

Reports

6-27-2018

Environmental and Ecological Benefits and Impacts of Oyster Aquaculture Chesapeake Bay, Virginia, USA

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Kellogg, M. L., Turner, J., Dreyer, J., & Massey, G. M. (2018) Environmental and Ecological Benefits and Impacts of Oyster Aquaculture Chesapeake Bay, Virginia, USA. Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.25773/hdb1-xf91>

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ENVIRONMENTAL AND ECOLOGICAL BENEFITS AND IMPACTS OF OYSTER AQUACULTURE



6/27/2018

Chesapeake Bay, Virginia, USA

A final report to:
The Nature Conservancy

Prepared by:
M. Lisa Kellogg, Jessica Turner, Jennifer Dreyer
and Grace Massey

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& MARY**
VIRGINIA INSTITUTE OF MARINE SCIENCE

Environmental and ecological benefits and impacts of oyster aquaculture

CHESAPEAKE BAY, VIRGINIA, USA

Award Information

Project Title: Environmental and ecological benefits and impacts of oyster aquaculture

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Award Period: 15-August-2016 to 30-June-2018

Grantee Org.: Virginia Institute of Marine Science, College of William & Mary

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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, we collected samples 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 oysters harvested

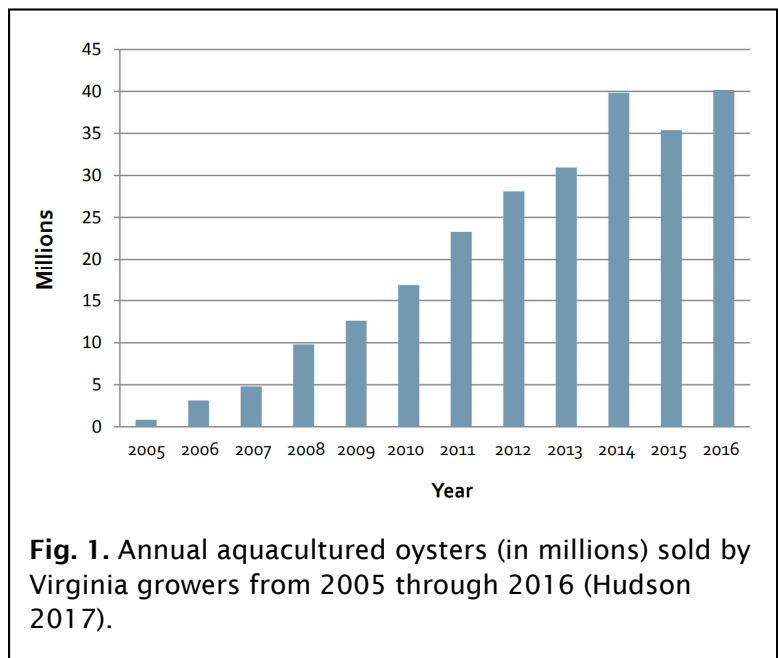
at each site and estimated the total amount of nitrogen and phosphorus harvested at each site. Differences in water quality, sediment quality, and macrofauna community structure between areas within and outside the farm footprint were rare and of small magnitude and varying direction (i.e. negative versus positive impact) when they did occur. 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 nitrogen (N) and phosphorus (P) harvested per unit area. 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 resulted 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 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 aquaculture”) or to lines or racks that keep them at or just above the sediments at the bottom of the water column (hereafter “on-bottom aquaculture”). Both floating and on-bottom aquaculture can concentrate organic matter on the sediment surface, potentially



creating hypoxic or anoxic conditions that negatively impact macrofaunal communities living in those sediments. However, these effects likely vary significantly in both space and time depending upon 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 on-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 on-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. White Stone Oyster Company (WS) and Big Island Aquaculture (BI) both use cages floating at the surface of the water column 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 (LR) grow their oysters in bottom cages that have similar designs (Fig. 3b, d). Sites also differed in wave exposure. WS had 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 (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 studied in 2017 and 2018. At BI, the cages were distributed on

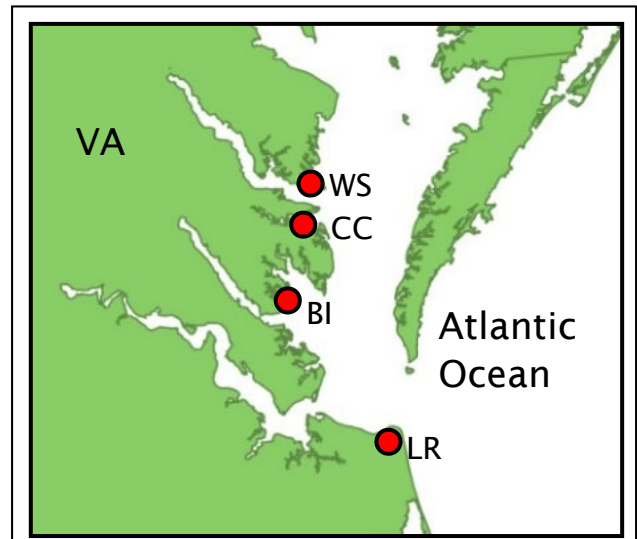
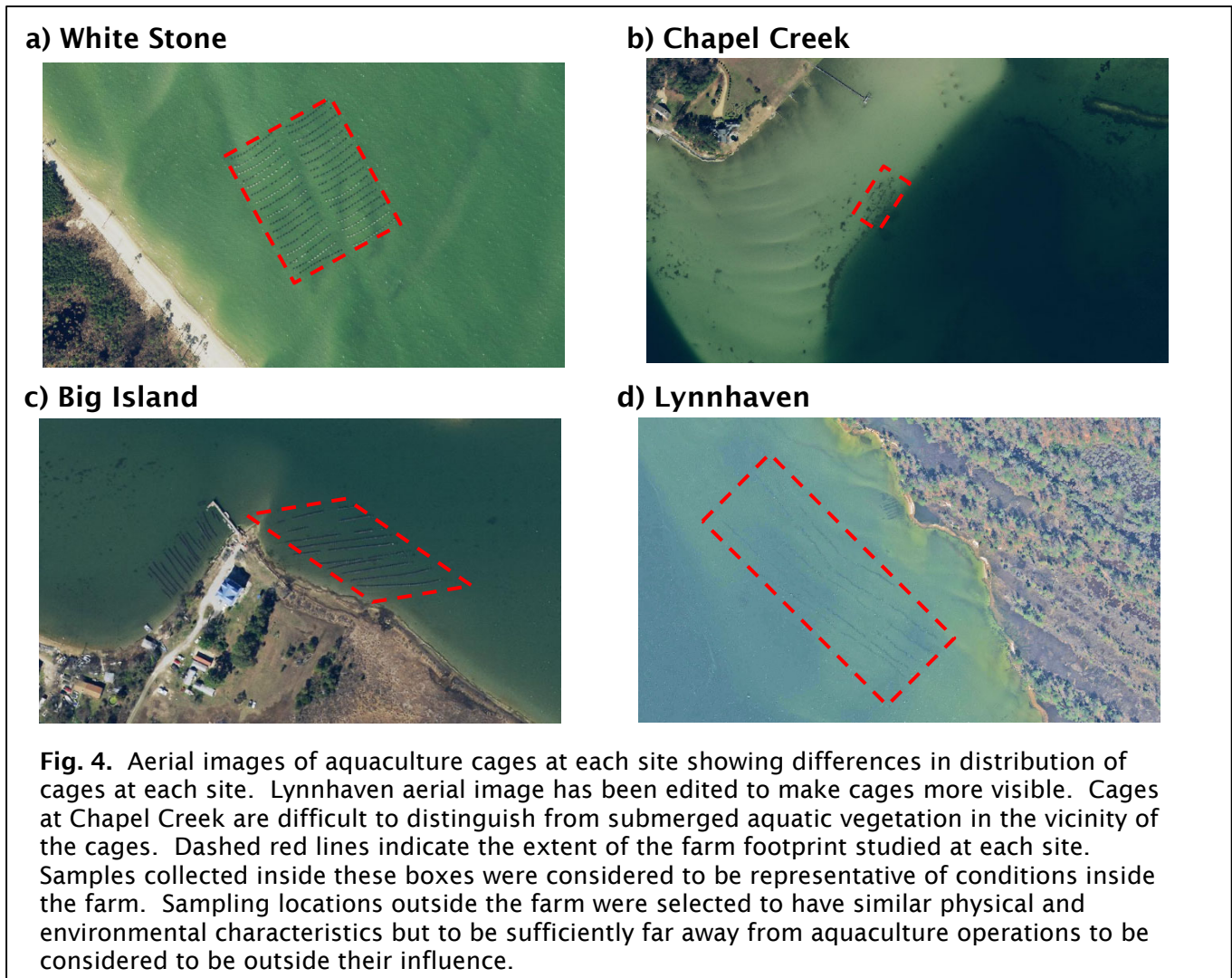


Fig. 2. Location of study sites in the Virginia portion of Chesapeake Bay: White Stone Oyster Company (WS), Chapel Creek Oyster Company (CC), Big Island Aquaculture (BI) and Lynnhaven River Oyster Company (LR)

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.



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 northwest of the Windmill Point site, used the same type of gear with similar oyster 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	On-bottom	Moderate	2017 - Spring, Summer
Big Island	Floating	Very low	2017 - Spring, Summer
Lynnhaven	On-bottom	Low	2017 - Spring, Summer, Fall

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 based on 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. Size classes included 8-phi(clay), 4-phi (silt), 63-850 um (sand) and >850 um (gravel and debris). 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 as a proxy for organic mass. Percent organic content was calculated by 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 of their choice based on which data they thought would yield 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 aquacultured 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 0.01mm. Oysters were then carefully shucked to do as little damage to the shell as possible. For each oyster, both shells and meats were dried to a constant weight 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 sent to VIMS Analytical Services Center to determine the percentage of nitrogen (N) and phosphorus (P) 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 samples 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 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 floating aquaculture sites 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 (Chl) *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 Chl *a* 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 site, 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 TSS concentrations, 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 compare data between areas inside and outside the farm footprint and to assess differences between sites. For all tests, 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.

Results

Preliminary site characterization:

Data collected in Spring 2017 indicated that salinity across the four sites spanned a relative narrow range with the lowest mean salinity (15.1) found at WS and the highest (22.0) found at LR (Table 2). 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

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

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.

Farm characteristics: The area of the footprint of the farm at study sites varied by an order of magnitude (Table 3). 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 show 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 the statistical approach 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.

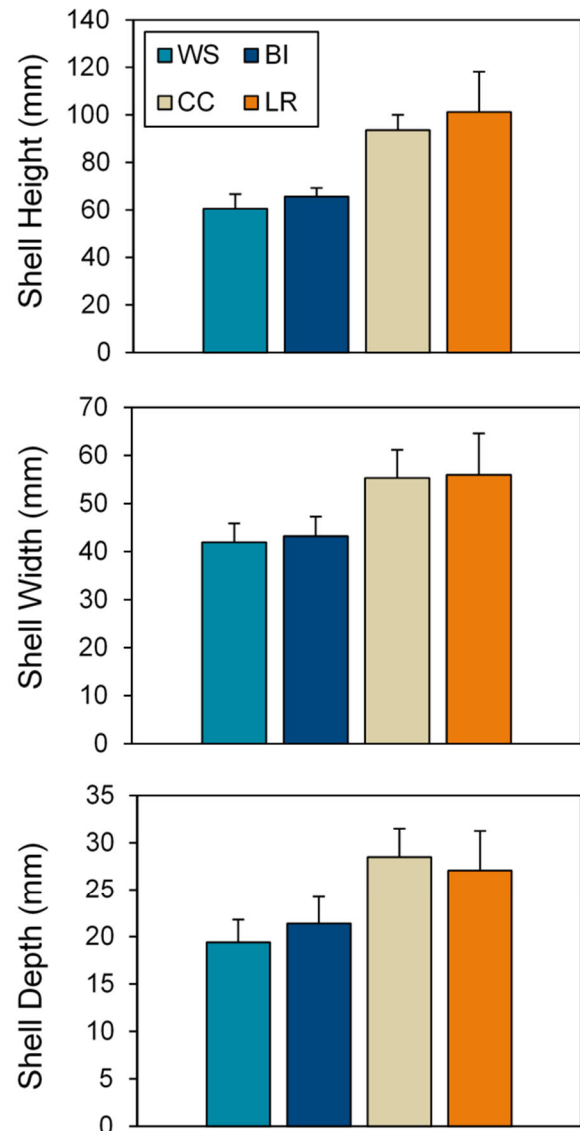


Fig. 5. Mean shell heights, widths and depths for harvested oysters from each farm. Error bars represent one standard deviation here and throughout. Significant differences between sites are described in text.

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 nitrogen and phosphorus 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

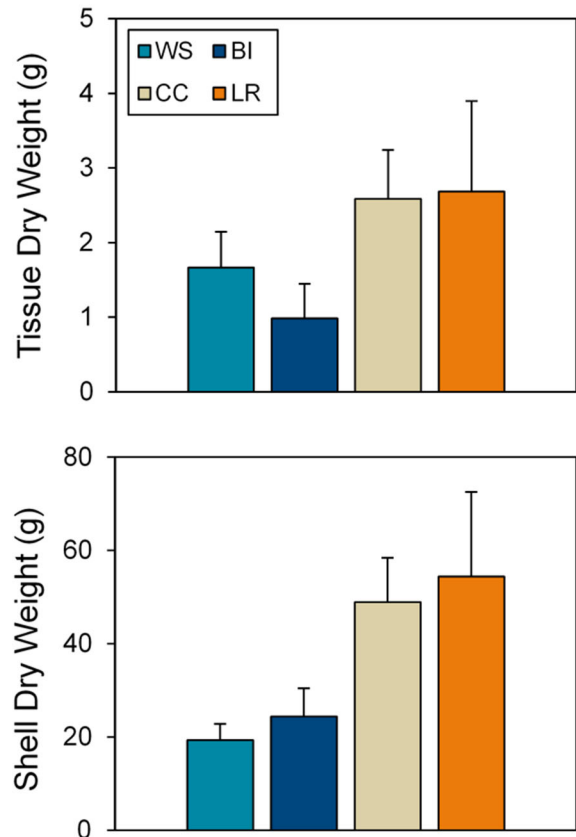


Fig. 6. Mean tissue and shell dry weights for harvested oysters from each farm. Error bars represent one standard deviation. Significant differences between sites are described in text.

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

tended to increase over time while the amount of these nutrients in shell showed a tendency to decrease over time (Fig. 7).

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 cannot incorporate changes in the amount of oyster tissue and shell per oyster that likely occur through the year 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 calculated the average tissue and shell dry weights for each site based on our samples of 100 oysters from 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 also 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.

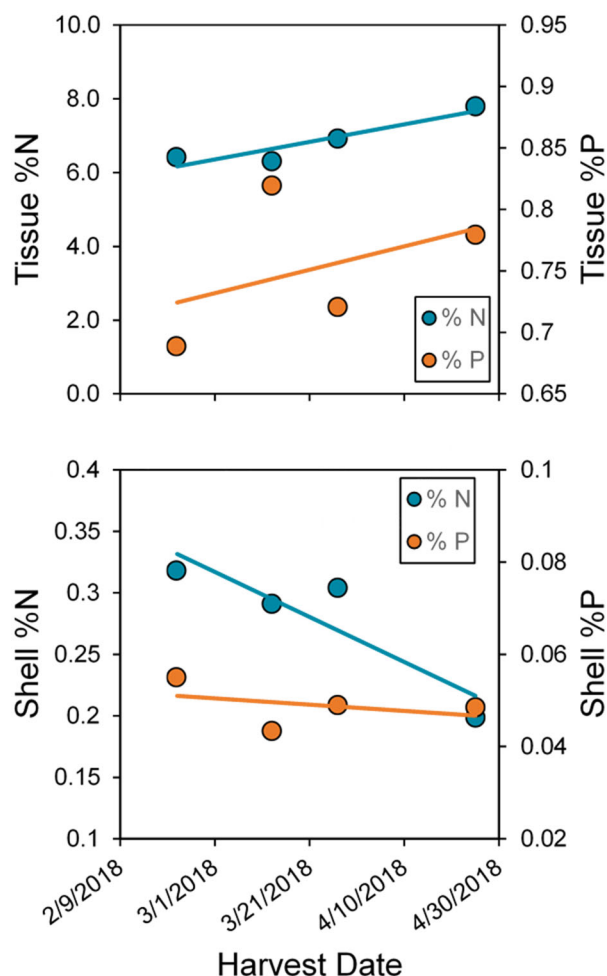


Fig. 7. Temporal trends in oyster tissue and shell nitrogen and phosphorus content. Correlations between time and nutrient content are not significant but the power to detect significant correlations is low because of low sample numbers. Significant differences between samples should be interpreted as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

Table 5. Number of oysters sampled at each site, mean nitrogen and phosphorus content per oyster, and amounts of nitrogen 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). 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 distinct than at any of the other sites.

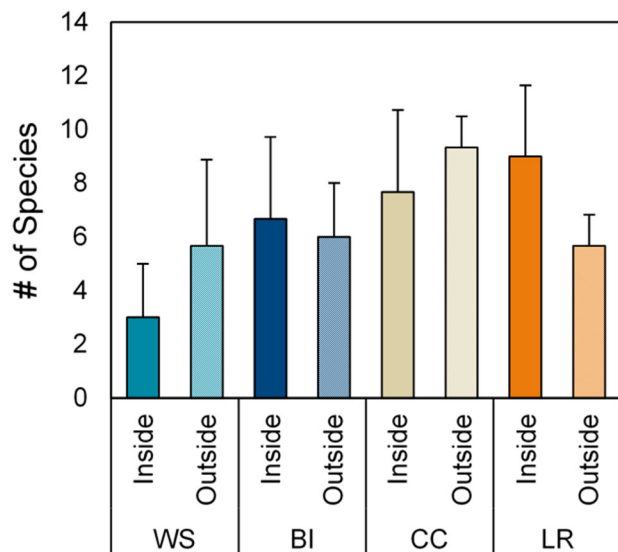


Fig. 8. Species richness in samples taken from inside and outside the farm footprint at each study site. Significance of differences is discussed in accompanying text.

The total biomass of benthic macrofauna was not significantly different between sites or seasons. PCO analyses show that three of the four samples from WS differ 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.

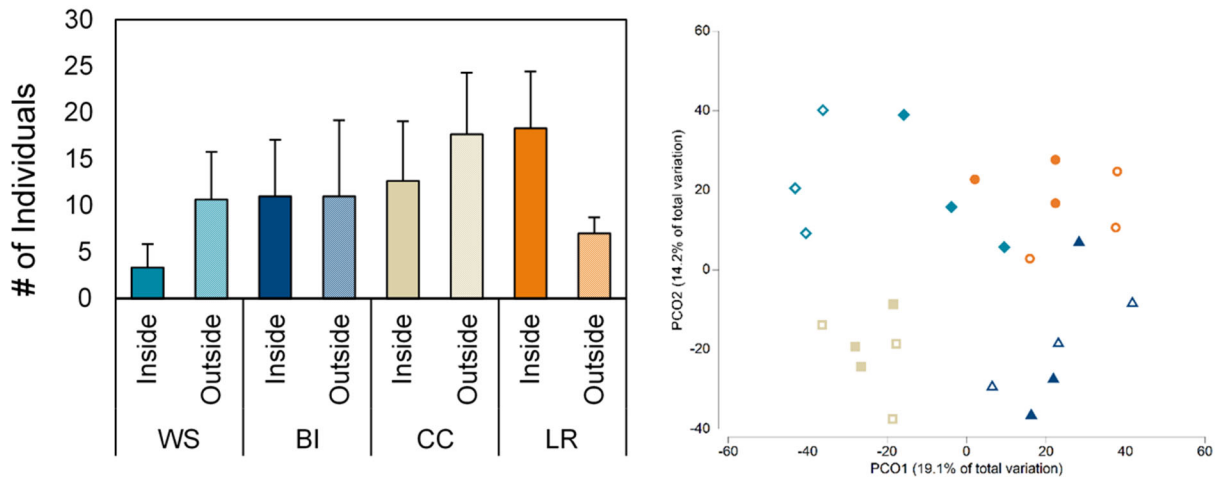


Fig. 9. Mean abundance of individuals (left panel) at each sampling site and results of principal coordinates analysis of species identity and abundance data (right panel). Colors in PCO plot correspond to the same sites as shown in the mean abundance graph. Filled markers indicate samples taken from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

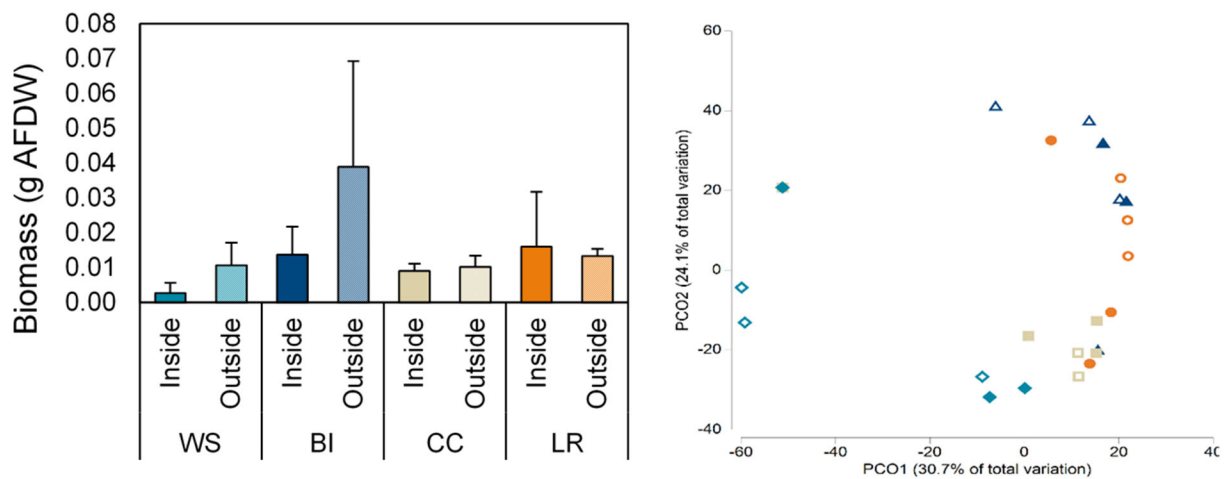


Fig. 10. Mean total macrofauna biomass (left panel) at each sampling site and results of principal coordinates analysis of species identity and biomass data (right panel). Colors in PCO plot correspond to the same sites as shown in the mean abundance graph. Filled markers indicate samples taken from 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 grabs 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 WS 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 2018 are most likely attributable to differences in sample location (Windmill Point vs. North Point) and 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.

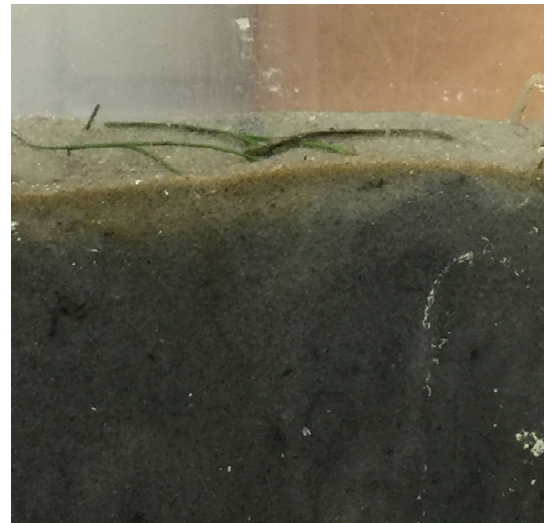


Fig. 11. Photograph of core sample from CC showing oxic surface sediments typical of samples taken at all sites.

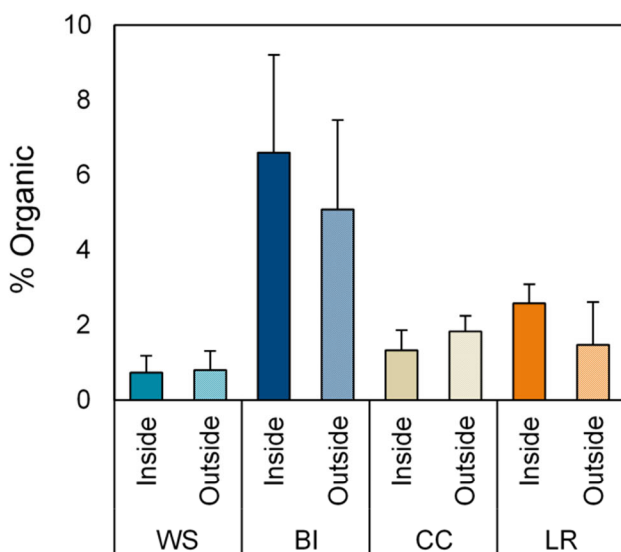


Fig. 12. Sediment organic content for samples collected in Summer 2017 at each site.

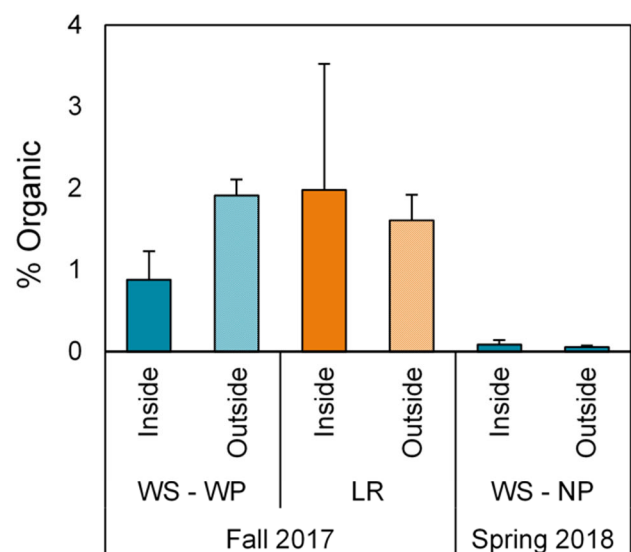


Fig. 13. Sediment organic content for samples collected at the Windmill Point site at WS and at LR in Fall 2017 and for samples collected in Spring 2018 at the North Point site at WS.

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 but found that the results were in agreement with those of the original ANOVAs and so assumed that original analyses were robust to violations and report the p-values associated with those analyses (Table 6).

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

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	Outside	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 <i>a</i> (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	

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 at any of the sites.

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 sampling periods at 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

Table 8. Mean values and standard deviations for total suspended solids (TSS) and their organic content for samples 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	Out side	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 of gear types, locations, and aquaculture farm scales along the western shore of Chesapeake Bay in Virginia, 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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