Using Satellite-Derived Total Suspended Matter Data to Evaluate the Impacts of Tributary-Scale Oyster Restoration on Water Clarity

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Abstract

Oysters, as filter feeders, have the capacity to remove particles from the water, enhancing clarity. In the Chesapeake Bay, restoration of oyster reefs is occurring at a scale of hundreds of acres within individual tributaries, delivering the potential to improve water clarity.

Using water clarity measurements from satellites at spatial scales close to that of the oyster restoration efforts, we explored whether detection of change in satellite-derived water clarity could be linked to the large-scale oyster restoration effort, along with other responses from improved clarity such as increases in submerged aquatic vegetation (SAV). We compared satellite-derived total suspended matter (TSM) and oyster biomass data sets in locations of different oyster management strategies, and we determined that the satellite data are useful in evaluating and identifying trends at a spatial scale relevant to large-scale oyster restoration and are useful in model analysis. Further, we show a spatial correlation between the location of the most mature restored oyster reefs and decreased TSM over time.

However, we do not demonstrate a causative relationship between estimated oyster biomass, SAV, and the water clarity trend. While TSM decreases significantly with increases in oyster biomass, only 3.9% of the variability in TSM can alone be explained by oyster biomass. A four-way ANOVA added year and location as variables increasing the explained variability. Eliminating low variability variables, a one-way ANOVA using location explains 51% of the variability in TSM, indicating that TSM is strongly linked to location effects alone. Location is a categorical variable bounding discrete variables in space and has no quantitative value; however, the selected locations do correspond to specific management strategies. Still, this suggests factors other than oysters influence the decrease in TSM.

The statistically significant TSM decreases are likely driven by locations with high TSM, low oysters, and low SAV, but the inverse does not hold: high oysters and high SAV do not suggest low TSM in all scenarios. Thus, additional data or a different modeling approach is warranted in locations of high oyster abundance and high SAV. Given the spatial correlation we detected between the most mature oyster reefs in Harris Creek with high oyster abundance and a decrease in TSM, this location will be the emphasis for future investigations of the potential for oyster restoration to improve water clarity.

Introduction

The Chesapeake Bay, known for its oysters, crabs, and striped bass, has not been known for clear water. The U.S. Geological Survey and the Chesapeake Bay Program report that in both the past 10-year and 30-year periods, nitrogen and phosphorus in the Choptank River watershed continue to increase. Sediment loading has decreased in the past 30 years, but the past decade shows an increase in sediment in the Choptank (Moyer and Blomquist, 2018).

A link between decimation of the oyster population and deteriorating water quality in the Chesapeake Bay was proposed by Newell (1988). Newell calculated the 19th-century oyster population could filter the entire volume of the Bay in less than a week and suggested that an increase in the oyster population could significantly improve water quality by removing large quantities of particulate carbon (Cerco, 2005). Nutrient and sediment inputs from subwatersheds around the Bay contribute to annual phytoplankton blooms and limited light penetration. This results in reduced water clarity, negatively affecting seagrasses and the estuarine biotic communities that rely on them. However, recent seagrass surveys show a resurgence in seagrasses Bay-wide, in the state of Maryland, and notably in the Choptank River (Orth et al., 2009-2017).

In 2010, Maryland set aside 24% of its harvestable oyster bottom in multiple non-harvest sanctuaries, a move designed to initiate the repopulation of oysters on a large scale. In 2011, federal, state, university, and nonprofit partners began planning and, in 2012, began implementing large-scale oyster restoration projects in three tributaries of the Choptank River that had been set aside as oyster sanctuaries. These projects are part of the Chesapeake Bay Program's goal to restore native oyster reefs in 10 tributaries by 2025. We explore whether these management actions, given their potential for increasing oyster populations and the Chesapeake's filtering capacity, are significant enough to create change in water clarity by comparing with areas where harvest is allowed.

We investigated changes in water clarity in relation to oyster tissue biomass for three different management strategies (oyster sanctuaries, oyster sanctuaries undergoing restoration, and public fishery harvest areas) using existing datasets. These data are useful in evaluating and identifying trends at a variety of spatial and temporal scales. To estimate water clarity, we used a TSM dataset from satellite measurements, which covers large areas at spatial resolutions of a few hundred meters with overpasses on a daily basis (cloud cover excepted). With multiple years of satellite data available, we explored whether satellite-derived TSM measurements support the detection of change at spatial scales represented by the different management areas. This work builds on that of Gernez et al. (2014, 2017), who used satellite measurements at scales similar to oyster aquaculture activities in Bourgneuf Bay, France, to determine that very high TSM concentrations negatively impacted oyster growth with implications for oyster aquaculture management.

Coupling the satellite TSM data with biological data sets of factors that influence water clarity—namely, oyster biomass—we attempted to determine whether a relationship exists between satellite observed water clarity measurements and this biological filtering mechanism, within the context of different oyster management strategies.

Design and Datasets

An initial investigation of satellite-derived turbidity data (satellite diffuse light attenuation coefficient at 490 nm, 1 km spatial resolution, Wang et al., 2009) at 10 point locations (Fig. 1) in the Choptank River over 66 months (2010-2016) revealed differences in the rate of water clarity change depending on point location. The data were split into two periods of 33 months each, one prior to large-scale oyster restoration, the other post initiation of large-scale oyster restoration. Sites influenced by Bay main stem water showed a modest decrease in turbidity during both periods, but sites that were more closely associated with tributaries/creeks nearer to land showed a significant decrease in turbidity for the post restoration period. These initial observations of tributary-based clarity improvement led to the question explored in this study of whether oysters, and oyster management strategies could be shown to influence satellite-derived clarity measurements.

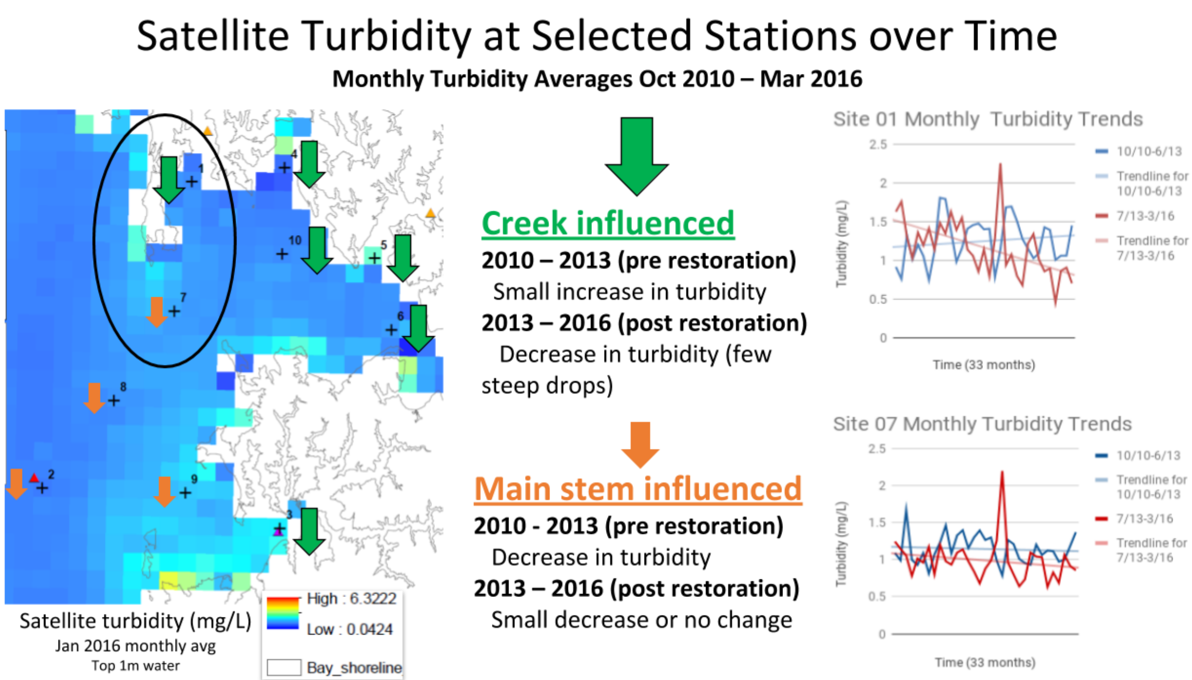


Figure 1. Ten sites were initially selected at which to investigate turbidity trends from satellite data. Two trends emerged, differentiated by whether the sites were creek influenced (green arrow) or main stem influenced (orange arrow). The graphs on the right represent examples of the two trends as seen at two sites. Site 01 is creek influenced and is in an area of oyster restoration (black oval). The sharp decrease in turbidity over the second half of the period at Site 01, as shown in the upper graph's red data and trend line, resulted in our deeper multi-dataset investigation described in this paper.

For this study, 13 Maryland tributaries in the mid-Chesapeake Bay (Fig. 2) were selected for evaluation based on a matrix of variables of presumed high and low oyster biomass and different oyster management strategies. Changes to the oyster management scenarios in 2010 created the classifications of oyster sanctuary not undergoing restoration, oyster sanctuaries undergoing restoration, and public oyster fishery harvest areas. As of the writing of this report, within the oyster sanctuaries that are undergoing restoration, Harris Creek had been completed and the others were in varying states of completeness. (Little Choptank River was completed in summer 2020.) Within the sanctuaries not actively being restored, varying degrees of natural recovery are represented. The public harvest areas offer a range of oyster biomass and SAV cover and undergo annual harvesting of oysters. With oyster restoration the focus of this study, the public harvest areas are the closest to study controls available.

Boundary Area	Code	Management Type	Status
Harris Creek	HARC	Restoration Sanctuary	Completed
Broad Creek	BROD	Public Harvest	NA
Tred Avon River	TRED	Restoration Sanctuary	Partially Complete
Middle Choptank River	CHOP	Sanctuary	NA
Little Choptank River	LILC	Restoration Sanctuary	Partially Complete
Honga River	HONG	Public Harvest	NA
Fishing Bay	FSHB	Public Harvest	NA
Nanticoke River	NANT	Sanctuary	NA
Wicomico River	WICO	Public Harvest	NA
Manokin River	MANO	Sanctuary	NA
Big Annemessex River	BIGA	Combined	NA
Pocomoke River	POCO	Combined	NA
St Marys River	STMA	Combined	NA

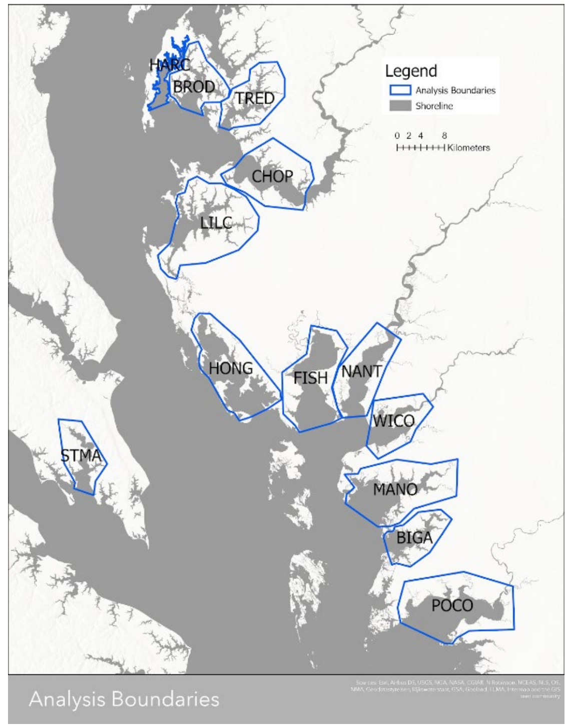


Figure 2. Thirteen areas of study within the middle Chesapeake Bay represent combinations of high and low oyster biomass and SAV, three oyster management strategies, and satellite-derived TSM concentration.

Watershed sizes of 11 of the 13 tributaries were similar. The middle Choptank River and Nanticoke River sites have larger watersheds compared to the others. Precipitation regimes were assumed to be similar among the sites' watersheds due to regional proximity and geographic characteristics. Two datasets were selected to investigate the influences on the changes in water clarity: Maryland Department of Natural Resources (MD DNR) Annual Fall (Oyster) Survey and National Oceanic and Atmospheric Administration (NOAA) TSM concentration from satellite.

1. The MD DNR Annual Fall (Oyster) Survey (AFS) evaluates trends in the number of oysters and oyster health across the state of Maryland at discrete locations sampled on a yearly basis each fall. AFS's number of oysters is represented in three oyster size classes: spat, small, and market size. The point locations were given a management descriptor of public harvest, sanctuary, or restored sanctuary determined by management area polygon boundary files. We calculated oyster biomass per sample location based on the weight to length linear regression method of Jordan et al. (2002)

   Oyster biomass estimate per sample and location in grams dry tissue weight = (No of Market Size*(10^((LOG10(Average Market Size)*2.06)-3.76))+No of Small Size*(10^((LOG10(Average Small Size)*2.06)-3.76))+No of Spat Size*(10^((LOG10(Average Spat Size)*2.06)-3.76)))/Sample Volume Size (bushels)

2. NOAA TSM concentration from satellite was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the NASA Aqua satellite, which passes over the Chesapeake Bay region twice per day, once in the daytime and once at night. Only the daytime data are used for visible wavelength measurements, which occurs roughly between 1300 and 1500 local standard time for the Chesapeake Bay. TSM is calculated from satellite normalized water-leaving radiance of the 645 nm band, using the algorithm described by Ondrusek et al. (2012). Spatial resolution of this wavelength band is 250 m per pixel at satellite nadir. Gernez et al. (2014), in comparing TSM at satellite spatial resolutions of 20 m, 300 m, and 1200 m, demonstrated that spatial scales of several hundred meters (approximately 300 m) adequately captures TSM spatial variability at oyster aquaculture farms.

   The NOAA TSM pixel data were gridded to a 250 m spatial resolution Mercator grid on a per-overpass basis. Gridded overpasses were then averaged by grid cell into a daily composite on the same Mercator grid. The daily composites were then averaged into a monthly composite grid at 250 m, and the monthly composites were averaged into an annual composite gridded data set. TSM represents suspended matter concentration in surface water only. Data is available back to 2009. We used the annual TSM averages for this study as broadly co-occurring with the yearly sampled AFS oyster biomass.

   We had initially explored a tighter temporal co-occurrence between the two data sets, i.e., less than annual, by regressing seasonal TSM averages with AFS oyster biomass for both narrow (May-September) and wide (April-October) summer seasons (relating to oyster growing season), but we found that, while there were significant relationships between TSM and oyster biomass for each of the temporal windows, oyster biomass explained even less variability in the TSM than for the annual TSM average. We therefore used the annual average TSM for comparing with the annual oyster sampling.

3. The VIMS annual SAV survey covers the entire Chesapeake Bay and evaluates both cover and density ranges of subaquatic vegetation. The SAV dataset is a vector polygon dataset. Total SAV coverage within each of the 13 tributary boundaries was calculated with ArcGIS by clipping the SAV to the tributary boundary polygons and aggregating the individual polygons of SAV cover across all densities within each tributary study area. A second tributary polygon was created to estimate the available area for SAV growth between the 4-foot depth contour and the shoreline. The 4-foot depth contour was generated from a 30 m Bay bathymetric grid data set (BayBathy30m) within each of the tributary boundary polygons. The use of the 4-foot contour approximated the depth limit at which SAV is routinely observed in the middle Chesapeake Bay. We then calculated percent cover of available bottom by dividing the aggregated total SAV cover by the submerged area between the shoreline and 4 feet. Thus, each of the 13 tributaries has a single aggregated value of percent cover of available bottom. The threshold between low and high SAV cover given the distribution of percentages across the 13 tributaries was 3%.

The years 2009-2017 were selected for this study because of the co-occurence of the three datasets for this time period, limited by the start of the TSM data set. The study time frame incorporates a span of time before sanctuaries were designated in 2010 and before the start of oyster restoration construction and seeding in 2012. Figure 3 depicts the spatial co-occurrence of these data sets.

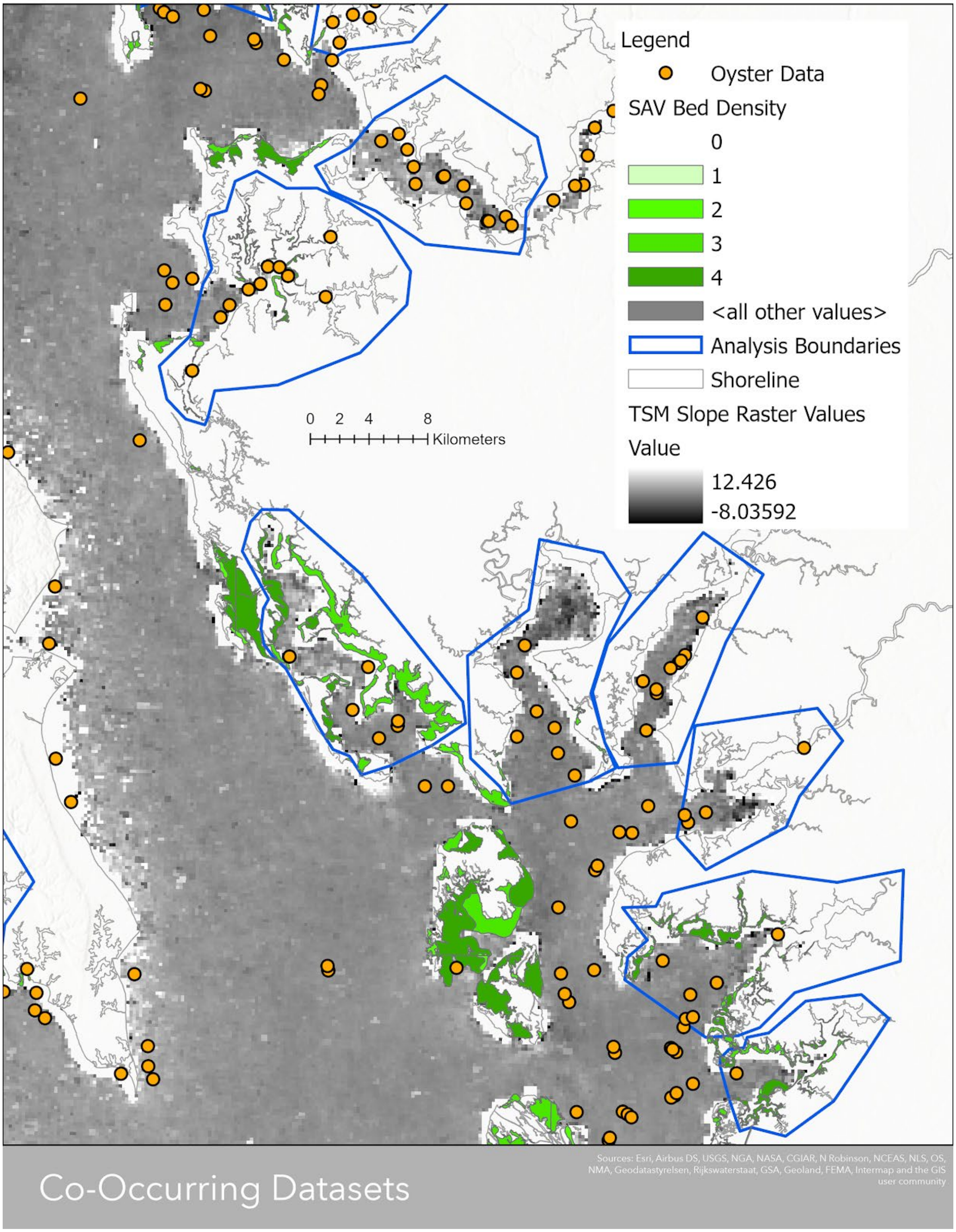


Figure 3. Spatial co-occurrence of the satellite-derived TSM cells, the Annual Fall Survey data points (black triangles), and the SAV polygons (colored shoreline polygons).

Unique values exist for each AFS location and its corresponding TSM grid point, with a single tributary-aggregated SAV percent cover value determined for each year within each tributary boundary polygon. As an example, each AFS data point (orange circle in Fig. 3) in 2013 is assigned the corresponding annual TSM grid value (250 m square) for 2013. The AFS point was assigned a management strategy based on whether it was within or outside a sanctuary and whether that sanctuary was undergoing restoration. A single SAV percent cover value for 2013 was assigned to all AFS points within the analyzed boundary. Because SAV percentage of available bottom is based on the 4-foot depth contour polygon, and no AFS points occur in water less than 4 feet, a relationship based on proximity is assumed.

We assess the data sets for spatial and temporal trends over the years of this study in Section 3.0, and then we investigate relationships between the data sets using statistical models in Section 4.0, to see if oysters have an observable impact on TSM.

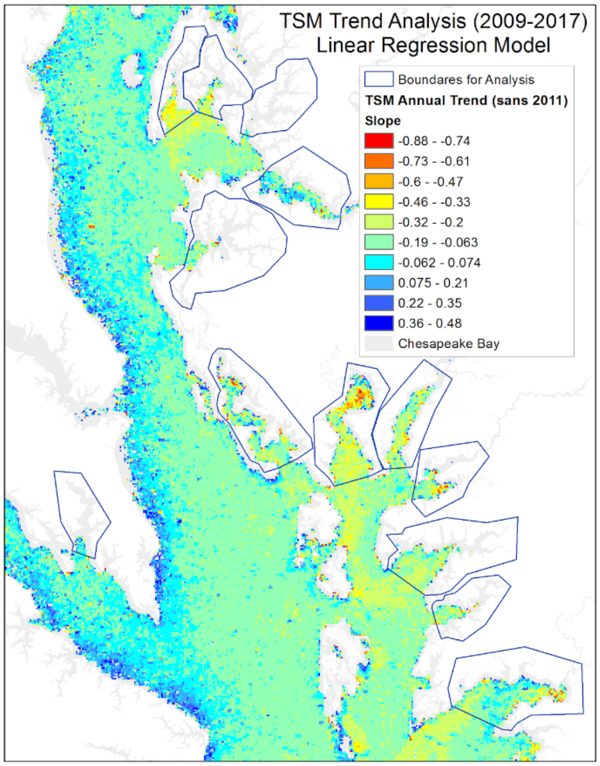
Spatial and Temporal Trend Analyses: Methods and Results

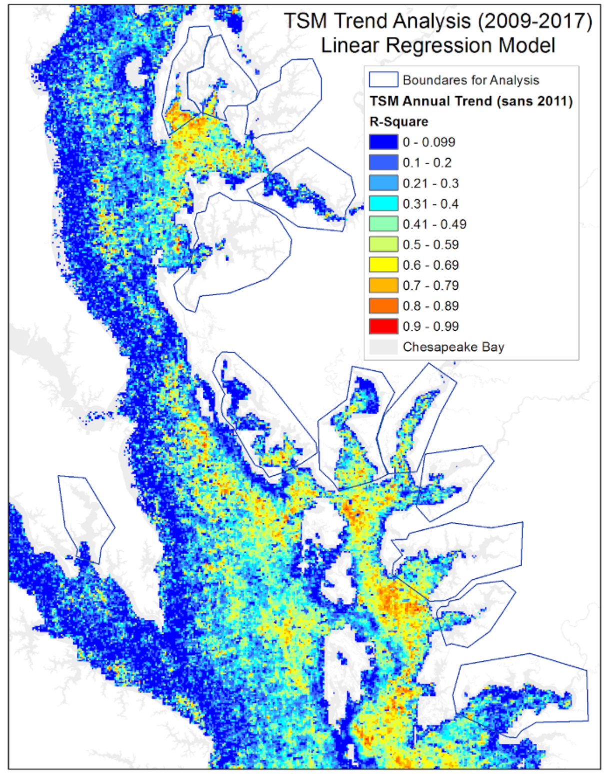
Spatiotemporal Trend Analysis of TSM

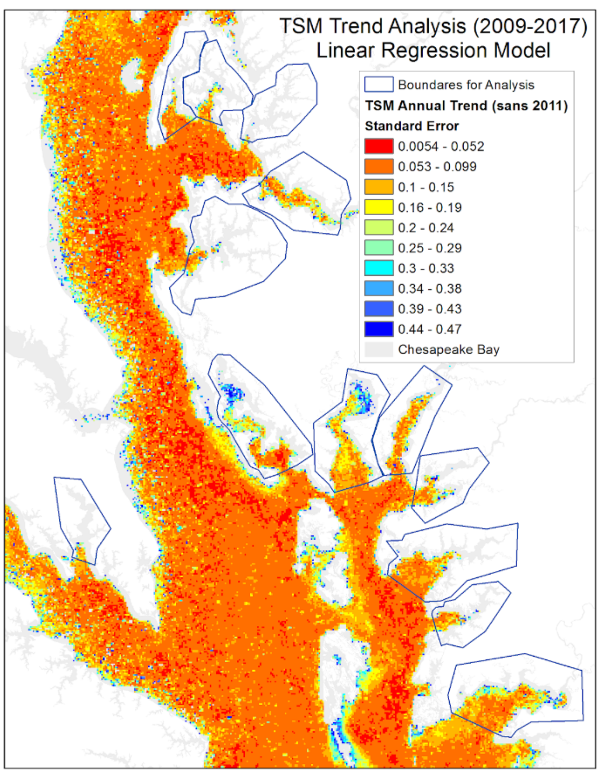
We performed a spatiotemporal trend analysis to determine how TSM varies in both time and space. Given the 2009-2017 annual TSM georeferenced map images (GIS raster data sets), a regression analysis was run for the study years (using the Curve Fit 2.0 GIS extension for ArcMap) to determine the rate of change of TSM. The regression slope was calculated for each TSM grid cell giving the spatial distribution of the rate of change, and the regression's slope standard error (SSE) and R-square were calculated for each grid cell to assess the reliability of the rate of change. Areas of high and low rate of change were evaluated.

A map of slope values for each TSM grid cell over the study years shows the spatial distribution of the rate of change of TSM (Fig. 4). Gradual negative slopes for the lower Maryland portion of the Chesapeake Bay suggest improving conditions overall. The southern study area of Tangier Sound and the northern study area of the lower Choptank River suggest the improvement in clarity is greater in these two regions than surrounding areas. The highest negative slopes are found in Harris Creek and Fishing Bay.

The regression SSE and R-square for each grid cell show the reliability of the slope (Figs. 5 and 6, respectively).







Figures 4-6. Starting in the top left (Fig. 4), temporal trends in TSM are represented spatially by the slope (rate of change); R-squared (reliability of the slope value) (upper right, Fig. 5); and slope standard error (variability in the slope measurement) (lower left, Fig. 6) maps for the area of study. Harris Creek represents a combination of the greatest rate of improvement (high negative slope), year after year reliability (high R-squared value), and low variability (low slope standard error) within the measured cells.

While Harris Creek (sanctuary completely restored) and Fishing Bay (public harvest area) appear to have the highest rates of improvement for the nine-year period, the high SSE and low R-square for Fishing Bay suggests its slope does not represent a gradual linear decline so is therefore an unreliable measure of TSM improvement. In contrast, the high rate of improvement in Harris Creek is coupled with very low SSE and a high R-square value, suggesting a reliable year-over-year rate of improvement consistent with a tributary receiving regular restoration seeding and greater than the surrounding areas.

Temporal Trend Analysis of Oyster Biomass

Temporal trends in estimated oyster biomass for the 13 tributary study locations were plotted using the mean estimated biomass value across all AFS data points within each study location per year. Figure 7 shows estimated biomass increases in sanctuaries and restored sanctuaries within the study areas and an inconclusive trend in public harvest bars within the Honga River and Fishing Bay. Study areas with mixed management strategies show a very modest biomass increase. Broad Creek is a public harvest site where oyster biomass increased over the study period. The trends were plotted to see where and if oyster biomass is increasing and are not meant to be a comparison between tributaries.

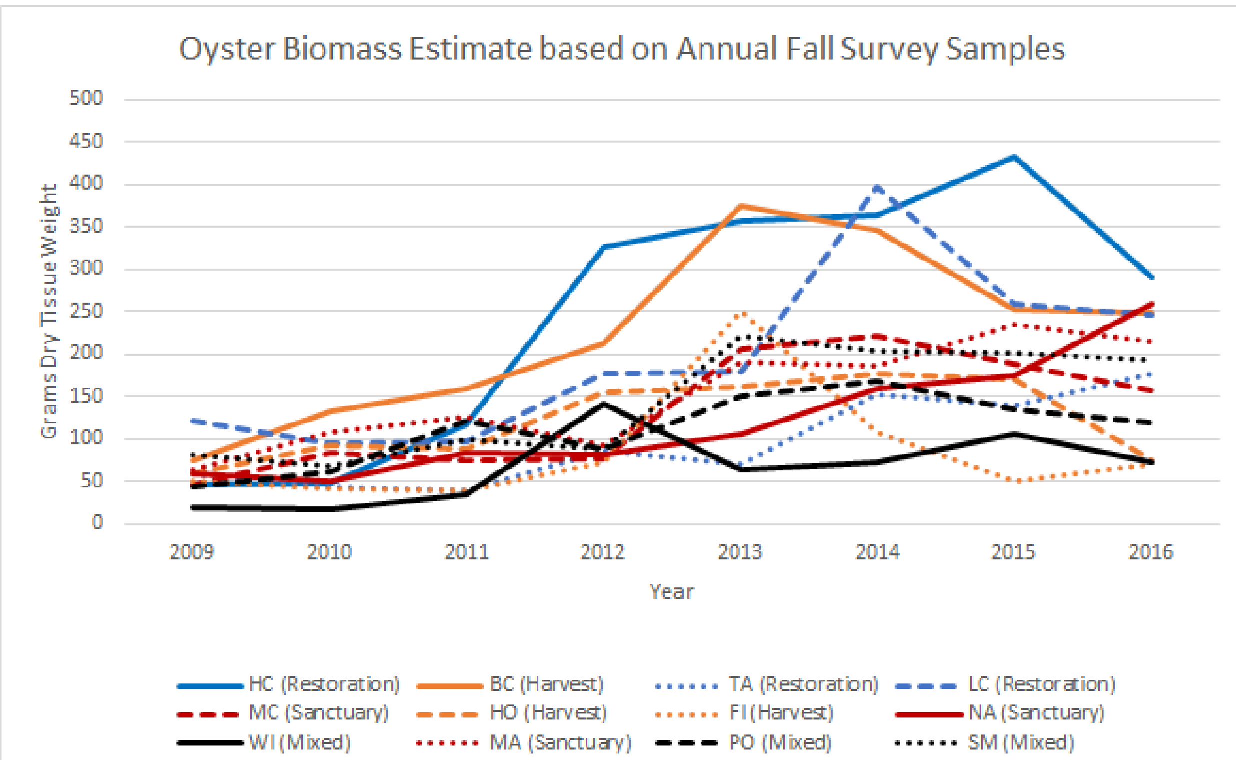


Figure 7. Estimates of oyster biomass trends within the study areas that include harvest bars (orange), sanctuaries (red), restoration sanctuaries (blue), and mixed sites (black). Harvest bars, with the exception of Broad Creek, are trending toward low biomass values while sanctuaries and restored sanctuaries are showing significant increases in biomass. Trends in mixed areas are more difficult to determine.

Temporal Trend Analysis of SAV

To understand the temporal trend in SAV for the 13 study locations, we plotted the SAV percent cover of available bottom over time per study area. For the purpose of the analysis, the area from the shoreline to the 4-foot contour generated from the 30 m Bay bathymetric grid was used to represent the limits of available bottom for SAV. Temporal trends of SAV cover within the study areas (Fig. 8) show strong growth in the northwest lower Choptank (Harris Creek and Broad Creek), Honga, and Big Annemessex rivers. The latter two started with 10-20% of available bottom already covered at the study outset, while Harris and Broad Creeks started with very little existing SAV in the system. The trend in SAV cover increase among all polygon areas analyzed is greatest for Harris Creek and the neighboring Broad Creek. The trends were plotted to see where and if SAV is increasing and are not meant to be a comparison between tributaries.

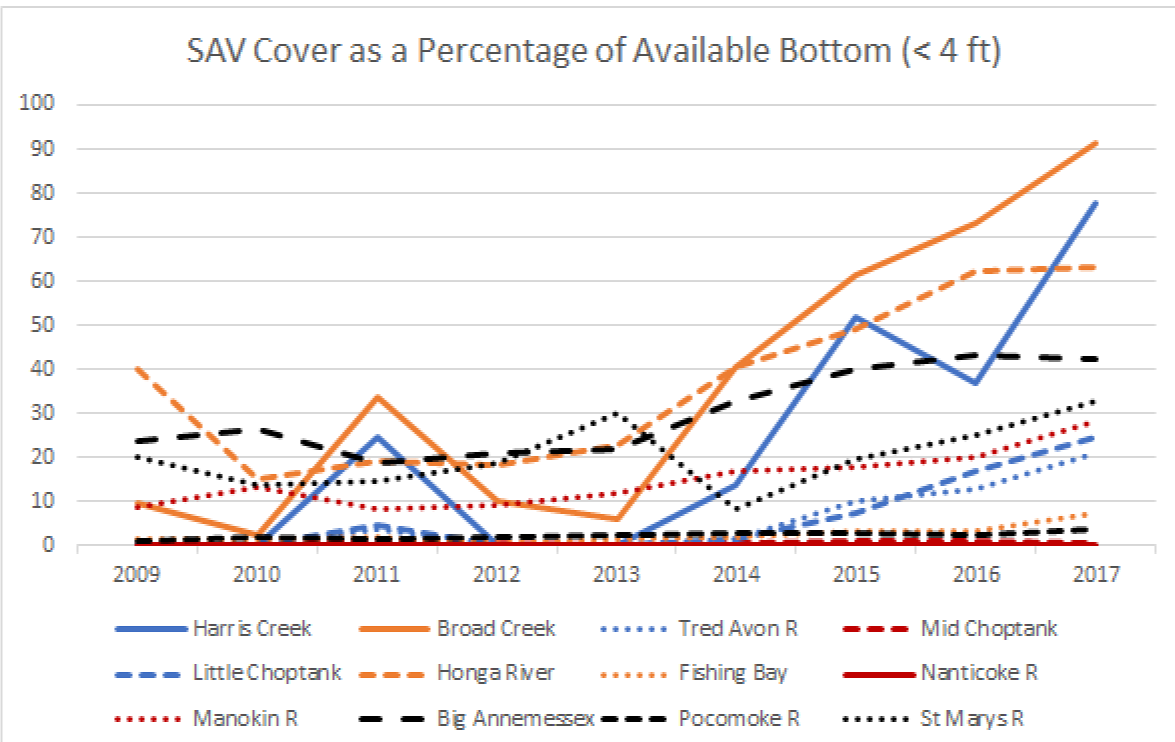


Figure 8. SAV cover as a percentage of available bottom (seabed less than 4 feet depth) by study area and by year of the study. Seagrass cover trends are generally increasing Bay-wide. With the exception of Broad Creek, the greatest rates of recovery are associated with the restored sanctuaries. Big Annemessex and Honga River SAV cover were higher than all other sites at the start of the study.

Statistical Models: Methods and Results

Statistical models were run for a combination of independent and dependent variables to determine the strength of the following relationships:

1. How does TSM change with management strategy?
2. How does TSM change with oyster biomass?
3. Do any of the variables influence TSM to a greater or lesser degree?

Variation in TSM and Oyster Biomass Relative to Management Strategy

Comparison of mean TSM and oyster biomass relative to three fishery management strategies (public fishery, sanctuary unrestored, and sanctuary restored) for 10 locations and all years was conducted using a one-way General Linear Model with a class variable (SAS; Proc GLM). Tukey's HSD tests ($\alpha = 0.05$) were used for pairwise comparisons of the mean values. Biomass values were transformed (log[(biomass+1]) because oyster density is highly skewed to lower values. The three restored sanctuaries are located in Harris Creek, Tred Avon River, and the Little Choptank River; the restoration effort is complete only in Harris Creek.

TSM varied significantly according to management strategy (GLM; $p = 0.0136$): Pairwise comparisons indicated that mean TSM at restored sanctuaries was significantly less than TSM at public fishery areas (Fig. 4; Tukey HSD $\alpha = 0.05$). Oyster biomass varied significantly with management strategy (GLM; $p < 0.0001$): Mean biomass at restored sanctuaries was significantly greater than at public fishery sites and at unrestored sanctuaries (Fig. 9; Tukey HSD $\alpha = 0.05$).

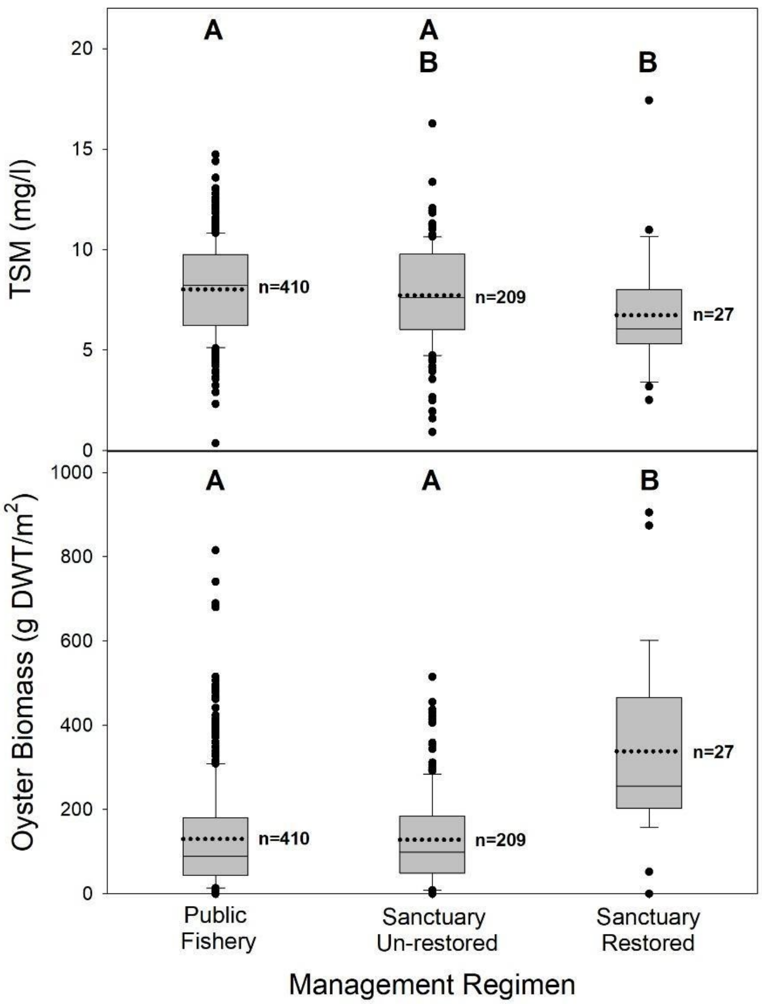


Figure 9. Data distributions of TSM and oyster biomass, 2009-2016, relative to fishery management strategy for all 13 study locations. Mean values are represented by dotted horizontal lines. Means with the same letter designation (A or B) were not significantly different (Tukey test; alpha = 0.05). Biomass was log transformed to meet normality assumptions. The number of observations is identified at the right of each box plot.

Relationships between TSM and Oyster Biomass

The relationship between TSM and oyster biomass was assessed with linear regression (SAS; Proc REG). For this analysis, we used the oyster biomass value at each AFS location and its corresponding TSM grid point value, for all tributaries and for all years. Biomass was skewed to lower values and was normalized with a log transformation (log[(biomass+1]); this also minimized heteroscedasticity observed in residual plots. Biomass values of zero were removed from the analysis.

The slope parameter of the regression model prediction line was significantly different from zero ($p < 0.0001$; Fig. 10), indicating that the predicted value of TSM changes with changes in oyster biomass. The value of the slope parameter (-0.49) is negative, demonstrating that TSM generally decreases with greater oyster biomass. The value of the r^2 statistic indicates that biomass explains only 3.9% of the variability in TSM, and that the predictive power of the model and the correlation of the two variables is poor. However, the significance and sign of the slope parameter demonstrate that sample sites with higher oyster biomass generally have lower values of TSM.

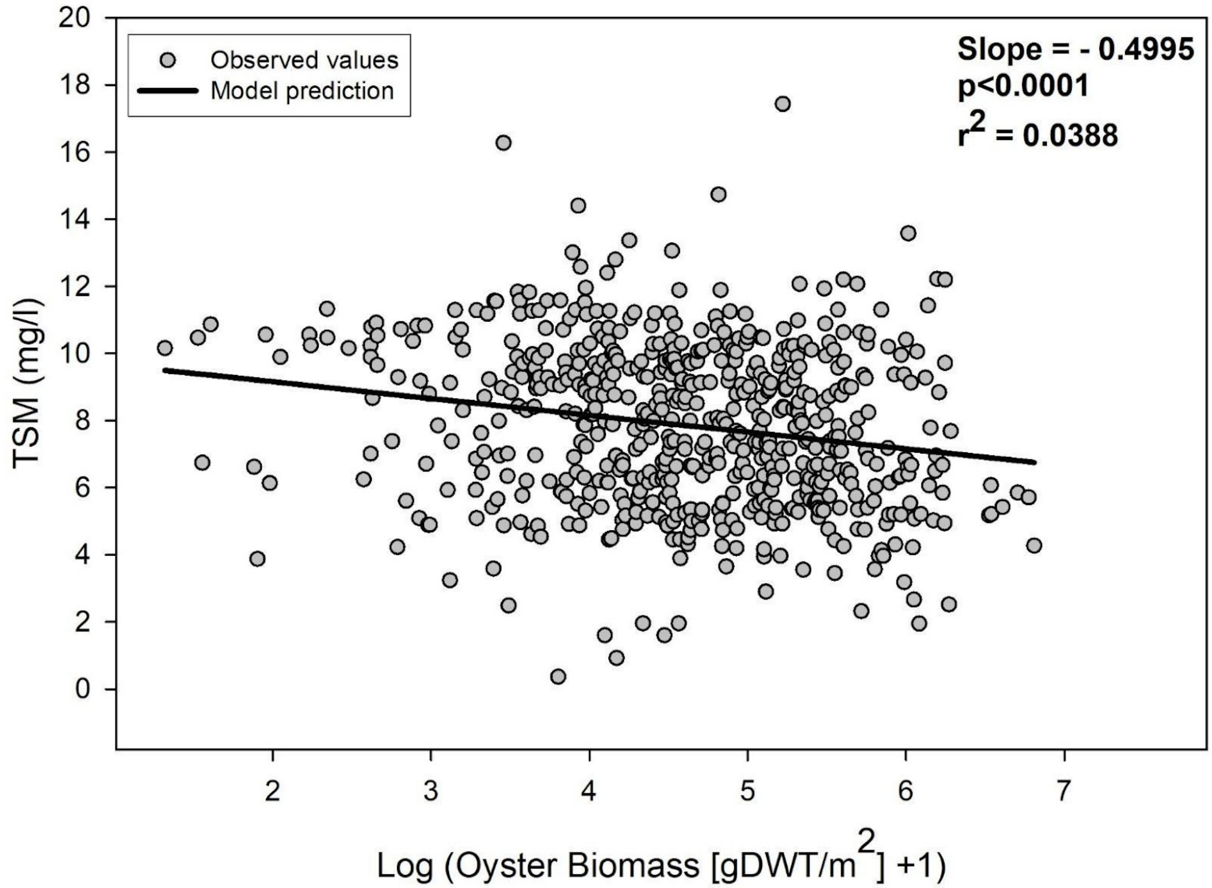


Figure 10. Linear regression relationships between TSM and oyster biomass, 2009-2016, for the 13 study locations. Biomass was log transformed to meet normality assumptions.

Other Factors That Contribute to Variability in TSM

An assessment of variation in TSM relative to multiple factors was conducted using a four-way General Linear Model analysis of variance with mixed effects (SAS; Proc GLM). Oyster biomass and SAV coverage values were continuous independent effects and were transformed to satisfy normality assumptions. Location and year were categorical independent effects with location representing 11 of the 13 tributaries. Analysis of Type III sums of squares (SS) determines which independent variables contribute to variation in TSM when all variables occupy the model. The coefficient of determination (R-square) from the four-way model was compared to the coefficient from a one-way model with location as the only independent variable.

When oyster biomass, SAV coverage, location, and year are in the model, TSM varies significantly with location and year only (Table 1; $p < 0.0211$). This four-way model explains 51% of the variability (R-square = 0.509) in TSM, suggesting that relative to spatial and temporal factors, TSM levels are not strongly related to oyster and SAV abundance. A two-way model further explored spatiotemporal effects and explained 53% of the variability in TSM (Table 2). TSM varied significantly with location and year ($p <= 0.009$); however, the interaction term was not significant ($p = 0.094$), indicating that the expected value of TSM at a specific location generally does not vary by year. The exact variables that influence spatial variation in TSM are not defined in these models, but may include other factors such as drainage basin area, land use, and tidal flushing rates.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	13	1744.7650	134.2127	44.45	<.0001
Error	556	1678.7919	3.0194		
Corrected Total	569	3423.5570			

R-Square
0.509635

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Log SAV Coverage	1	0.8766	0.8766	0.29	0.5902
Log Oyster Biomass	1	1.7679	1.7679	0.59	0.4445
Location	10	1514.9761	151.4976	50.17	<.0001
Year	1	16.1513	16.1513	5.35	0.0211

Table 1. Four-way analysis of variance table identifying variability in TSM relative to SAV coverage, oyster biomass, location, and year.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1872.3010	81.4044	28.55	<.0001
Error	577	1645.3970	2.8516		
Corrected Total	600	3517.6980			

R-Square
0.5323

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Location	11	1802.4445	163.8586	5.746	<.0001
Year	1	19.5895	19.5895	6.87	0.0090
Location x Year	11	50.2671	4.5697	1.60	0.094

Table 2. Two-way analysis of variance table identifying variability in TSM relative to location and year.

Summary of TSM and Oyster Biomass by Location

Given that our regression analyses found general inverse relationships between TSM and oyster biomass, TSM values were plotted in ascending order (Fig. 11) by location to determine if the inverse relationship held relative to spatial variation. For this analysis, TSM and oyster biomass were averaged by tributary for all years, removing a temporal trend element.The use of the color-coded shapes provides a clear visualization of the management context of each tributary.

Locations with the highest TSM values generally had low oyster biomass (Fig. 11). For locations with low TSM, however, biomass values were highly variable, suggesting that the observed inverse relationships with biomass are driven largely by the sites with high TSM or insufficient data within the oyster biomass dataset.

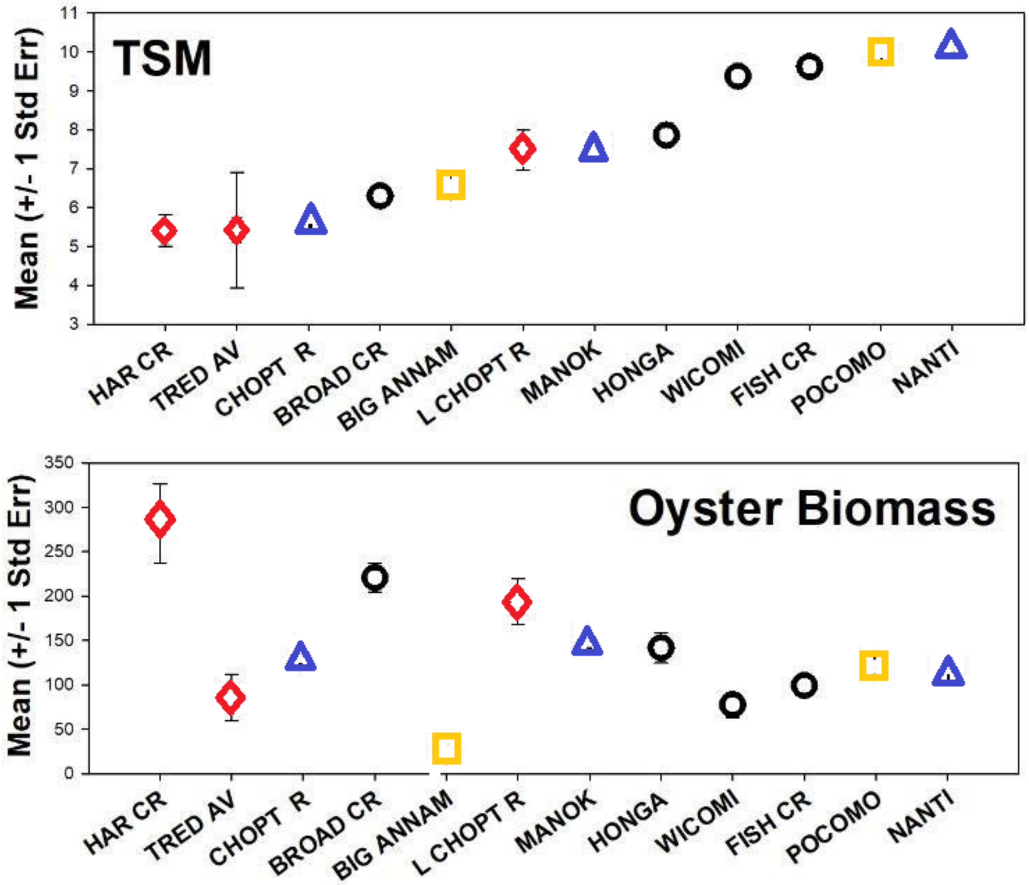


Figure 11. TSM and oyster biomass relative to location. TSM values were sorted in ascending order. Restored tributaries are represented with diamonds, unrestored sanctuaries are represented with triangles, mixed tributaries are represented with squares, and public harvest tributaries are represented with circles.

Discussion

The large-scale effort to restore oyster reefs in the Chesapeake Bay has placed millions of spat on shell into restoration tributaries in Maryland oyster sanctuaries. The scale of this effort prompts us to consider whether we are able to observe improvement in local water clarity, and whether any improvements can be tied back to the restoration effort? While we found that significant improvement in water clarity is detectable by satellite within several of the tributaries studied, questions still remain regarding the relationships between these filtering mechanisms and the observed water clarity improvement.

TSM declines significantly with increased oyster biomass (slope of -0.5, $p < 0.0001$), but TSM variability is very large with oyster biomass, explaining only 3.9% of the variability in TSM (Sec. 4.2). Questions remain around the modeling approach and the ability of the oyster biomass dataset to adequately characterize the populations in restored tributaries and elsewhere.

When including four factors in the analysis of variance (oyster biomass, SAV, year, and location), these factors explain 51% of TSM variability. When oyster biomass and SAV are removed, the two-way model explains 53% of the variability (Table 2; R-square = 0.5322) in TSM, indicating that TSM is strongly linked to location and year effects; oysters do not contribute significantly to TSM's variability when included in the model (Sec. 4.2). Location is a categorical geographic variable without a quantitative component. The location effect may be due to any number of factors that we have not explored.

Given these results, we sorted the 13 tributaries by TSM in order to gain additional understanding of how the variation in TSM among the tributaries relates to oysters. We found that locations with high TSM generally had low oyster biomass values. However, because tributaries with low TSM had variable oyster biomass (Sec. 4.4), we are not able to demonstrate a strong correlation between increased oyster biomass and low TSM using this temporally averaged sorting approach.

The AFS locations were assigned to different oyster management strategies (Sec. 4.4): public fishery (circle), mixed between public fishery and unrestored oyster sanctuary (square), unrestored oyster sanctuary (triangle), and restored oyster sanctuary (diamond). By ordering the tributaries by TSM from low to high, a clearer picture of the role that management context plays can be observed. These are that Harris Creek (location of a completed restoration effort) dominates the restoration tributaries (red diamonds), unrestored sanctuaries and mixed tributaries are mixed (blue triangles and yellow squares), and a consistent relationship for the public harvest sites (black circles) exists.

We compared the mean TSM and mean oyster biomass for three of the four categories with mixed results (Sec. 4.1). Oyster biomass was significantly higher in restored sanctuaries than in unrestored sanctuaries or in public fishery locations, and TSM was significantly lower between restored sanctuaries and the public fishery sites. This result may indicate that perhaps restored sanctuaries demonstrate a connection to the increase in oyster biomass and improvement in water clarity (Sec. 4.1).

Our spatiotemporal trend analysis revealed that Harris Creek is unique among the regions studied with its marked decrease in TSM over the years of the study (Sec 3.1). While this site coincides with an area of intensive oyster restoration and increase in SAV coverage, our results do not suggest a causation between management practices and improved water clarity. However, the spatial correlation between this restoration site and improved water clarity does provide motivation toward further investigation of these relationships and can be linked to the location variable.

Conclusions

We found that satellites are a good method of observing large-scale spatial and temporal patterns in water clarity at the spatial scales of the oyster restoration efforts. This confirms the prior work of Gernez et al. (2014, 2017), which assessed the effects of TSM on oyster aquaculture at spatial scales of hundreds of meters in satellite data. Although Gernez et al. studied the negative effects of very high TSM on oyster growth, we extend their work to water clarity improvement over time. Our spatiotemporal TSM trend analysis suggests meaningful improvement in the Choptank River and Tangier Sound regions where large-scale oyster restoration projects or naturally occurring reefs exist.

While we found significant decreases in TSM with increases in oyster biomass, our statistical analyses show a weak correlation between these factors. High TSM variability in the 13 study locations at the AFS sample sites, as seen in Figures 10 and 11, demonstrates that the factors in this study alone do not explain the variability in TSM or that the data used are inadequate for the purpose of the study. Figure 9 points toward significant differences between restored sanctuary and other management strategies for oyster biomass, and these differences appear to be driven largely by conditions at Harris Creek, the only completely restored sanctuary. Figure 11 demonstrates variability within the restored sanctuary strategy: There is an inverse relationship between TSM and oyster abundance at Harris Creek that is not yet observed at the Tred Avon and Little Choptank sanctuaries, where restoration is still in progress. Figure 11 also suggests a possible relationship within the four public fishery locations between low TSM and high oyster biomass. A further step in this research may include analysis of additional parameters that affect TSM variability.

The statistically significant decrease in TSM is driven by those tributary locations with high TSM. While these locations had low oyster biomass, the inverse—low TSM with high oyster biomass —does not hold as a true relationship. However, oyster biomass was significantly higher in restored sanctuaries than in unrestored sanctuaries or in public fishery locations, and TSM was significantly lower at restored sanctuaries than at public fishery sites. This result may indicate that perhaps restored sanctuaries contribute to decreases in TSM. Although we do not demonstrate a strong connection between the improvement in water clarity and the increase in oyster biomass, these analyses suggest additional investigation is warranted in locations with high oyster biomass to discern trends in TSM.

We recognize that our data sets and the current status of progress in the large-scale restoration effort may limit our ability to draw stronger conclusions. Our oyster biomass estimates were calculated from the AFS, a survey designed to observe trends in the fishery but not measure oyster density on reefs, which inhibits an accurate estimation of total oyster biomass. We therefore did not have oyster population values for this study. This suggests a need for a more accurate dataset of the oyster population across the Chesapeake Bay. A next step in this research would be to explore oyster population data sets other than AFS that are increasingly becoming available from sanctuary and restoration monitoring efforts. By focusing on the sanctuary and restoration sites in the Choptank River region only, where oyster abundance is currently being collected, we may be able to better assess relationships between oyster abundance and water clarity.

We note the simultaneous increases in oyster biomass and SAV coverage during the study period, indicating that both may have an effect on sediment reduction or that one has an effect on the other. The work of Newell and Koch (2004) suggests that oysters have a much higher filtering capacity than the stabilizing effect of SAV, although they concede their modeling design with evenly distributed oysters does not match the real-world clustering of oysters in reefs. Because the oyster restoration activity occurred after their 2004 work, our spatiotemporal trend analysis results showing improved water clarity in Harris Creek may indicate the benefit that oysters' high filtering capacity brings to improving water quality on the large spatial scales of the restoration efforts.

While TSM and oyster abundance at the Tred Avon and Little Choptank rivers are generally similar to those at the unrestored sanctuaries, it is notable that the available TSM data cells are further away from the actual restoration area. Other factors may contribute to the large variability in TSM, such as precipitation, Bay hydrodynamics, or sediment run-off from different land uses. Although these parameters were discussed and the study designed with them in mind, data representing these factors were not included in our analyses and may also contribute to the significance of the location effect.

Since most large-scale restoration sites are still undergoing restoration activity, waiting several years until the restored reefs have had a chance to mature may give us a more complete picture of the impact of biological filtering and oyster management strategies on water clarity.

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