The Relation of Sedimentation to Growth Rate in the Eastern Oyster (*Crassostrea virginica)*

Liahna M. Gonda-King
Andrew G. Keppel
Michael A. Kuschner
Christopher N. Rodkey
Department of Biology
St. Mary's College of Maryland
St. Mary's City, MD 20686

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Crassostrea virginica, the eastern oyster, has experienced extreme population decline in the Chesapeake Bay since the arrival of Europeans in North America. Healthy oyster populations were important both economically and environmentally to the region until their decline. This study sought to examine the affect of sedimentation, one of the biggest anthropogenic impacts on the Chesapeake, on the growth of juvenile *Crassostrea virginica* in St. Mary's County, Maryland. While some evidence was seen that intermediate rates of sedimentation are most conducive to oyster growth, many confounding variables may also have played a role; however, it was determined that one specific area of the river was most conducive to growth, and a recommendation was made to place a future restored oyster bar in this area.

Introduction:

The Chesapeake Bay, the largest estuary in North America, was once a thriving ecosystem renowned for historically abundant Eastern Oyster (*Crassostrea virginica*) reefs. The Algonquin Indians declared the bay *Chesepiooc* translated as "The Great Shellfish Bay." Sustainable oyster populations are the foundation of a fishery that has contributed significantly to the region's economic and cultural richness, but the Chesapeake's legacy is in danger. Early watermen reported 123 million pounds of oysters harvested in 1880 (Ernst, 2003). Today, populations are at 1% of historic levels (Pisani, 2009).

Vibrant oyster reefs throughout the bay region play a key ecological role in the estuary. Oysters reduce suspended sediments in the water column by pumping up to two gallons of water every hour across the gills where it is filtered for food sources, packaged into pseudofeces, and deposited as substrate (Newell, 1988; Lenihan and Peterson, 1998; MDNR, 2009). The detrimental affects of eutrophication and phytoplankton blooms can also be reduced by this filtering process (Newell, 1988; Lenihan & Peterson, 1998).

The physical oyster reef structure is also critical for supporting over 300 estuarine species by providing the largest source of hard substrate in the ecosystem, in contrast to the bay's ubiquitous soft sediment bottom (CBP, 2009). The complexity of the oyster reef habitat is a high-quality nursery ground for oyster spat, sponges, barnacles, and many other invertebrates that benefit from the food sources and protective shelters (Jones et al., 2001; Thomsen and McGlatchery, 2006; CBP, 2009).

Human interactions with the land and environment have a large impact on the health and water quality of the Chesapeake Bay and its tributaries. Recreational boating, oyster dredging and watershed alterations including farming techniques, development and vegetated buffer degradation all contribute to higher turbidity levels in the watershed (Easter Oyster Biological Review Team, 2007). Urban centers augment the sediment load deposited in waterways because impervious surfaces like roads and roofs diminish the ability of rainwater to percolate into groundwater aquifers. Instead, increased volumes of storm water running off at higher velocities lead to excessive sedimentation and erosion. On a broader scale, global climate change, a process attributed to human activity, also influences rates of sedimentation due to severe storm surges and extreme hydrological conditions (CBP, 2009).

In the last century, dissolved oxygen and light attenuation levels in the Chesapeake Bay have become critically impaired due to the affects of these human influences (Hardaway et al. 2009). The Chesapeake Bay exhibits a high concentration of suspended sediments consisting primarily of soft sediments which impairs water quality and directly inhibits healthy oyster growth, increases oyster tissue abrasions, smothers

oyster beds and leads to mortality (Hardaway et al. 2000; Eastern Oyster Biological Review Team, 2007).

Though wide salinity ranges, significant temperature fluctuations and low levels of oxygen can all be withstood by *C. virginica* to an extent, recent studies indicate that turbidity and sediment load may be significant factors associated with the mortality of oysters (Widdows et al., 1989; Coco et al., 2006; Soletchnik et al., 2007). Research based on oysters in Virginia showed species abundance was impaired by stressful, high sediment conditions (Thomsen and McGlatchery, 2006). Turbidity affects the ability of oysters to filter feed because high sediment loads trigger the oysters to close and stop filtering. Suspended sediment loads are comprised of a large proportion of inorganic matter that is detrimental toward the growth of *C. virginica* by overwhelming the oyster and preventing growth (Jones et al., 2009; Coco et al., 2006; Crain et al., 2007).

Excessive sedimentation can also bury oyster beds, smothering the organisms and increasing population mortality (Eastern Oyster Biological Review Team, 2007). Furthermore, high sedimentation has the potential to erode oyster reefs in a long-term process when oyster reproduction and growth rates are negligible (Eastern Oyster Biological Review Team, 2007). Likewise, sediment load can have great effects on oyster spat and larvae that are more sensitive to suspended sediments than adults (Davis & Hidu, 1969; Saoud et al., 2000; Soletchnik et al., 2007). Research indicates that larval oysters are sensitive to siltation in the form of inhibited settling (Saoud et al., 2000).

The deterioration of the estuary is perpetuated by the decline of oyster reefs and loss of bay resilience. Today, fewer oysters are filtering sediments out of the water column while the input has increased. The loss of oyster reefs has greatly reduced both

the ecological and economic productivity of the bay region (CBP, 2009). Understanding the present environmental conditions of the watershed can provide advantageous information on the factors that promote the establishment of successful oyster reefs; this knowledge is imperative in order to restore oyster populations in the Chesapeake Bay watershed to promote a healthier, more productive estuary (CBP, 2009).

The St. Mary's River Watershed Association (SMRWA) received a grant from the Maryland Department of Natural Resources (MDNR) to raise oyster spat on docks throughout the tidal St. Mary's River and one out-group location. These oysters will be used to establish an oyster reef in the St. Mary's River. We propose to measure the growth rate of *C. virginica* at six MDNR sites (Fig. 1), one site being on St. Jerome's Creek in St. Mary's County, Maryland. The six sites include St. George's Creek, Carthagena Creek, and St. Inigoes in addition to two sites on the main body of the St. Mary's River at the St. Mary's College of Maryland dock and a location in the Upper St. Mary's River. The out group site, St. Jerome's Creek, is outside of the St. Mary's Watershed. Our experiment will provide data on the turbidity conditions throughout the watershed and identify areas most suitable for young oysters. The data may then be used to aid in the selection of the bar placement as well as in future oyster growth or restoration efforts. From the current scientific understanding of how sedimentation accretion affects the growth of juvenile oysters, we hypothesize that *C. virginica* will have the highest growth rate at the study site with least amount of sediment accretion. Conversely, the site with the most sedimentation will have the smallest growth rate over the period of the study.

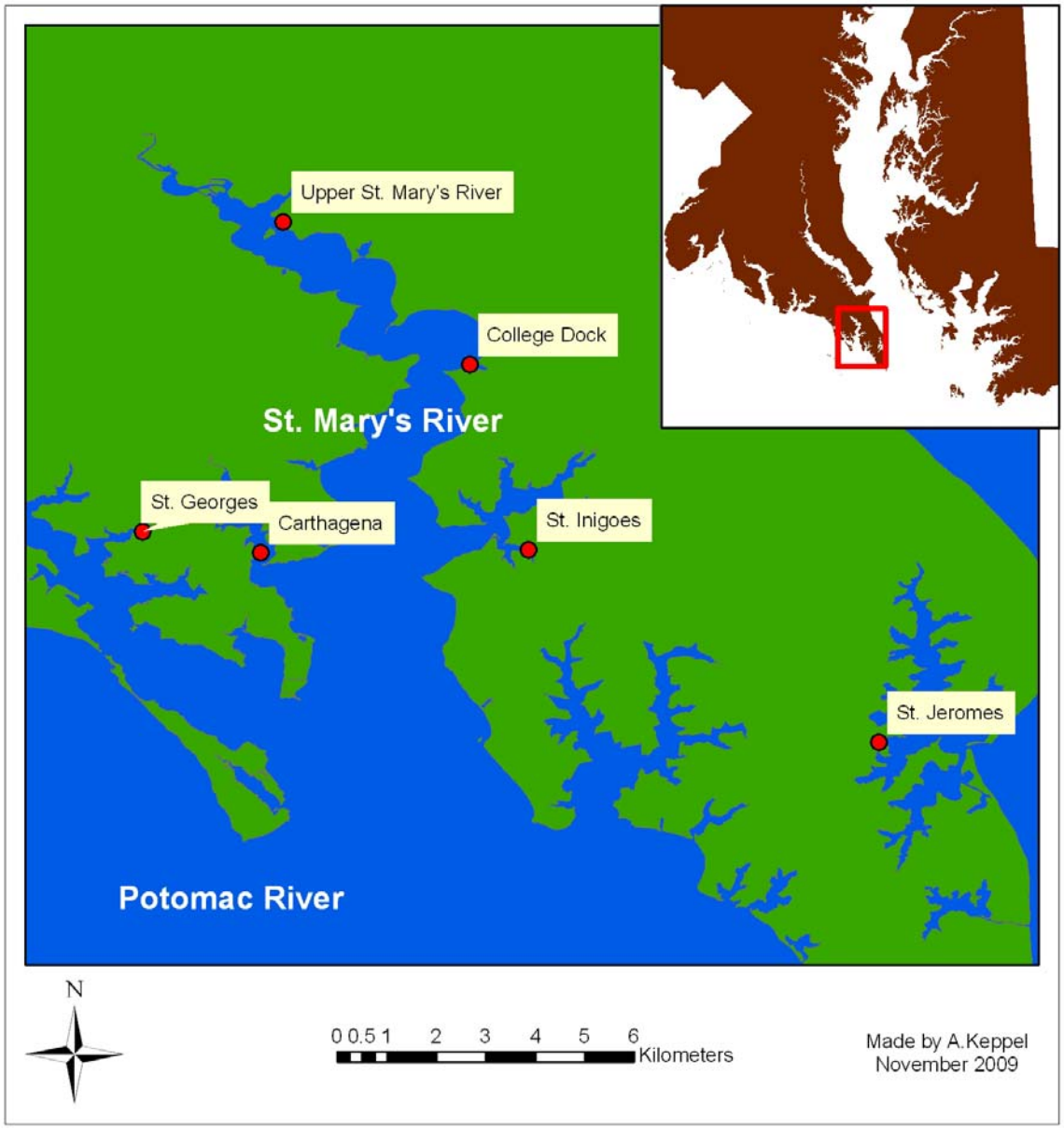

Figure 1. Study sites on the tidal St. Mary's River, St. Mary's County, Maryland, and one out group on St. Jeromes Creek.

Methods:

Study Sites:

We examined the growth rate of *C. virginica* at five sites on the St. Mary's River and one site on St. Jerome's Creek (Fig. 1), a tributary of the Chesapeake Bay east of the St. Mary's River watershed, for a six-week period starting in October 2009. The five

study locations in the St. Mary's watershed were located on St. George's Creek (38.158798° N, 76.492599° W), Carthagena Creek (38.154999° N, 76.47110° W), St. Inigoe's Creek (38.155602° N, 76.422401° W), at the St. Mary's College of Maryland dock (38.189201° N, 76.433098° W), and a site on the Upper St. Mary's River (38.215302° N, 76.467003° W) (Fig. 1). The sixth, out-group, site was located on St. Jerome's Creek (38.120499° N, 76.358597° W). This last site was selected due to anecdotal evidence that it had particularly high turbidity and might provide a higher rate of sedimentation than might be seen at any of the sites on the St. Mary's River (Tanner, personal communication).

Study Protocol:

Spat placed on empty oyster shell in 20x46x30 cm cages were suspended from docks around the St. Mary's River watershed by SMRWA in September 2009. In the second week of October, we assumed responsibility for four cages of oysters tethered approximately 0.5 meters below mean low water at each of our six study sites.

At week 0, we randomly selected four cages at each location and removed a random subset of shell with 15 oyster spat from each cage as a sample population. We took initial measurements of each spat from hinge to lip using metric (0.1 mm) calipers (Manostat Co., New York, New York, USA), and placed these select shells in five-millimeter mesh bags to ensure a consistent, identifiable study population for the duration of the experiment. We placed the mesh bags back in the original cages from whence the shell had come, and mixed the cages vigorously at the water surface to remove preexisting sediments.

At week 0, and every second week for six weeks, we measured total suspended solids (TSS), Secchi disk depth (cm), salinity (ppt), temperature, and dissolved oxygen (DO) at each site. We measured TSS (mg/L) according to the procedures in Standard Methods for the Examination of Water and Wastewater 20th Edition (Franson, 1998) using a Nalgene filtration system (Nalgene, Rochester, New York, USA) and Whatman GF/F 0.7 μm glass fiber filters (Whatman, Maidstone, UK). Salinity (ppt), temperature (°C), and DO (mg/L) were measured using an YSI Model 85 Handheld Dissolved Oxygen and Conductivity Meter (Yellow Springs Instruments, Yellow Springs, Ohio, USA).

At week 0 we attached sediment traps similar to those described in Lenihan and Peterson (1998), 12.7 cm high and 10cm in diameter, having a basal area of 0.00785 square meters, to the outside of each sample cage (Fig. 2). Every two weeks, we collected the traps and measured the dry weight of the sediment deposited during the previous two weeks (Franson, 1998; KC Denmark, 2009). Water and sediment which we collected from the traps was filtered onto dried, preweighed (nearest 10 mg) 19.0 cm Fisherbrand Qualitative P5 filter paper (Thermo Fisher Scientific Inc., Pittsburgh, Pennsylvania, USA) using a 19.0 cm Buchner funnel (CoorsTek, Inc., Golden, Colorado, USA). This process removed most of the liquid from the trapped sediment. We then dried the filters at 100°C for a period of at least 24 hours before taking a post-weight (also to the nearest 10 mg) to determine total dry sediment deposited in the trap. At the end of the six-week study period we pulled the oyster cages and measured the length of the study oyster spat in the same manner as in week 0, and recorded any observed mortality with the study oyster.

Each time we collected the sediment traps, we also rinsed and mixed the cages thoroughly by agitating them at the water surface as was requested by MDNR and SMRWA. While this removed previously accumulated sediments from the spat, and effectively restarted the sedimentation process, it was believed by MDNR and SMRWA to be necessary to keep the young oysters alive and therefore mandatory since the study oysters were part of a larger project that would have been detrimentally impacted by their death.

Statistics:

We converted total oyster growth and total sedimentation from each cage into oyster growth rate (mm/day) and sedimentation rate (g/day/0.00785m) by dividing the initial values by the total length of study time at each site. To meet the assumptions of normality and homogeneity for oyster growth rate, we transformed the data with an arcsine square root transformation, and performed a natural log transformation on sediment accretion rate to obtain normality. We were then able to run ANOVA's on total oyster growth, sediment accretion, and mortality across sites using SYSTAT 10.0 (Cranes Software International Ltd., Karnatka, India). We ran Scheffe post-hoc tests on each of these variables to determine significance between specific sites. Finally, we ran a Pearson correlation to determine if a relationship exists between the rate of sediment accretion and the oyster growth rate.

Figure 2. *Crassostrea virginica* cage provided by SMRWA & MDNR with attached PVC sediment trap.

Results:

The growth rates of *C. virginica* and sedimentation rates were statistically significant among the sites (ANOVA's, $P < 0.05$) (Fig. 3); no correlation existed between these two variables, however (Pearson Correlation, $p=0.484$). The Upper St. Mary's River site had a growth rate of 0.201 mm/day, significantly the highest according to an Scheffe post-hoc test. St. Georges and St. Inigoes had significantly lower growth rates, and the other three sites showed intermediate rates of growth that were not significantly different from either extreme.

The St. Jeromes site had the highest rate of sedimentation at 0.195 g/day over the area of the 78.5 square centimeter sediment trap, followed by St. Georges, Upper St.

Mary's River, Carthagena, College Dock, and finally St. Inigoes, with the lowest sedimentation rate at just 0.008 g/day. Sedimentation at St. Jeromes is significantly greatest according to another Scheffe post-hoc test, and St. Inigoes, College Dock, and Carthagena are significantly lower, but the Upper St. Mary's River and St. Georges sites are intermediate and not significantly different from the rest.

There was no significance in mortality (Fig. 4) among the six sites (ANOVA P=0.631); however, the Upper St. Mary's River site had the highest number of mortalities with an average of two deaths in thirty oysters, followed by St. Jeromes and St. Inigoes, which had the greatest and least rates of sedimentation respectively, and then by the College Dock and St. Georges, and finally by Carthagena with a mean of just one death out of sixty.

While statistics could not be run on the environmental data due to the lack of replicates, no differences were apparent in temperature, salinity, or TSS between any of the sites. Secchi disk depth and DO did appear to have consistent trends within sites and differences between sites. St. Inigoes in particular had consistently less turbidity (deeper Secchi disk depth) than other sites, while St. Jeromes had consistently higher turbidity (shallower Secchi disk depth) than other sites (Fig. 5). Less obvious trends existed in the dissolved oxygen data; however, St. Georges had consistently lower DO than the other sites.

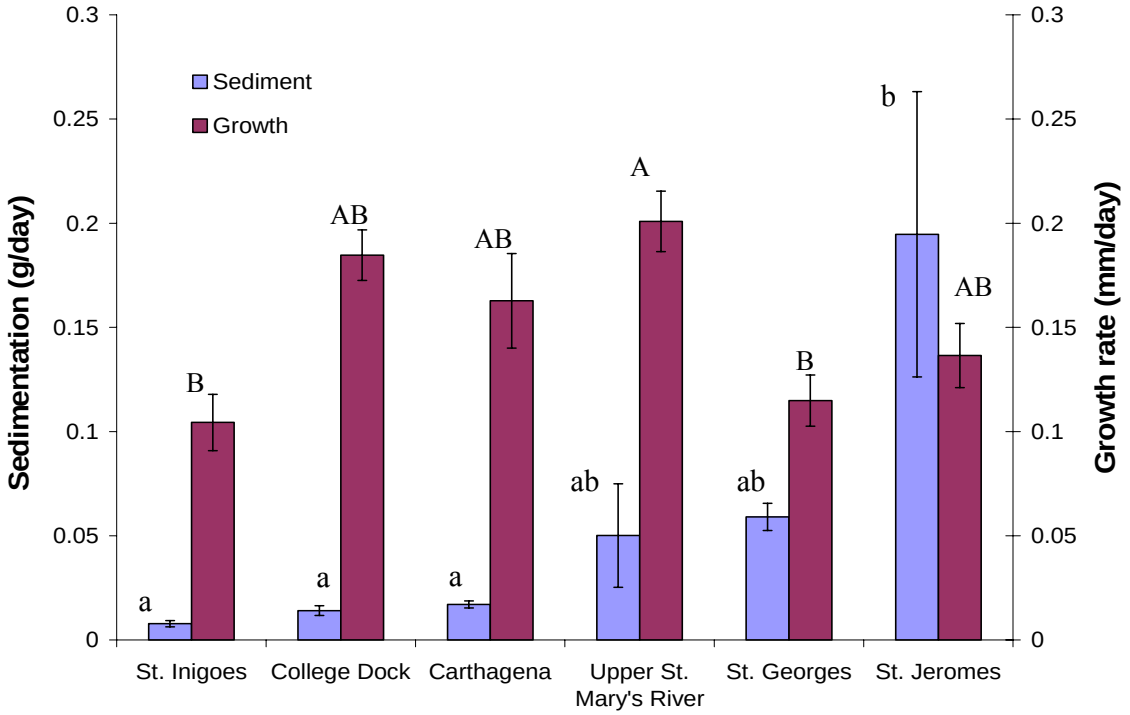

Figure 3. Mean spat growth +/-1 SEM and mean sedimentation rate +/-1 SEM, at six study sites in St. Mary's County, MD measured over a six week period (October - November, 2009) (n=4; ANOVA P < 0.05).

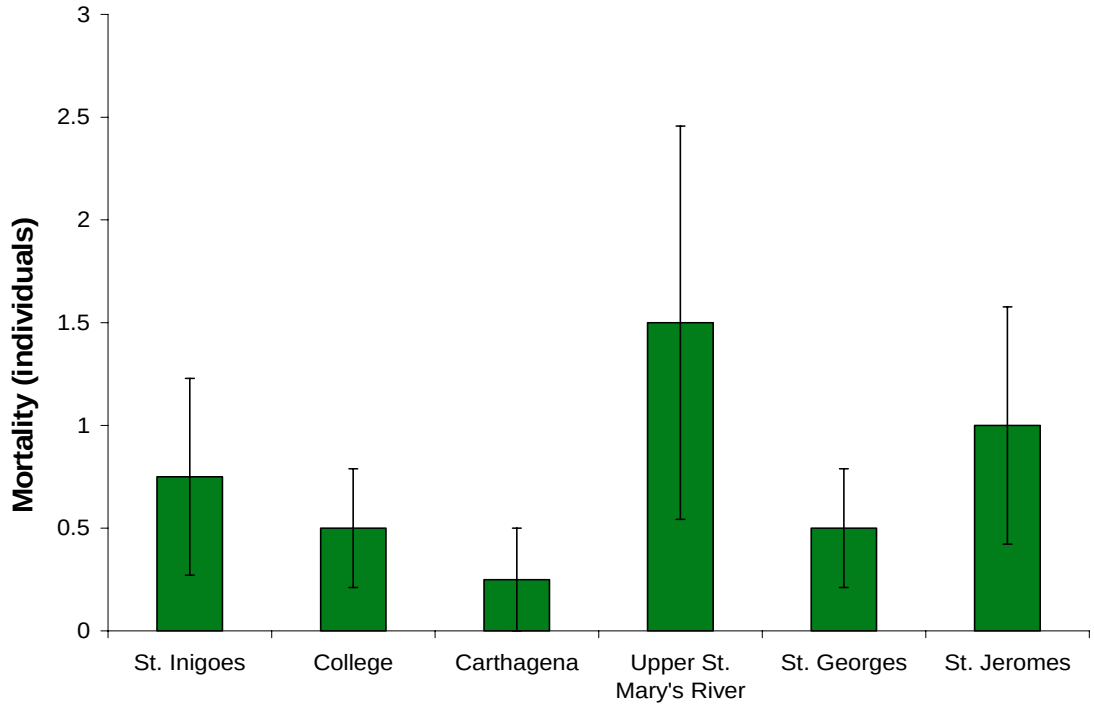

Figure 4. Mean spat mortality +/-1 SEM at six study sites in St. Mary's County, MD (n=4; ANOVA P=0.631).

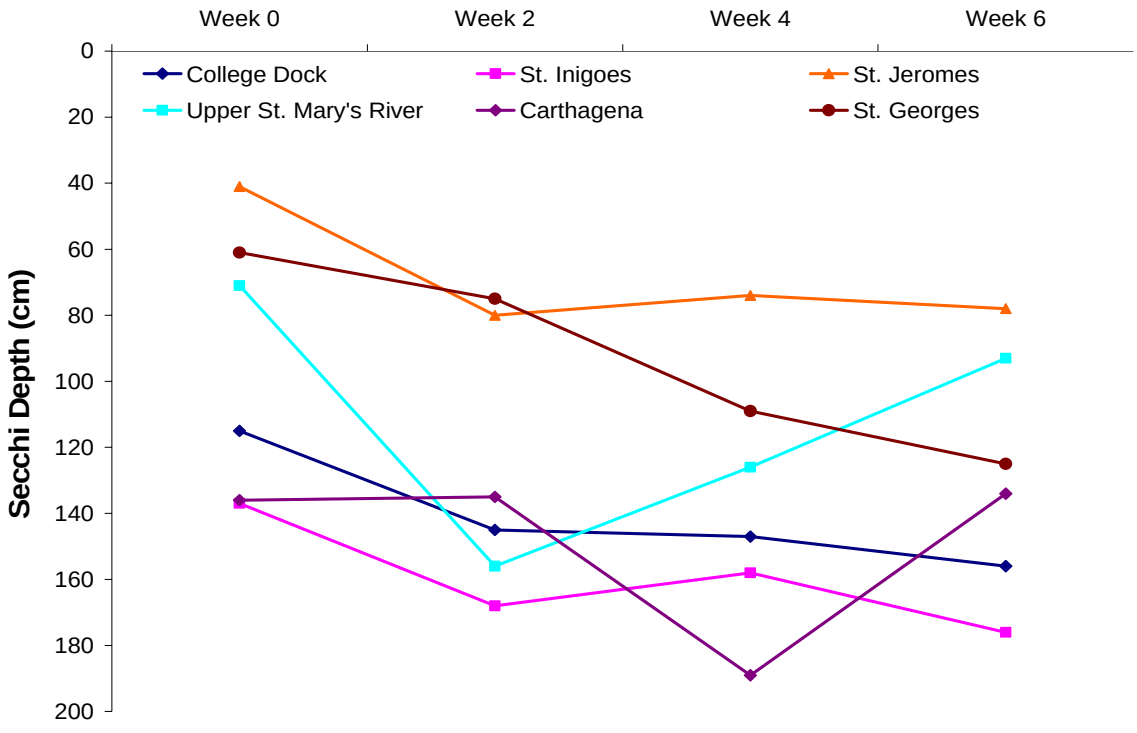

Figure 5. Secchi disk depth measured at the six study sites biweekly over the course of six weeks, October - November 2009.

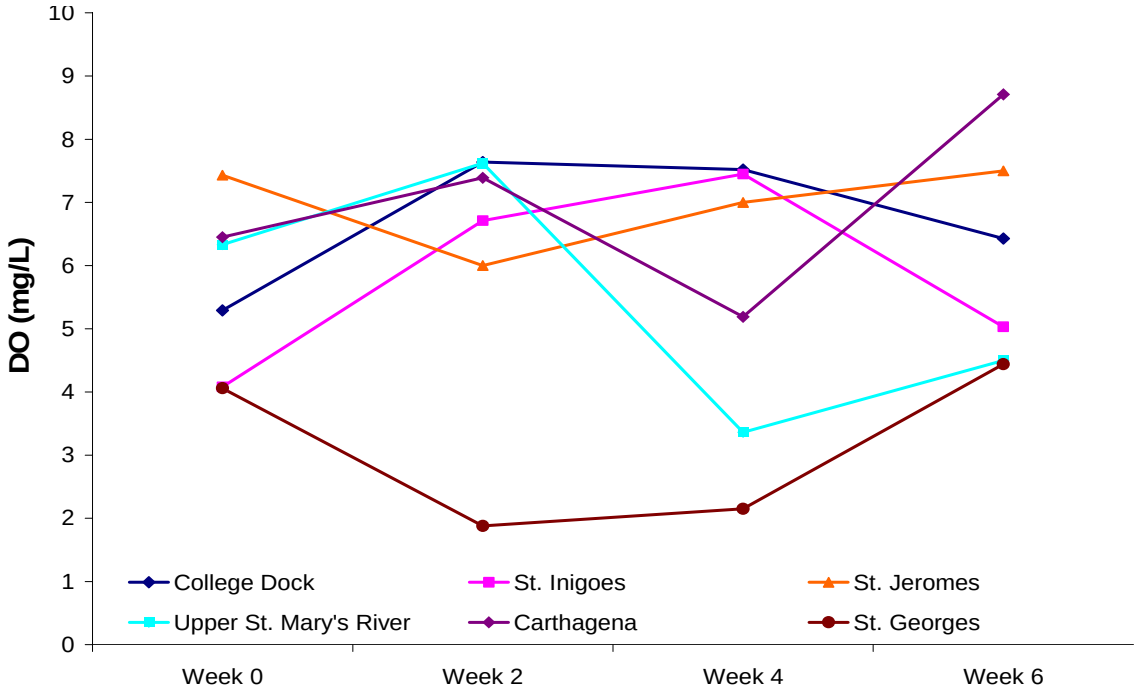

Figure 6. Dissolved oxygen levels measured at the six study sites biweekly over the course of six weeks, October - November 2009.

Discussion:

We found that no significant correlation between sedimentation rate and the growth rate of *C. virginica* existed. However, our data suggest that higher sedimentation rates do adversely affect the rate of growth for *C. virginica* as seen from both the sites of St. Georges and St. Jeromes. The site with the lowest sedimentation rate, St. Inigoes, also had a comparable growth rate to St. Georges. Although we found no correlation between sedimentation and *C. virginica* growth rate, the data suggest intermediate rates of sedimentation and the possibility of a combination of water quality factors yield the highest growth rates. Some sediment is likely necessary for spat growth but excessive levels may inhibit growth. This trend is contrary to our hypothesis that sediment and growth rate were inversely correlated.

Sediment loads have been shown to carry nutrients (Crain, 2001; Rasmussen et al., 2008) that stimulate the growth of phytoplankton, on which *C. virginica* feed (Fritz et al., 1984; Wikfors et al., 1984). Coco et al. (2006) observed extremely low levels of sedimentation eliminating growth in the pinnid bivalve *Atrina zelandica* in much the same way as high rates of sedimentation, possibly due to nutrient levels associated with the sediments. It is possible that allochthonous nutrients are not entering St. Inigoes Creek in enough quantity to support a phytoplankton population viable enough to support juvenile oysters at this site.

Mortality data do not seem to correspond with sediment rates or growth rates. It seems probable that, due to its proximity to the tidal headwaters of the St. Mary's River, the Upper St. Mary's River site would have the greatest fluctuations in salinity. Juvenile *C. virginica* are much more susceptible to stress than adults (Widdows et al., 1989).

During the study period, there were 4 significant peaks in discharge measured at USGS Gaging Station 01661500 St Mary's River at Great Mills, Md (USGS, unpublished data, http://waterdata.usgs.gov/md/nwis/rt). While our sampling period was too broad to measure any resultant fluctuation in salinity, these fluctuations may have stressed the juvenile oysters and lead to the increased mortality seen at this site. This mortality may also have been due to competition between the growing oysters, as their rapid growth rate brought them in to closer contact with each other, as has been seen in other bivalve species (Coco, et al., 2006). The fact that mortality was decreased at the other sites with intermediate rates of growth may indicate that mortality is a factor both of the same variable or variables affecting growth rate, and of intraspecific competition.

The highest growth rate and the highest mortality are seen at a site with a statistically intermediate rate of sedimentation (Upper St. Mary's River), no clear trend is seen in the rates of growth, and the next two greatest rates of growth occur at the two sites on the lower end of intermediate sedimentation rates (College Dock and Carthagena). This would indicate that rate of sedimentation may not be the only factor affecting growth rate, and that another factor, or a combination of other factors, also affect the rate of growth in *Crassostrea virginica*.

The St. Mary's River is a fairly homogenous body of water, so salinity and temperature did not vary noticeably between sites, but DO and Secchi depth did have obvious differences between sites. St. Georges was seen to have a DO considered hypoxic by MDNR (MDNR, 2009; Thomas, 2009) on one occasion during the study period. Baker and Mann (1992) found that spat in hypoxic conditions (less than 1.5 mg/l DO) showed decreased growth when compared to spat in normoxic conditions, and spat

in anoxic conditions (less than 0.7 mg/l DO) showed no growth and an increased mortality. While we never recorded DO at St. Georges as hypoxic under this definition of hypoxia, the lower oxygen levels in combination with the elevated rate of sedimentation may explain the decreased growth rate at this site.

St. Jeromes and St. Georges appear to be the most turbid of the study sites (shallowest Secchi disk depths). This matches the higher rates of sediment accretion at these two sites, indicating that turbidity may reasonably be correlated to sedimentation. The higher turbidity at these sites probably caused the oysters to cease feeding, impeding growth. St. Inigoes, Carthagena, and the College Dock sites all had relatively deep Secchi depths, corresponding to the lower rates of sedimentation at these sites. It seems from this data that sedimentation and turbidity are very closely associated. It seems probable that both factors contribute to impeding oyster growth, but it is difficult to say which has the greater affect on oyster growth.

A major confounding factor in this study is the season in which we carried out the research. The growth rates in this experiment may not truthfully indicate the actual growth rate of *C. virginica* at theses sites on a yearly bases because we only examined the growth over a six week period. Furthermore, growth rates are greater in spring and summer because there are elevated levels of food supply and high water temperatures resulting in a metabolic increase (Eastern Oyster Biological Review Team, 2007). As the water temperature cools in the fall the metabolic rate of *C. virginica* can reduce up to 75%, reducing growth rate (Stickle et al., 1989). Since this study was completed during the fall, the metabolic rate of *C. virginica* could have already slowed for the year. This would not reflect genuine yearly growth rates.

Other factors that were not measured in this experiment may also play a role in affecting oyster growth rates. It seems probable that nutrient levels, which were not accounted for in this experiment, may play a role in limiting growth as discussed at the St. Inigoes site. It is also possible that excess nutrients tied to higher levels of sedimentation might limit growth. We also observed differences in the nature of the sediments at each site, but failed to quantify these observations. The nature of the sediments at varying sites may also affect oyster feeding and resultant growth. Sediments at the St. Jeromes and St. Georges sites both appeared to consist of very fine silt, while sediment at the Upper St. Mary's River and College Dock sites appeared much loamier, and the Carthagena, and St. Inigoes sites appeared to contain more detritic material. It is possible that the finer material at the St. Jeromes, St. Georges, Carthagena, and St. Inigoes sites was more stressful to the growing oysters and caused them to cease feeding at lower rates of sedimentation, limiting growth at these sites.

In future we would like to examine the effect of sedimentation rate under more controlled conditions. This study will confirm whether or not the rate of sedimentation truly affects growth rate. We might also examine the effect of different types of sediments on the growth rate, to test the conclusions based on observation that finer sediment is more detrimental to oyster viability. It would also prove beneficial to examine the other variables measured in this experiment under more controlled conditions to determine the most important factors affecting *C. virginica* growth. Ultimately, a study examining more sites on the St. Mary's River would also be ideal, to determine a more specific ideal location for establishing a new oyster bar, as well as to

gain more data on actual environmental conditions suitable for *C. virginica* growth and establishment.

Conclusion:

Based on this work, we would recommend attempts to establish *C. virginica* in the St. Mary's River be focused in the upper portion of the river. This area has recently been proposed as a sanctuary by the MDNR, and we hope that the product of the "Marylanders Grow Oysters" program along the St. Mary's River will be placed in this area. A protected oyster bar in this area will support the *C. virginica* population of the entire river as veligers from the preserved reefs replenish the fished reefs in the lower river, making this an ideal place for establishment.

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