ENVIRONMENTAL AND ECOLOGICAL BENEFITS AND IMPACTS OF OYSTER AQUACULTURE: ADDENDUM

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Chesapeake Bay, Virginia, USA

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Abstract

The data described in this addendum are provided to enhance the resolution and/or expand the temporal scope of the information already provided in the final report (Kellogg et al. 2018). High-resolution water quality transect data were collected at all four sites in Summer 2017, at White Stone (Windmill Point site) and Lynnhaven River in Fall 2017, and at White Stone (North Point site) in Spring 2018. During each sampling period, data were collected from multiple transects through and outside of each farm. Resulting data were detrended as needed based on temporal and salinity-related patterns found in data collected outside the farm footprint. Comparison of the resulting data from inside and outside the farm identified significant differences between water quality inside the farm footprint and outside for the majority of site x season combinations for all parameters. However, differences were consistently small enough to have no biologically significant impact, positive or negative, on farm-scale water quality.

Benthic macrofaunal communities inside and outside the farms were assessed at White Stone and Lynnhaven River sites in Fall 2017 and White Stone's North Point site in Spring 2018. Data on species richness, macrofauna abundance, and macrofauna biomass were compared between samples taken inside the farm footprint and outside the farm footprint for all site x season combinations. These data were compared to data previously reported from Summer 2017 collected at all four aquaculture sites. Overall, patterns in species richness and macrofauna abundance were not consistent across seasons within site, across sites within seasons or within gear type. With the exception of one of the farm sites studied, there was a trend towards increased macrofauna biomass inside the footprint of aquaculture farms. This pattern is consistent with the assumption that food for benthic macrofauna at these sites is enhanced by oyster biodeposition. Overall, we found no biologically significant negative impacts on macrofaunal communities inside aquaculture farms and some evidence that suggests a possible positive impact on benthic macrofauna production.

Project Narrative

To better understand the environmental and ecological benefits and impacts of oyster aquaculture, we sampled water quality and benthic macrofaunal communities within oyster aquaculture sites and compared those data to data collected from the areas surrounding each farm. See Kellogg et al. (2018) for detailed information on farm locations and site characteristics.

Methods

Study sites: The same four sites were sampled during the same seasons as described in Kellogg et al. (2018). At each site, we delineated the footprint of the farm (hereafter "inside") based on a combination of GPS coordinates and aerial photography (Fig. 1). Data from inside the farm footprint were compared to data collected adjacent to but outside of the farms (hereafter "outside").

a) White Stone

b) Chapel Creek

c) Big Island

d) Lynnhaven

Fig. 1. 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 approximate extent of the farm footprint studied at each site.

Sampling periods: In Summer 2017, all four sites were sampled to compare water quality and macrofaunal community structure inside and outside the farms. In Fall 2017, additional samples of each type were taken at the White Stone and Lynnhaven River sites. In Winter 2017/2018, White Stone shifted production from the Windmill Point location previously sampled to a nearby location at North Point. Water quality and macrofauna community structure were assessed at the North Point site in Spring 2018.

Water quality transects: During each sampling period, data were collected from along transects that ran upstream, downstream and through the aquaculture farm parallel to aquaculture gear (Fig. 2). 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 as sites utilizing bottom cages, with adjustments made as needed to avoid oyster cages. Along each transect, 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. All data were paired with location information from a GPS unit.

Fig. 2. Example of the spatial distribution of water quality transects. Each white dot represents a sample collected by the water quality sonde. Box 5 represents the footprint of the aquaculture farm at White Stone's Windmill Point site. All dots within box 5 were "inside" points. All other points were "outside" points.

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 62.2cm^2 area to a depth of ~10cm at all four sites in Summer 2017 and at White Stone and Lynnhaven River sites in Fall 2017. In Spring 2018, a petite ponar grab (216 cm^2 sample area) was used to collect macrofauna community samples from White Stone's North Point site. 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.

Statistical analyses: Prior to statistical analyses, all water quality transect data were detrended as needed based upon data collected outside the farm footprint. This process consisted of regressing outside data against time of collection using a first, second or third order polynomial regression. If the regression was significant, the time trend was removed from the entire dataset (i.e. inside and outside data) using the regression function. Data were then regressed in the same manner against salinity and any significant salinity trends were removed. This approach results in means for the outside data that approach zero and means for the inside data that are positive if the measured parameter is higher inside the farm and negative if it is lower inside the farm.

The effect of farms on water quality and benthic community structure was determined using one-way ANOVAs with two levels (inside farm and outside farm) to determine significant differences between means for all macrofauna community parameters and detrended means for all water quality parameters. Data that violated ANOVA assumptions of normality and/or equal variance were transformed as needed to meet these assumptions. Some of the water quality datasets that violated ANOVA assumptions of normality and/or equal variance were resistant to transformation. In these cases, we assumed that ANOVA were robust to these violations, an assumption justified in part by the large number of samples included in analyses. For all tests, p-values ≤ 0.05 were considered statistically significant.

Results

Water quality transects: Significant differences in water quality inside and outside the farm footprint were common for all parameters during all sampling periods. Only the Chapel Creek site showed no significant differences between water quality inside and outside the farm for all parameters. A finding that is likely related to the small size of the farm footprint at this site and the resulting in relatively low sample numbers compared to other sites. Although the farms frequently had impacts on water quality, the scale of these impacts was consistently small enough to be biologically insignificant, leading to the conclusion that these farms have minimal positive or negative impacts on water quality.

Current speed: Flow was significantly reduced in four of the seven sets of samples and was not significantly different in the other three sets. Big Island, the site with the highest density of cages, had the greatest effect on flow, reducing it by more than 4 cm sec^{-1}. Flow was also reduced by ~2-3 cm sec^{-1} at White Stone's Windmill Point site (sampled in summer and fall) and at the Lynnhaven site in fall. Chapel Creek, the site with the smallest footprint, had no detectable effect on flow.

Table 1. Effect of aquaculture farm on current speeds measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	**Season**	**Samples (#)**		**Current Speed (cm/sec)**		**Detrended Current Speed (Mean ± SD)**		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	370	1121	10.8	10.9	-4.25 ± 10.68	<	0.00 ± 6.04
Chapel Creek	Summer	57	693	9.4	8.0	1.34 ± 6.14	≈	0.00 ± 5.29
Lynnhaven	Summer	797	1893	11.3	11.8	0.49 ± 6.33	≈	0.00 ± 5.95
	Fall	338	996	11.9	12.2	-2.29 ± 6.92	<	0.00 ± 6.13
White Stone	Spring	788	1062	16.2	15.9	-0.11 ± 9.49	≈	0.00 ± 9.42
	Summer	859	1533	16.8	18.4	-2.14 ± 7.33	<	0.00 ± 7.83
	Fall	657	1948	13.4	16.7	-3.11 ± 7.64	<	0.00 ± 9.08

Dissolved oxygen: Aquaculture farms had a very small but significant positive effect on dissolved oxygen in five of the seven datasets (Table 2). Data indicate that farm-scale water quality at these sites is not negatively impacted by oyster respiration. It is important to note that all data were collected during daylight hours. Visual observations at White Stone's North Point site suggest that the slight increase in dissolved oxygen within farms may be attributable to benthic microagal or macroalgal growth on aquaculture gear, leading to increased rates of photosynthesis during daylight hours resulting in increased oxygen concentration. At night, when photosynthesis shuts down, it is possible that different patterns in oxygen concentration would be observed.

Table 2. Effect of aquaculture farm on dissolved oxygen measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	Season	Samples (#)		Dissolved Oxygen (mg L^{-1})		Detrended Dissolved Oxygen (Mean ± SD)		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	159	778	7.4	7.3	0.01 ± 0.10	≈	0.00 ± 0.11
Chapel Creek	Summer	31	383	7.2	7.1	0.00 ± 0.03	≈	0.00 ± 0.05
Lynnhaven	Summer	523	1259	6.1	5.9	0.08 ± 0.09	>	0.00 ± 0.07
	Fall	245	732	6.1	6.1	0.07 ± 0.11	>	0.00 ± 0.12
White Stone	Spring	549	763	9.7	9.7	0.02 ± 0.03	>	0.00 ± 0.05
	Summer	564	1109	8.4	8.4	0.01 ± 0.04	>	0.00 ± 0.06
	Fall	448	1526	7.9	7.9	0.02 ± 0.04	>	0.00 ± 0.07

pH: Effects on pH were significant but extremely small with a maximum difference between means of 0.023 (Table 3). In five of the seven datasets, pH was slightly higher inside the farm. Because increases photosynthesis lead to increases in pH, these findings are generally consistent with dissolved oxygen results. As for dissolved oxygen, all samples were taken during daylight hours making it possible that different patterns in pH would be observed at night.

Table 3. Effect of aquaculture farm on pH measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	Season	Samples (#)		pH		Detrended pH (Mean ± SD)		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	159	778	7.9	7.9	-0.023 ± 0.030	<	0.000 ± 0.022
Chapel Creek	Summer	31	383	8.1	8.1	0.004 ± 0.005	>	0.000 ± 0.009
Lynnhaven	Summer	523	1259	7.9	7.8	0.011 ± 0.011	>	0.000 ± 0.011
	Fall	245	732	7.6	7.6	0.004 ± 0.011	>	0.000 ± 0.016
White Stone	Spring	549	763	8.4	8.4	-0.005 ± 0.019	<	0.000 ± 0.024
	Summer	564	1109	8.1	8.1	0.002 ± 0.009	>	0.000 ± 0.011
	Fall	448	1526	8.0	8.0	0.000 ± 0.005	>	0.000 ± 0.011

Chlorophyll: Aquaculture farms had significant but very small effects on chlorophyll with no consistent direction in the effect (Table 4). Three of the datasets indicate enhanced chlorophyll concentrations, three indicate reduced concentrations, and, again, there was no significant effect of the farm at Chapel Creek. 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, the scale of that consumption appears to be small enough that it has minimal impacts on water quality at the farm scale. Note that the method used to assess farm-scale chlorophyll concentrations measures only the amount of chlorophyll suspended in the water column and could not account for the chlorophyll in algae attached to aquaculture gear. This incomplete accounting of chlorophyll at the farm scale may partially explain the lack of a consistent pattern between dissolved oxygen data and chlorophyll data.

Table 4. Effect of aquaculture farm on chlorophyll measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	**Season**	**Samples (#)**		**Chlorophyll** $(\mu g\ L^{-1})$		**Detrended Chlorophyll (Mean ± SD)**		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	159	778	9.2	9.6	-0.19 ± 0.77	<	0.00 ± 0.73
Chapel Creek	Summer	31	383	3.6	3.6	-0.11 ± 0.58	≈	0.00 ± 0.57
Lynnhaven	Summer	523	1259	12.6	12.6	-0.11 ± 0.77	<	0.00 ± 0.57
	Fall	245	732	5.4	5.1	0.18 ± 0.53	>	0.00 ± 0.54
White Stone	Spring	549	763	2.4	2.5	-0.04 ± 0.29	<	0.00 ± 0.42
	Summer	564	1109	1.8	1.8	0.12 ± 0.93	>	0.00 ± 0.54
	Fall	448	1526	2.9	2.6	0.38 ± 1.52	>	0.00 ± 0.88

Turbidity: Turbidity is a measure of the amount of light scattered by particles in the water column. As oysters filter feed, they consume both sediments and phytoplankton. Sediments are repackaged into pseudofeces that are larger and have a greater sinking velocity than the sediments originally consumed. These larger particles scatter less light leading to the expectation that oyster feeding activities reduce turbidity via both direct consumption of phytoplankton and repackaging of sediments. Turbidity was significantly lower inside the farm for five of the seven datasets (Table 5). Again, no significant difference was found at Chapel Creek, likely due to the small footprint of the farm. As for other parameters, the magnitude of differences between inside and outside the farm are not large enough to be biologically meaningful.

Table 5. Effect of aquaculture farm on turbidity measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	Season	Samples (#)		Turbidity (NTU)		Detrended Turbidity (Mean ± SD)		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	159	778	5.5	6.3	-0.59 ± 0.30	<	0.00 ± 0.41
Chapel Creek	Summer	31	383	1.7	1.7	0.04 ± 0.05	≈	0.00 ± 0.13
Lynnhaven	Summer	523	1259	9.7	10.0	-0.63 ± 0.67	<	0.00 ± 0.64
	Fall	245	732	4.7	4.9	-0.43 ± 0.22	<	0.00 ± 0.36
White Stone	Spring	549	763	0.3	0.3	-0.10 ± 0.17	<	0.00 ± 0.19
	Summer	564	1109	1.8	1.7	0.05 ± 0.22	>	0.00 ± 0.23
	Fall	448	1526	1.2	1.3	-0.08 ± 0.10	<	0.00 ± 0.43

Temperature: Although significant effects on temperature were identified for all sites except Chapel Creek, the scale of the impact was extremely small with a maximum difference of 0.09 ˚C (Table 6). The two sites with floating aquaculture gear consistently reduced water temperatures. One possible cause for reduced temperatures at these sites is shading of the water column by the floating aquaculture gear. Observation of the greatest impact at Big Island, the site with the highest gear density, is consistent with this hypothesis. Again, the small spatial extent and relatively small sample size of the Chapel Creek farm may partially explain its lack of significant impact.

Table 6. Effect of aquaculture farm on temperature measured inside and outside the farm footprint. Refer to text for methods used to detrend data. Significant differences between detrended means are indicated by "<" or ">" depending upon whether means were lower or higher, respectively, inside the footprint of the farm. Means that are not siginifcantly different are indicated by "≈".

Farm	Season	Samples (#)		Temperature (°C)		Detrended Temperature (Mean ± SD)		
		Inside	*Outside*	*Inside*	*Outside*	*Inside*	*Sig.*	*Outside*
Big Island	Summer	159	778	25.1	25.2	-0.09 ± 0.10	<	0.00 ± 0.09
Chapel Creek	Summer	31	383	24.6	24.5	0.01 ± 0.02	≈	0.00 ± 0.02
Lynnhaven	Summer	523	1259	29.3	29.3	0.03 ± 0.02	>	0.00 ± 0.04
	Fall	245	732	22.2	22.4	-0.08 ± 0.16	<	0.00 ± 0.13
White Stone	Spring	549	763	18.8	18.8	-0.08 ± 0.07	<	0.00 ± 0.07
	Summer	564	1109	24.1	24.3	-0.04 ± 0.04	<	0.00 ± 0.06
	Fall	448	1526	19.2	19.3	-0.02 ± 0.08	<	0.00 ± 0.16

Benthic macrofaunal community: Data from summer 2017 have been reported previously but we include them again here to place them in the context of observed patterns for other seasons. Although significant differences were occasionally found between the benthic macrofaunal communities inside and outside the farm footprint at some sites during some seasons, there was no consistent effect, positive or negative, across sites in terms of species richness (Fig. 3) or macrofauna abundance (Fig. 4 and 5). There was a trend towards enhanced macrofauna biomass inside farms (Fig. 6).

Of the macrofauna community characteristics examined, species richness was the most consistent across sites and seasons (Fig. 3). Only two of the seven site x season datasets show significant differences between species richness inside and outside of the farm footprint, with White Stone's Windmill point site showing reduced species richness inside the farm footprint in summer and Lynnhaven showing increased species richness inside the farm footprint in summer. Of the other five site x season combinations, four showed a tendency towards higher species richness inside the farm footprint. Trends were not consistent across seasons within site, across sites within seasons or within gear type.

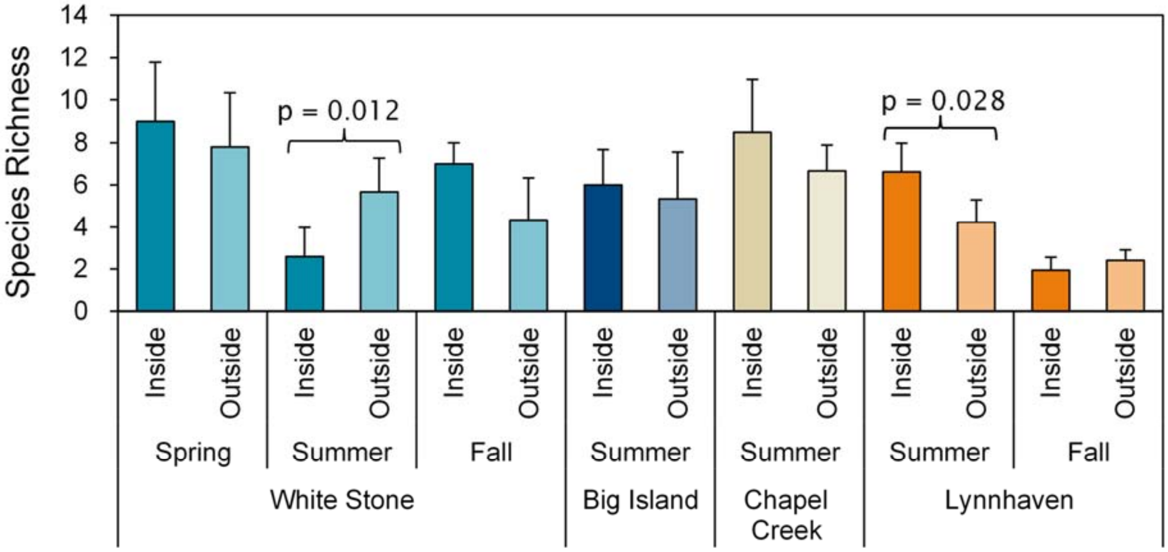

Fig. 3. Mean species richness for all sites and sampling periods. Error bars represent ± 1 standard deviation. P-values are given for site x treatment combinations in which there was a significant difference between areas inside and outside the farm footprint.

Macrofauna abundance showed greater variation than other macrofauna community characteristics. By far, the most organisms were found at White Stone's North Point site in the spring (Fig. 4). This pattern was driven almost entirely by high abundances of the amethyst gem clam, *Gemma gemma*. During this sampling period, the mean abundance of organisms inside the footprint of the aquaculture site was significantly higher than outside the footprint.

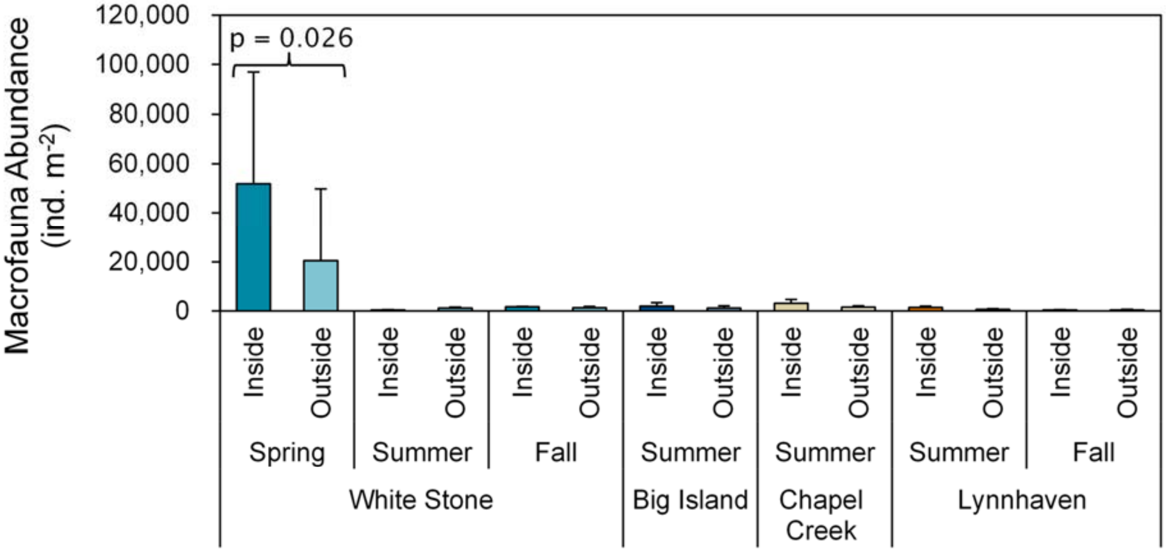

Fig. 4. Mean macrofauna abundance for all sites and sampling periods. Error bars represent ± 1 standard deviation. P-value is given only for White Stone spring samples. Other significant p-values are shown in Figure 5.

For the other six site x sampling period datasets (Fig. 5), significant differences between mean organism abundance inside and outside the farm footprint were observed three times, all during summer months. Mean abundances were higher inside the farm footprint at both Chapel Creek and Lynnhaven and significantly lower at White Stone's Windmill Point site. Of the other three site x season combinations, two showed

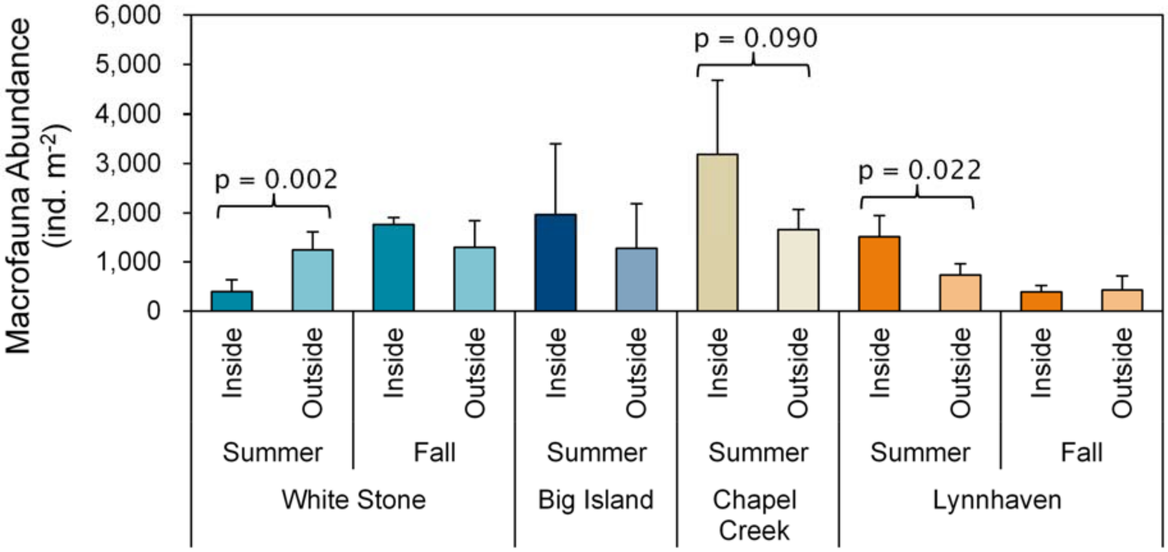

Fig. 5. Mean macrofauna abundance for all sites and sampling periods except White Stone spring samples. Error bars represent ± 1 standard deviation. P-values are given for site x treatment combinations in which there was a significant difference between areas inside and outside the farm footprint.

a tendency towards higher macrofauna abundance inside the farm footprint. Overall, trends in macrofauna abundance were not consistent across seasons within site, across sites within seasons or within gear type.

Mean macrofauna biomass only differed significantly between inside and outside the farm at White Stone's North Point site in spring where higher biomass was found within the footprint of the farm. This pattern is similar to that seen for macrofauna abundance and is again largely attributable to large populations *Gemma gemma* at the site. Of the other six site x season combinations, four show a tendency towards higher biomass inside the farm. The two that do not follow this pattern are the samples collected at White Stone's Windmill Point site. Observations made at the time of sampling suggest that the tendency towards slightly lower biomass inside the farm at Windmill Point is unlikely to be the result of negative impacts associated with enhanced organic deposition. The tendency towards higher biomass inside the farm footprint observed for the majority of season x site combinations is the most consistent pattern observed in macrofauna community structure during these studies and is consistent with the expectation that oyster biodeposits enhance the supply of food available to benthic organisms at these sites. This tendency towards increased benthic biomass inside the farms even during summer months suggests that organic loading of the sediments is not great enough to result in negative impacts on benthic habitat quality.

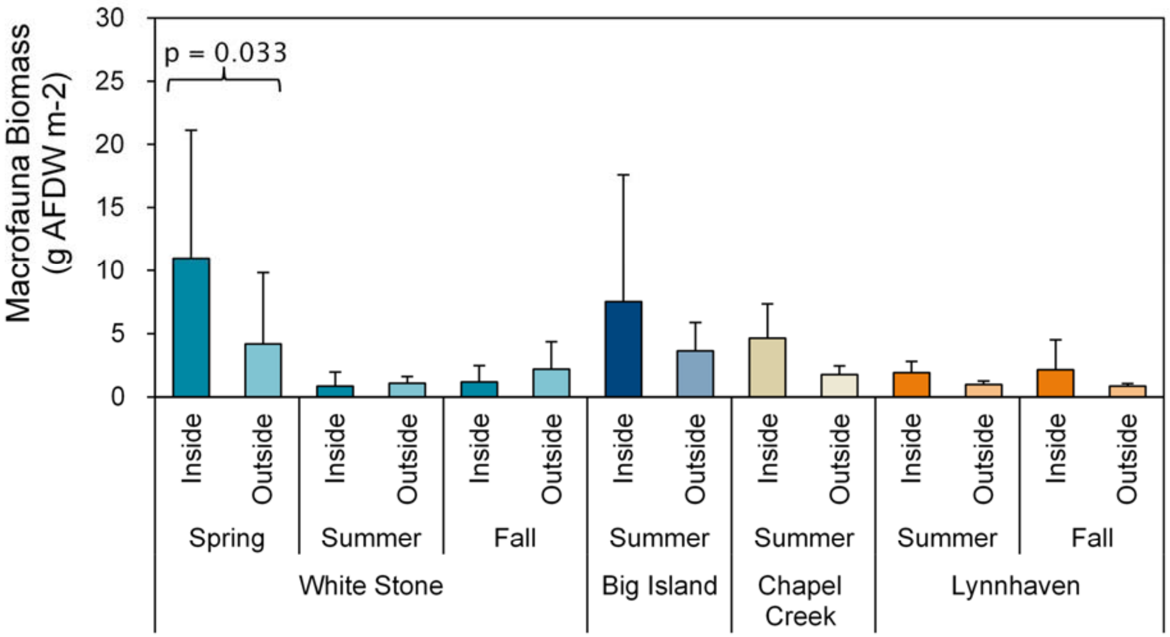

Fig. 6. Mean macrofauna biomass for all sites and sampling periods. Error bars represent ± 1 standard deviation. P-values are given for site x treatment combinations in which there was a significant difference between areas inside and outside the farm footprint.

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 biologically significant negative impacts on benthic macrofauna community structure or water quality.
- Our approach to measuring water quality differences between aquaculture farms and the surrounding area followed by detrending of data based on time and salinity allowed us to detect very small differences in water quality between waters within the farm footprint and areas outside the farm footprint for farms ≥1.35 acres. We believe this approach is likely to be useful for future studies of water quality impacts for farms of medium to large spatial scales.
- The failure to detect any significant water quality differences at Chapel Creek despite high oyster biomass density suggests that the effects of farms at this spatial scale (≤ 0.28 acres) are difficult to detect against background levels of variation in water quality parameters using the transect approach.
- Significant differences between water quality inside the farm footprint and outside were detected for the majority of sites x season combinations for all parameters, but differences were consistently small enough to be biologically insignificant.
- Trends in species richness and macrofauna abundance were not consistent across seasons within site, across sites within seasons or within gear type.
- With the exception of one of the farm sites studied, there was a trend towards increased macrofauna biomass inside the footprint of aquaculture farms. This pattern is consistent with the assumption that food for benthic macrofauna at these sites is enhanced by oyster biodeposition. The tendency towards higher biomass inside the farm footprint during summer at three of the four sites studied also suggests that biodeposition rates are not high enough to result in degradation of benthic habitats at these sites.

Literature Cited

Kellogg, ML, J Turner, JC Dreyer, G Massey. 2018. Environmental and ecological benefits and impacts of oyster aquaculture. Final Report to The Nature Conservancy. 18 pgs.