|
| TSS (mg/l) | Fall 2017 | WS-WP | 4.41 ± 0.73 | 4.28 ± 1.19 | 0.798 |
| | Fall 2017 | LR | 20.53 ± 3.72 | 23.30 ± 4.58 | 0.218 |
| | Spring 2018 | WS-NP | 9.77 ± 1.14 | 10.46 ± 1.64 | 0.371 |
| Organic (%) | Fall 2017 | WS-WP | 0.37 ± 0.11 | 0.42 ± 0.09 | 0.368 |
| | Fall 2017 | LR | 0.21 ± 0.05 | 0.17 ± 0.03 | 0.093 |
| | Spring 2018 | WS-NP | 0.40 ± 0.04 | 0.41 ± 0.07 | 0.560 |

Conclusions

- After studying a range aquaculture farms along the western shore of Chesapeake Bay in Virginia which varied in scale and gear type, we found no evidence of significant negative impacts on benthic macrofauna community structure, sediment quality or water quality.
- In the few instances in which we found significant differences between areas inside and outside the farm footprint, differences in mean values were small.
- Oyster aquaculture sites vary widely not only in area and annual harvest, but also vary by an order of magnitude in harvest per unit area.
- Differences in total nitrogen and phosphorus removal via harvest differ by an order of magnitude across sites and are driven primarily by the number of individual oysters harvested, secondarily by differences in mean tissue and shell dry weights between sites, and to a lesser extent by differences in the percentages of N and P in oyster tissues and shells across sites.
- In contrast to the negative environmental impacts associated with other forms of animal protein production for human consumption, oyster harvest from aquaculture sites studied here results in the removal of 21-372 lbs. of N and 3-49lbs of P per farm per year.

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