# THE RELATIONSHIP BETWEEN THE RIBBED MUSSEL (GEUKENSIA demissa)

# AND SALT MARSH SHORELINE EROSION

By

# JOSHUA ANDREW MOODY

A thesis submitted to the

Graduate School- New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate Program in Ecology, Evolution and Natural Resources

written under the direction of

Dr. David Bushek

and approved by

New Brunswick, New Jersey

May, 2012

#### ABSTRACT OF THE THESIS

The relationship between the ribbed mussel (Geukensia demissa) and salt marsh shoreline

erosion

by

#### JOSHUA ANDREW MOODY

Thesis Director:

#### Dr. David Bushek

Marsh erosion is a major concern for estuaries as various factors threaten shorelines. The ribbed mussel *Geukensia demissa* is a prominent component of the Delaware Bay estuarine ecosystem. A synergistic relationship exists between the ribbed mussel and the salt marsh cordgrass *Spartina* alterniflora in which the deposition of nutrient rich feces from the mussels enhances *S. alterniflora* production, helping to create natural levees along the marsh edge. These levees and marsh vegetation trap sediments enhancing vertical accretion. From this synergistic relationship, it is hypothesized that, *within certain energy regimes, salt marsh shoreline erosion decreases as mussel density increases*.

To test the hypothesis, mussel and plant demographics, mass transfer rates (energy), nutrient concentrations and annual lateral shoreline movement were quantified at three sites within four tributaries of the Delaware Estuary (n = 12 sites). In order to avoid spurious correlations due to the large number of potential interactions, Bayesian factorial and hierarchical modeling techniques were employed to identify potential relationships that occur between the variables within and among study sites. Results indicated that while the presence of mussels and the mass transfer rate of the adjacent

ii

water body influence the degree of erosion or accretion measured at the study sites, the river, and the location of the site within it, plays a major role in determining the degree to which these factors have an effect.

#### Acknowledgements

I would like to thank Drs. David Bushek, Edwin Green and Rick Lathrop at Rutgers University, Dr. Danielle Kreeger at The Partnership for the Delaware Estuary and Dr. Bob Scarborough and Mike Mensinger at the St Jones Delaware National Estuarine Research Reserve. All provided invaluable advice and assistance. The National Estuarine Research Reserve System, the National Shellfisheries Association and the Society of Wetland Scientists provided financial support for this research. Both the Atlantic Estuarine Research Society and the Partnership for the Delaware Estuary provided travel assistance to regional and national scientific meetings where valuable input was obtained as this research progressed. Finally staff at both The Partnership for the Delaware Estuary and the Haskin Shellfish Research Laboratory of Rutgers University provided valuable and necessary assistance in the field and laboratory.

A special acknowledgement is extended to the memory of Dr. Joan G. Ehrenfeld, whose guidance, support and inspiration helped to shape this research.

This thesis is dedicated to the memories of Stephen John and Sophie Joan Polacek, Laura Catherine Bruska, and Elizabeth Theresa Moody. All of whom believed in the value of education and the potential inside of me. You are all missed.

Table of Contents	Page
Abstract	ii
Acknowledgements	iv
Table of Contents	v
List of Tables	vi
List of Figures	vii
Introduction	1
Material and Methods	6
Statistical Analysis	11
Results	14
Discussion	19
Conclusion	27
Bibliography	30

List of 1	Tables Transect Level Data Collected	Page 33
2	Site Level Data Collected	34
3	Bayesian Factorial Model Beta Values	37
4	Pair-Wise Difference Between Sites for Change in Transect Length	38
5	Pair-Wise Difference Totals and Percentages	39
6	One-way Analysis of Variance (ANOVA) Results	40

List of Figures		Page
1	River Locations	41
2	Hierarchical Study Design	42
3	Study Site Locations in the Maurice River	43
4	Study Site Locations in Dividing Creek	44
5	Study Site Locations in Oranoaken Creek	45
6	Study Site Locations in the St. Jones River	46
7	Study Site Schematic	47
8	Plaster-of-Paris Hemispheres	48
9	Design Matrix	49
10	Bayesian Factorial Model	50
11	Final Transect Length By River	51
12	Final Transect Length By Site	52
13	Percent Mussel Cover By River	53
14	Percent Mussel Cover By Site	54
15	Percent Spartina alterniflora Cover By River	55
16	Percent Spartina alterniflora Cover By Site	56
17	Mussel Density By River	57
18	Mussel Density By Site	58
19	Mussel Biomass By River	59
20	Mussel Biomass By Site	60
21	Below Ground Biomass By River	61
22	Below Ground Biomass By Site	62
23	Mass Transfer Rate By River	63

24	Mass Transfer Rate BY Site	64
25	Kjeldahl (Total) Nitron By River	65
26	Kjeldahl (Total) Nitrogen By Site	66
27	Inorganic Nitrogen By River	67
28	Inorganic Nitrogen By Site	68
29	Phosphorous By River	69
30	Phosphorous By Site	70
31	River*Mass Transfer Rate Interaction	71
32	Site*Mass Transfer Rate Interaction	72
33	River*Percent Mussel Cover Interaction	73
34	Site*Percent Mussel Cover Interaction	74
35	Mass Transfer Rate*Percent Mussel Cover Interaction	75

### Introduction

*Geukensia demissa*, the ribbed mussel, is a prominent component of estuarine ecosystems where it is typically associated with the marsh grass *Spartina alterniflora*, often in close association with the lower edge of marshlands (Kuenzler 1961, Bertness 1984). Like many bivalve mollusks, *G. demissa* provides important ecological functions such as increasing habitat complexity (Newell 2004), nutrient cycling (Kuenzler 1961), and water column filtration (Jordan and Valiela 1982). Beds of *G. demissa* have been observed with populations as large as 2000-3000/m<sup>-2</sup> in New York and southern New England (Franz 2001), and the mussels are often associated with fringing intertidal oyster reefs in South Carolina (Luckenbach *et al.* 2005).

While studies indicate that fringing oyster reefs can act as protective buffers to coastal marshes that reduce erosion by absorbing wave energy and trapping sediments (Meyer *et al.* 1997, Piazza *et al.* 2005), information concerning the potentially similar relationship between *G. demissa* and coastal erosion is lacking. The aim of this study was to determine whether or not a relationship exists between populations of *G. demissa* and shoreline erosion, and if so, under what conditions does *G. demissa* provide salt marsh shoreline fortification.

In addition to shoreline stabilization, "soft armor" barriers of dense intertidal shellfish aggregations provide ecological benefits that "hard armoring", like bulkheads and dikes prevent, and that non-natural porous structures like revetments and rip-rap cannot provide. But unlike oysters whose intertidal fringing reefs are seen only as far north as Virginia, *G. demissa* grows intertidally from Florida to Newfoundland, Canada, and extensive intertidal populations are a common feature in the Delaware Estuary. Also unlike oysters, *G. demissa* is not a commercially viable species, which virtually eliminates human health concerns related to shellfish gardening activities in waters closed to shellfish harvesting – a major impediment to shellfish restoration in New Jersey and several other states.

Marsh erosion is a major concern for estuaries as increasing storm severity, boat wakes, and sea-level rise threaten shorelines. For example, high rates of erosion in the mouth of the Maurice River, a tributary of Delaware Bay, have led to the disappearance of an entire meander and threaten nearby towns. High rates of erosion have also been documented in existing fringe marshes along the western edges of the coastal bays of Delaware, including lateral inland erosion of up to one half meter per year in Rehoboth Bay, DE (Schwimmer 2001).

A 5 to 20 percent wetland loss has been estimated by 2080 along U.S. coasts due to sea-level rise (Nicholls *et al.* 1999, Nicholls 2004) if important processes such as marsh accretion cannot keep pace with increasing sea levels. According to The Partnership for the Delaware Estuary's 2010 Climate Report, a minimum of 26% loss of tidal wetlands is expected in the Delaware Estuary, and the State of Delaware is planning for losses in excess of 90% by the turn of the century. It has been shown that plant canopies can provide the drag required to trap suspended sediments that are ultimately incorporated into the rhizome matrices of marsh plants increasing their resistance to erosion (McCaffery and Thomson 1980, Bricker-Urso *et al.* 1989, Friedrich and Perry 2001). As sea level rises, healthy, dense marsh vegetation may therefore augment vertical accretion by trapping more sediments than would sparse vegetation, helping the

marsh grow vertically at a rate equal to, or above, the rising water (Leonard and Luther 1995, Nepf 1999).

As mentioned above, ribbed mussels are known to act synergistically with the salt marsh cord grass *Spartina alterniflora*, facilitating the development of natural levees along marsh edges and enhancing ecological productivity through the deposition of pseudofeces and (often nutrient rich) feces (Bertness 1984). While the *S. alterniflora* root mass is commonly recognized as a stabilizing force and a wealth of data has been collected concerning *G. demissa's* productivity (Bertness 1984), resource allocation (Franz 1997 and 2001), and role in ecological energy cycling (Jordan *et al.* 1982, Kreeger *et al.* 1996, Kuenzler 1961), relatively little attention has been paid to the physical integrity formed by the synergistic ribbed mussel-*Spartina* assemblage, particularly when the mussels exist in dense aggregations.

Initial observations of intertidal shorelines along sections of the Delaware Estuary, seemed to show higher degrees of shoreline erosion in areas where *G. demissa* is largely absent. I hypothesized that, **within certain energy regimes, there was an inverse relationship between coastal erosion and mussel density**; similar to the results shown in Meyer *et al*, 1997 and Piazza *et al*, 2005 concerning the relationship between fringing intertidal oyster reefs and coastal erosion. It was unclear however, whether the presence of *G. demissa* was having an effect on the erosion. Perhaps dense populations of *G. demissa* were simply found in areas where the marsh had been stable enough to allow recruitment over a long period of time. These areas could include long continuous stretches of saltmarsh in low energetic areas or smaller stretches of saltmarsh in higher energetic areas where the morphology of marsh edge creates micro-refuges from erosion. If certain densities of mussels do provide this protective ecological service under specific energetic conditions, they may not be acting in isolation. Since ribbed mussels are predominately found attached to the root mass of *S. alternaflora* (Bertness, 1984), the availability of roots for attachment may influence mussel densities and thereby influence the ability of ribbed mussels to provide shoreline protection. Moreover, since the allocation of plant growth above ground and below ground is affected by nutrient availability delivered either by tides, storm surges or bio-deposited by organisms (Redfield 1972; Turner *et al.* 2000; Turner *et al.* 2006; Bertness 1984), nutrient concentration along the marsh edge and in sediments may also play a role.

Since salt marsh plant growth is limited by nitrogen (Cargill and Jefferies 1984) and erosion of the organic surface layer reduces its overall availability (Wilson and Jeffereies 1996, McLaren and Jefferies 2004), the presence of ribbed mussels may help to increase nutrient availability in areas suffering from high rates of marsh surface erosion through feces and pseudofeces deposition. However, increases in nutrient availability result in the allocation of resources to aboveground biomass production at the expense of belowground biomass production (Valiela 1976; Morris 1982) potentially reducing the rhizome availability for ribbed mussel attachment in areas where the nutrient availability is very high. In order to evaluate the potentially complex relationship between mussel density and salt marsh erosion under specific energetic conditions, the role of vegetation and nutrients must therefore also be evaluated.

In this study, I focused on mussel-erosion relationships within four different tributaries of Delaware Bay in which I also characterized belowground plant biomass, nutrient concentrations and energetic conditions. My ultimate goal was to determine the potential role of enhancing *G. demissa* populations as a viable component of strategies for living shoreline fortification to help reduce salt marsh shoreline erosion.

#### **Materials and Methods**

Twelve study sites were chosen across four rivers within the Delaware Estuary: the Maurice River, St. Jones River, Dividing Creek and Oranoaken Creek (Figure 1). Each river contained three 150 meter study sites which in turn, contained 31 one-meter transects at five meter intervals (Figure 2). Study sites were selected that varied in mussel density and appeared to vary in erosion across the site. Data were collected on mussel density, energy regime, percent mussel cover, percent *Spartina alterniflora* cover, below ground *Spartina alterniflora* biomass, mussel biomass, and nutrient profiles at each site. The lateral shoreline movements of the marsh edge at each site were monitored over the course of one year. The goal of the study was to determine if any of these variables, or interactions among them, influence salt marsh shoreline erosion or accretion.

**River Selection.** Rivers were selected for use based on two criteria: ease of access and presence of mussels. Each river chosen had to have sufficient water depth to insure access to and movement among sites at low tide using a vessel in order to maximize the time available to work at each site. It was also desirable that study areas be located near a boat launch to minimize fuel consumption and travel time, thereby maximizing sampling time and ensuring access in most weather conditions. In addition, rivers were included in the study only if they contained a reasonably contiguous mussel population, extending from the mouth of the river, upstream beyond the second meander. Selected rivers were assigned numeric values for analysis as follows: Dividing Creek = 1, Maurice River = 2, Oranoaken Creek = 3, and St. Jones River = 4.

**Study Site Selection.** Three study sites were chosen within each river to span an apparent gradient of energy based on field observations, fetch and boat traffic (Figures 3,

4, 5 and 6). In general, site 1 was located near the river mouth of the river and was open to the fetch of the Delaware Bay, site 2 was protected by the first meander, and site 3 was located one as far upriver as ribbed mussels were present. Each study sites was 150 m in length -- delimited by rolling a measuring wheel along the marsh edge in order to incorporate marsh edge morphology into the total length measurement of each site. The marsh edge was defined as the point at which the marsh surface ended and beyond which there was a vertical drop or steep slope to the foreshore of the intertidal zone. In the few instances where the slope was more gradual (small reach segments of a study area), the marsh edge was defined as the contiguous grass-line from the elevated marsh surface, down along the mudflat, and returning to the elevated marsh surface.

**Transect Demarcation.** Every 5 m (+/- 0.025) along the marsh edge of each 150 m site, perpendicular transects were established that extending from the edge of the marsh landward (n = 31 transects/site; Figure 7). A numbered survey flag was placed approximately 15 cm into the marsh from the marsh edge at each transect location. To demarcate each transect, a short post was placed vertically against the marsh edge and a meter stick was placed against the post to create a right angle perpendicular to the marsh edge such that it passed directly over the survey flag. A half meter section of PVC was inserted into the marsh at the end of the meter stick to mark the marshward end of each transect. Immediately after all transects were installed, each was re-measured to obtain an estimate of accuracy in measuring transect length.

**Data Collection.** Data were collected at the level of transect (Table 1) or at the level of site (Table 2).

**Percent mussel cover (PM) and percent** *Spartina alterniflora* **cover (PS)** were determined at each transect by placing a 625 cm<sup>2</sup> quadrat on the marsh edge and visually estimating percent cover.

Mussel density (MD), mussel biomass and below ground biomass of S. *alterniflora* (the dry weight of plant material below the surface of the marsh) were estimated at the site level from fifteen  $625 \text{ cm}^2$  quadrats excavated to a depth of 10 cm at ten locations along the 150 m site using a stratified random selection process that avoided transects and distributed one quadrat every 10 m. Both mussel density and below ground biomass were quantified using published methods (Bertness and Grosholz 1985). The samples were placed into plastic bags and returned to the laboratory where samples were individually washed through a 2 mm sieve to separate all plant and animal material from soil. All mussels larger than 2 mm were counted and measured to the nearest mm. The number of mussels per  $0.25 \text{ m}^2$  sample indicated the mussel density per sample. Mussel measurements were converted to biomass using regression equations provided by Dr. Danielle Kreeger, The Partnership for the Delaware Estuary via personal communication. The below ground *Spartina* biomass was quantified by placing the plant material in a  $60^{\circ}$ C oven and weighing it daily until no further decrease in weight due to evaporation of moisture was observed.

**Mass transfer rate (MTR)** was defined as the relative energy associated with water exposure and movement (waves and currents). MTR was determined by the dissolution rate of plaster-of-Paris hemispheres deployed at each transect. According to Porter *et al.* (2000), this methodology has been widely used as an inexpensive integral measure of 'water motion' in the field and laboratory" and although it "is not a universal integrator of 'water motion' it can be used as a good direct indicator of mass-transfer rates" if used in similar flow environments. The hemispheres were made and deployed according to a protocol adapted from Yokoyama et al. (2004). Hemispheres were made from a 2:1 ratio of water to plaster-of-Paris formed into hemispheres in silicone molds of  $\sim 2.5 \text{ x} 5 \text{ cm}$  with the head of a 3.18 cm wood screw embedded into each hemishere. Each batch was dried for more than 3 days, sanded to within 1.5 grams of each other, and weighed again after 1 hour of immersion in water before deployment. Each deployment consisted of 31 hemispheres attached to wooded dowels and inserted into the marsh 3 cm from the marsh surface at each transect in order to characterize the mass-transfer rate at the areas where the mussels were present (Figure 8A). Each deployment lasted 2 days. Upon retrieval, hemispheres were removed from dowels, rinsed in fresh water to remove salt and re-weighed for their final weight (Figure 8B). Four deployments occurred at each site over the course of the study: two during spring tides and two during neap tides. Hemispheres were deployed during low tide when the marsh edge was exposed. Due to limitations resulting from tides and travel time between rivers, deployment at sites within a river were contemporaneous whereas deployments between rivers were not. Water temperature and salinity were recorded during deployment and retrieval. Weight loss was then standardized to 20°C and 20 psu salinity using calibration equations presented in Jokiel and Morrissey (1993).

**Soil samples** were collected to investigate whether nutrient concentrations differed among study areas. At each site, five 10 cm deep core samples were taken at the marsh edge at even intervals along the length of the site. Cores were then combined into a single composite sample per site. A subsample of each composite was extracted and sent to Rutgers University Agricultural Soil Testing Laboratory for soil nutrient analysis. Analysis consisted of total available nitrogen (Kjedahl nitrogen), total inorganic nitrogen, and phosphorous.

**Final Transect Length (FTL)** was measured one year after the initial measurement and represents the response variable for comparison with other measurements. As when installed, each transect was measured twice in order to determine accuracy of the final measurements. Each transect had a beginning length of 100cm. Final transect lengths less than 100cm indicated erosion occurred over the course of one year and final transect lengths of greater than 100cm indicated that accretion had occurred over the course of one year.

**Statistical Analysis:** All data were initially evaluated by comparing each variable using analysis of variance (ANOVA) at the river and site level. The large number of variables and potential interactions made simple parametric analyses susceptible to spurious correlations. To minimize the likelihood of spurious correlations, two levels of Bayesian statistical analysis were employed in place of classical multiple regression analysis. First, a Bayesian Factorial Model was used to evaluate the association and potential influence of transect level variables listed in Table 1. Subsequently, a Bayesian Hierarchical Model was employed to assess whether there were differences or similarities among site level variables listed in Table 2.

The Bayesian Factorial Model assessed the influence of explanatory variables, or combinations of explanatory variables, on the response variable, final transect length. A factorial model was used since there were multiple potential influents. A hierarchical Bayesian approach to fit the factorial model was used because it naturally accommodated the structure of the data. For each transect, there was one value for each variable except for mass transfer rate, which had four observations per transect. In the Bayesian model, the response (change in transect length) was related to the mean mass transfer rate per transect. Unlike traditional two-stage regression procedures, the Bayesian approach naturally accommodated the error in estimating the mean mass transfer rate per transect. The models were fitted using the WinBUGS software package (Lunn et al. 2000).

The Bayesian factorial analysis occurred at the transect level where each observation of change in transect length had the corresponding explanatory variables river (river it is located in), site (site it is located in), percent mussel cover, percent *Spartina* cover, and mean mass transfer rate (see above). Since the explanatory variables

"river" and "site" contained categorical data, as opposed to the other explanatory variables that contained continuous data, a design matrix was created to differentiate between the data types (Figure 9). Using the matrix, WinBUGSs was able to evaluate interactions for each river and site independently with the continuous data of the other explanatory variables. A potential five-way factorial model (Figure 10) was fitted and the model's Deviance Information Criterion (DIC) used to assess model complexity (Spiegelhalter et al. 2002). The five-way interaction was then removed and the remaining four-way model tested and its DIC calculated. This process was repeated for three-way, two-way, and no interaction versions of the model. The resulting DICs were compared and the model with the smallest DIC was identified as optimal. Once an optimal model was identified, the potential range of the model coefficient values (Figure 10, beta values) for each metric and their interactions was determined at the 95% credible interval level. If the credible interval for a coefficient included zero, then it was concluded that zero was a reasonable value for that coefficient and the corresponding term was dropped from the model. The result of this analysis was a model that best explained all sets of observations (n=375) of effects of explanatory variables on the response variable, change in transect length.

A separate Bayesian analysis allowed investigation of whether sites located within rivers were similar or different for all measured variables. WinBUGS was used to generate posterior samples for each variable at each site. This process facilitated simultaneous examination of the differences in the mean of the variable between sites and rivers. Differences whose 95% credible intervals included 0 were judged to not be statistically significant: this does not mean that the sites were similar, only that there was not enough evidence to confidently discern a difference. A pair-wise analysis was completed for all possible combinations of sites within rivers (n=66) for each variable (n=9). If the analysis was able to confidently discern a difference (i.e., the credible interval did not include zero), then this difference was denoted as a pair-wise difference. From this analysis, all possible pairs of sites for each variable were compared in terms of differences between sites in rivers, complementary locations (same placement in river), and combinations of differences. Once the Bayesian analyses were complete, raw data were reexamined to interpret relationships between combinations of explanatory variables that were identified as relevant by the Bayesian Factorial Model.

#### Results

**Final Transect Length.** ANOVA results indicated that final transect lengths differed significantly between the rivers (p < 0.0001) and sites (p < 0.0004). A Tukey post-hoc multiple comparisons indicated that Dividing Creek and Oranoaken Creek experienced significantly less erosion than the St. Jones River and the Maurice River (Figure 11), and also indicated that site 3 (the upriver site) experienced significantly less erosion than site 1 at the mouth of river and site 2 located near the first meander (Figure 12).

**Percent Mussel Cover.** Percent mussel cover differed significantly between rivers (one-way ANOVA, p < 0.0001) and by site (one-way ANOVA, p < 0.0001). The Tukey post-hoc analysis indicated that percent mussel cover was significantly higher in Dividing Creek than all other rivers (Figure 13), but decreased in an upriver fashion (Figure 14).

**Percent** *Spartina alterniflora* **Cover.** Percent *Spartina alterniflora* differed significantly by river (one-way ANOVA, p < 0.0001) and by site (one-way ANOVA, p = 0.0001). Tukey's post-hoc multiple comparisons indicated that the Maurice river had significantly higher plant cover than both Dividing Creek and the St. Jones River, but was not significantly different than Oranoaken Creek (Figure 15). At the site level, site 2 had significantly higher *Spartina alterniflora* cover than both site 1 and 3, which were not significantly different (Figure 16).

**Mussel Density.** Mussel density differed significantly by river (one-way ANOVA, p < 0.003) and by site (one-way ANOVA, p < 0.0001). Tukey's pos-hoc multiple comparisons indicated that Dividing Creek differed significantly from all other

rivers, which did not differ from each other (Figure 17) and site 1 had significantly higher mussel density than sites 2 and 3 (Figure 18).

**Mussel Biomass.** Mussel biomass differed significantly by river (one-way ANOVA, p < 0.002) and by site (one-way ANOVA, p < 0.0001). Tukey's post-hoc multiple comparisons indicated that Dividing Creek differed significantly from all other rivers, which did not differ from each other (Figure 19) and site 1 had significantly higher mussel density than sites 2 and 3 (Figure 20).

**Below Ground Biomass.** Below ground biomass differed significantly by river (one-way ANOVA, p < 0.0003). Tukey's post-hoc multiple comparisons indicated that Dividing Creek and Oranoaken Creek did not differ significantly from each other and Maurice River and St. Jones River did not differ significantly from each other (Figure 21). Below ground biomass did not differ by site (one-way ANOVA, p = 0.6916; Figure 22).

**Mass Transfer Rate.** Mass Transfer Rate differed significantly at the river (p < .0001) and site (p < 0.0001) levels. Tukey's post-hoc multiple comparisons indicated that Dividing Creek and the Maurice River both differed significantly from Oranoaken Creek and the St. Jones River, but not from each other (Figure 23). Site 1 was found to be significantly different from sites 2 and 3, which were not significantly different from each other (Figure 24).

**Total (Kejdahl) Nitrogen.** Total Nitrogen did not differ significantly by river (p = 0.433, Figure 25) or by site (p = 0.6849, Figure 26).

**Inorganic Nitrogen.** Inorganic Nitrogen did not differ significantly by river (p = 0.1837, Figure 27) or by site (p = 0.7385, Figure 28).

**Phosphorous.** Phosphorouus did not differ significantly by river (p = 0.2496, Figure 29) or by site (p = 0.938, Figure 30).

**Bayesian Analysis.** The two-way interactive Bayesian Factorial Model received the lowest DIC score indicating that two-way interactions helped to explain the observed change in transect length at the transect level. Further analysis of the two-way interactive model resulted in the selection of variables that had a significant effect on final transect length. The final explanatory model was:

Final Transect Length =  $\beta_{3,4}$  (River 4\*Site2) +  $\beta_{3,6}$  (River 4 \* Mass Transfer Rate) +  $\beta_{3,7}$  (River 4 \* Percent Mussel Cover) +  $\beta_{4,7}$  (Site 2 \* Percent Mussel Cover) +  $\beta_{5,6}$  (Site 3 \* Mass Transfer Rate) +  $\beta_{6,7}$ (Mass Transfer Rate \* Percent Mussel Cover)

This result indicates that the interactive effects of river and site, river and mass transfer rate, river and percent mussel cover, site and percent mussel cover, site and mass transfer rate, and mass transfer rate and percent mussel cover were not the same across all rivers and sites or combinations of rivers, sites and metrics. More specifically, the credible intervals for the coefficients (beta values) of these interactions did not contain the value zero, and thus these metrics significantly influenced the change in transect length to some degree in this data set (Table 3, highlighted values). Simply put, no single explanatory variable can rationalize the differences measured in the response variable, final transect length, without taking into account the levels of all the other explanatory variables. These interactive effects are visualized in Figures 31-35.

The effect of mass transfer rate on final transect length differed by river (Figure 31) and by site (Figure 32), although similar interactive effects were observed in Dividing

and Oranoaken Creeks as well as in the Maurice and St. Jones Rivers. The effect of percent mussel cover on final transect length showed no discernible pattern by river (Figure 33), but final transect length tended to increase for a given percent mussel cover by site moving up river (Figure 34). Finally, the effect of mass transfer rate on final transect length was influenced by percent mussel cover (Figure 35). Specifically, the presence of mussels, even a small amount, reduced the effect of mass transfer rate substantially. Larger reductions were observed with increasing mussel presence, but the greatest reduction occurred with the presence of only a few mussels.

Results of the pair-wise comparisons for change in transect length from the Bayesian Hierarchical Model showed that Rivers fell out into two distinct groups (Table 4). Sites within Dividing Creek and Oranoaken Creek were not significantly different from each other, but differed from all sites in Maurice River and St. Jones River. Additional differences were detected among sites within the Maurice and St. Jones rivers. Specifically, St. Jones river sites 2 and 3 were different from each other, but did not differ from site 1, and there were detectable differences among all Maurice River sites (Table 4).

A comparison of discernable pair-wise differences revealed greater overlap among explanatory variables identified in the two-way factorial model when compared to non-explanatory variables (Table 5). For example, 70% of pair-wise differences among sites for change in transect length coincided with pair-wise differences in mass transfer rate. Upon further analysis, 77% of the sites that differed in final transect length and mass transfer rate were negatively correlated, indicating a reduction in final transect length (increase in erosion) as mass transfer rate increases. Similarly, 56% of pair-wise differences in change in transect length coincided with pair-wise differences in percent mussel cover and 79 % percent of these pair-wise differences showed a positive correlation. These observations indicate that these variables are not acting independently. In contrast, coincidental pair-wise differences observed between change in transect length with non-explanatory variables showed less overlap (e.g., percent *Spartina* cover showed a 47% overlap, kjeldahl nitrogen a 21% overlap, and mussel density a 9% overlap). No discernable coincidental pair-wise differences were detected between change in transect length and inorganic nitrogen, phosphorous, or below ground biomass (data not shown). Finally, pair-wise differences between sites for mass transfer rate and percent mussel cover showed 73% coincidence (that is, 37 of the 48 pair-wise comparisons that were different for mass transfer rate were also different for percent mussel cover).

### Discussion

Initial analysis of the raw data indicated that Dividing Creek and Oranoaken Creek are experiencing significantly less erosion than the St. Jones and Maurice rivers (Figure 11). This conclusion was supported by the Bayesian Hierarchical Model. All sites in Dividing Creek and Oranoaken Creek were different from all sites in the Maurice and St. Jones Rivers (Table 4), suggesting that they may share similarities that they do not share with the Maurice or the St. Jones Rivers. Since sites in the Maurice River not only differ all sites in Dividing Creek and Oranoaken, as well as few sites in the St. Jones, but also from all sites within itself, this river may be isolated in terms of commonalities at the river level. These results support the pattern found in the raw data (Figure 11) and indicate that Dividing Creek and Oranoaken Creek are similar and are different from the St. Jones and Maurice Rivers, which are also different from each other. Clearly, river is an important variable in influencing the degree to which other variables contribute to change in transect length and, according to the Bayesian Hierarchical Model, that position within a river can also have an effect on observed erosion patterns in some rivers.

A similar pattern was evident at the river level for below ground biomass in the raw data (Figure 19), but the factorial model did not identify below ground biomass as having a significant influence on final transect length at the river level (Table 3). Since no significant difference was found between measurements of below ground biomass at the site level (Figure 20) even though significantly less erosion occurred at site 3 compared to sites 1 and 2 (Figure 12), we can infer that below ground biomass may not have as great an impact at the site level as it does at the river level.

Comparisons of the percent mussel cover and mussel density raw data at the river and site level depict similar patterns (Figures 13, 14, 17 and 18). The differences measured for mussel density do not show as many significant differences as the measurement for percent mussel cover, but this may be due to the larger variances in the mussel density measurements. Mussel biomass analysis showed the same significant differences as mussel density at the river and site level (Figures 19 and 20) and the similarities observed in the basic patterns of these metrics indicate that percent mussel cover may be a reliable estimator for differences in mussel density along the marsh edge.

These metrics however, did not depict similar patterns as below ground biomass which might have been expected since net primary productivity has been shown to have been strongly correlated with mussel density along the marsh edge (Bertness 1984). One reason for this may be nutrient availability. Bertness (1984) found that mussel density was also positively correlated with soil nitrogen levels, which helps to stimulate primary production. Cargill and Jefferies (1984) also found that biomass was limited by nitrogen availability. No significant difference in total or inorganic nitrogen was found between rivers or sites, but this may be due to the sampling procedure employed. Five samples from each site were combined into one composite sample that was subsequently subsampled for analysis at each site. This protocol may have obscured any differences in nitrogen between rivers and sites.

At the river level, the explanatory variables percent mussel cover and mass transfer rate follow different patterns from each other and from final transect length (Figures 11, 13 and 23), but were found to impart significant influence on final transect length by the Bayesian factorial model (Table 3). This seems to indicate that at the river level, decreasing mass transfer rate and increasing mussel density do not necessarily result in increased final transect length (reduced erosion) and that the influences of these variables on final transect length are different in different river systems.

At the site level, mass transfer rate was significantly greatest at sites in the mouth of the rivers (Figure 24) as was percent mussel cover (Figure 14), but final transect length was greatest upriver (site 3, Figure 11). We might expect that while mass transfer rate would be negatively correlated to final transect length (i.e., increased energy leads to shorter final transect lengths), percent mussel cover would be positively correlated if the animals prevented erosion. The Bayesian factorial model (Table 3), however, indicated that there was an interactive effect of mass transfer rate and percent mussel cover on final transect length. This explanation is congruent with the results from Piazza *et al.* 2005 who found that while a barrier of oyster cultch along the marsh edge reduced erosion at low energy sites, no significant effect was measured at high energy sites. In the present study, percent mussel cover provided different levels of fortification at different energy levels and the percent cover of the mussels within a particular energy regime also influenced this protective effect (Figure 35).

The conclusion that the effect of mussels on final transect length is not only contingent on the amount of mussels present, but also on the energy regime in which they are located may also help to explain why pair-wise differences for mass transfer rate and percent mussel cover do not completely coincide with final transect length at the site level (Table 5) in the results from the hierarchical model. If these pair-wise difference metrics had a 100% coincidence with pair-wise differences in final transect length, then the factorial model would have indicated that mass transfer rate and percent mussel cover significantly influenced final transect length independently. The fact that the interaction terms are included, and the non-interactive terms are not, indicates that these factors do play a role, but the degree of their influence changes among and within rivers.

According to the Bayesian Factorial Model, the river and site interactions with mass transfer rate and percent mussel cover play an important role in contributing to the degree that erosion or accretion occurs (final transect length). The differences in the effects of these interactions at the river and site level can be observed by looking at trends in the raw data. For example, Figure 31 shows that erosion (a decrease in final transect length) increased in a similar manner with respect to mass transfer rate in all rivers except Dividing Creek where little change occurred. Even though there is a general negative trend between mass transfer rate and final transect length in all rivers, the ranges of these metrics differ by river. Dividing Creek, the St. Jones River and the Maurice River show similar ranges of mass transfer rate, but longer final transect lengths trends were observed in Dividing Creek and Oranoaken Creek than in the other rivers (Figure 31). Also, even though final transect length in Dividing Creek and Oranoaken Creek were not significantly different (Figure 11), there was an overall trend of less mass transfer rate in Oranoaken Creek than in Dividing Creek (Figure 31).

The generally negative trend between mass transfer rate and final transect length was also observed at the site level (Figure 32). Sites 2 and 3 have similar ranges for mass transfer rate and are significantly different from site 1 (Figure 24). Sites 1 and 2 have similar ranges for final transect length (Figure 32) and differ significantly from site 3 (Figure 12), but when examined together, the influence of mass transfer rates on final transect length was not the same across all sites (Figure 32).

The influence of the interaction between river and percent mussel cover on final transect length in Oranoaken Creek and the Maurice River showed strong negative slopes, while the slope for Dividing Creek was again nearly level, although in this case it is slightly positive as opposed to the slightly negative slope present in Figures 31 (Figure 33). The most noticeable difference between the interactions of river and percent mussel cover on final transect length is visible in the St. Jones River which shows a strong positive slope (Figure 33). This contrast tells us that the interaction between river and percent mussel cover does not have the same effect on final transect length in all rivers.

At the site level, there was a significant decrease in percent mussel cover moving upstream (Figure 14) and significantly longer final transect lengths at site 3 (Figure 12), suggesting the greater the percent mussel cover, the greater the erosion. But when looking at the interactive effect of percent mussel cover by site on final transect length, a different picture emerges (Figure 34). This trend suggests that increasing percent cover of mussels, results in a longer final transect length by site and supports the results of the Bayesian factorial model that the degree to which percent mussel cover influences final transect length is not uniform across all sites.

Figure 35 depicts the general trend within the raw data that for any given mass transfer rate value, an increase in percent mussel cover will result in an increase in final transect length. The Bayesian factorial model also identifies the interaction between mass transfer rate and percent mussel cover as having a significant influence on final transect length (Table 3). Also, Figure 35 depicts the largest change in slope of the trend lines between 0% mussel cover and 1-25% mussel cover. These data indicate that generally, the presence of a small amount of mussels can greatly change the rate of

erosion for a given mass transfer rate. As the percent mussel cover increases, further reduction in erosion is observed in a given energy regime, but the largest effect is observed between areas with no mussels present and a small amount present.

In 1997, Meyer *et al.* found that oyster cultch placed in front of marsh edges decreased erosion. In 2005, Piazza *et al.* found that although oyster cultch did help to reduce erosion, but only in their low energy study areas. This seems to be intuitive in the sense that processes occurring in a natural system, such as a river or position within it, will play an important, possibly leading, role in how that system maintains itself or changes. This would suggest that even though percent mussel cover and mass transfer rate play a role in influencing the degree of erosion or accretion that occurs in a river, the river itself, placement (site), or other metrics not investigated in this study, may determine the degree to which these factors play a role.

Although no significant differences were found in nutrient levels (Figures 25-30) and no clear patterns emerged in the below ground biomass and percent *Spartina alterniflora* data (Figures 15, 16, 21, 22) at the river and site levels, it has been shown that these factors have an impact on marsh stability. Increases in nutrient levels lead to a decrease in below ground marsh production (Valiela *et al.* 1976; Morris 1982), which in turn leads to a decrease in peat production and soil retention (Redfield 1972; Turner *et al.* 2000; Turner *et al.* 2006) resulting in decreased marsh stability. The spatial and temporal scales at which these data were collected may have been inadequate to capture the subtle differences in these metrics between rivers and sites.

This study did not investigate differences related hydrology, morphology of riverbeds, or components of energy such as shear stress or current velocity changes

24

within channels. Differences among these factors may contribute to differences in the type of erosion occurring between two rivers or sites. For example, one river or site may be experiencing a slow wearing away of the marsh edge while another experiences undercutting of the marsh edge resulting in the loss of large sections of the marsh in a single occurrence. These factors may have contributed to the observed erosion patterns in this study especially when one takes into account differences between the river systems themselves.

Dividing Creek and Oranoaken Creek showed similar erosion rates which significantly differed from erosion rates in the Maurice River and the St. Jones River which were also similar (Figure 11). The Maurice River and the St. Jones River are both large rivers that drain uplands and urban areas in addition to tidal salt marshes while Dividing Creek and Oranoaken Creek drainage areas are limited to tidal salt marshes. The difference in scale of drainage area as well as the resulting potential differences in nutrient input and delivery may be important factors relating to local erosion rates and may explain the similarities and differences within and between these two groups of water bodies.

As a result, the level of energy and mussel cover that result in a certain degree of erosion or accretion in one location may play a more or less important role in another location. By using the raw data to visualize the result of Bayesian factorial model, one can see how river and site have an influence in determining the effects that the other explanatory variables have on the response variable, final transect length. The Bayesian Factorial Model indicates that although mass transfer rate and percent mussel cover play a role influencing change in transect length in this data set, the larger entities of the river and site will determine the degree to which these metrics are important.

Since the majority of ribbed mussels are found along the marsh edge (Bertness and Grosholz 1985) and, in addition to alleviating erosion in some areas, also provide a suite of ecosystem services that are beneficial to the salt marsh and benthic habitats, what does edge retreat mean for salt marsh ecology? As the rate of edge retreat increases, natural armament provided by mussels is lost and mussel recruitment may not be fast enough to make up for population losses. Since a small amount of mussels may provide a significant amount of protection to the edge of salt marshes (Figure 35), and since sea level rise increases vulnerability of salt marshes (Valiela *et al.* 1976; Morris 1982), the supplementation of mussel populations in specific areas may result in increased salt marsh stability, vertical growth and health. It is for these reasons that the promotion of ribbed mussels as a valuable component of wetlands is necessary, and that recommendations for management strategies in already protected, as well as nonprotected wetlands, should include the advancement of ribbed mussels as primary component of health and viability.

## **Conclusion:**

The ribbed mussel *Geukensia demissa* plays a prominent role in the ecology of estuarine ecosystems by providing a plethora of ecosystem services including filtration (Kreeger and Newell 1996), nutrient cycling (Kuenzler 1961) and increased habitat complexity (Newell 2004). Its synergistic relationship with the saltmarsh cordgrass *Spartina alterniflora* (Kuenzler 1961, Bertness 1984) promotes the creation of marshedge levees that contribute to the marsh sedimentation process. Although other bivalve species such as the eastern oyster, *Crassostrea virginica*, have been recruited to help alleviate saltmarsh erosion by utilizing the hard structure created by dense assemblages of oysters along shorelines (Meyer *et al.* 1997, Piazza *et al.* 2005) there is a clear gap in research when it comes to the question of whether or not the ribbed mussel can also provide this service.

Traditional methods of armoring the shoreline with bulkheads and revetments are effective but disconnect marsh habitats from coastal waters, compromising their function and the ecological services that they provide. Living shorelines provide an alternative and the ribbed mussel, *Geukensia demissa*, may provide a natural armament to stop or slow erosion while providing valuable ecosystem services. This study examined the relationship between the ribbed mussel and salt marsh shoreline erosion while taking into account the influence of other physical and biological factors, such as: nutrient availability, below ground biomass, energy and *Spartina alterniflora* cover. There are numerous other factors that could affect mussel productivity, and hence their ability to potentially help stem erosion. Recruitment, food conditions, salinity, prevalence of predators, marsh elevation and hydroperiod are examples of local biotic and abiotic

conditions that could differ among tributary systems around the Delaware Estuary, as well as along gradients extending from the mouth of tributary rivers upstream.

Even though it has been shown that ribbed mussels help to bind sediments and contribute to below ground biomass production, which reduces erosion (Bertness 1984), it has also been shown that the relationship between shellfish and erosion may not be simple or straightforward. Energetic conditions (Piazza 2005), nutrient loads (Valiela 1976 and Morris 1982), below and above ground plant communities (Redfield 1972; Turner *et al.* 2000; Turner *et al.* 2006) as well as other unidentified variables may all play roles in rates of erosion. In this study, ribbed mussels were identified as playing a significant role in salt marsh shoreline stabilization, but results also indicate that that it is not the effects of isolated variables, but rather the interaction among variables at different levels (e.g., river, site) that played a significant role on the observed erosion.

Overall, sites within rivers display discernible differences in change in transect length from each other in fewer instances than they do from sites in other rivers, that is to say, final transect length tended to fall out by river and that final transect length increased upriver. Furthermore, explanatory variables cited by the models as having a significant influence on final transect length did not have the same effects in all rivers or at all sites These results show the importance of location, in conjunction with other physical and biotic factors, in determining the role that ribbed mussels play in controlling erosion and their potential use as a component of shoreline fortification strategies.

As we move forward in exploring new tactics to protect salt marsh shorelines from erosion and rising sea levels, it is important to fully understand where and how ribbed mussels interact with other biotic and abiotic factors of the salt marsh community
and the role that these interactions play in community stabilization and health. It is also beneficial to consider these roles when making recommendations to wildlife and natural resource managers who have the ability to prioritize resources for investigation and protection efforts. If it can be ascertained where ribbed mussel provide shoreline armament, in addition to the myriad of other beneficial ecosystem service that have been documented, we will be better able to utilize this indigenous shellfish as a natural component of shoreline fortification tactics as well as promote them as a valuable component of already protected areas.

## **Biliography**

- Bertness, M. D. 1984. Ribbed Mussels and *Spartina alterniflora* production in a New England salt marsh. *Ecology*. 65(6):1794-1807.
- Bertness, M. D. and E. Grosholz. 1985. Population dynamics of the ribbed mussel, *Geukensia demissa*: The costs and benefits of an aggregated distribution. Oceologia 67: 192-204.
- Bricker-Urso, S., S. W. Nixon, J. K. Cochran, D. J. Hirshberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries* 28: 823-832.
- Bushek, David, Joshua Moody, Danielle Kreeger, Angela Padeletti and Laura Whalen. 2008. Delaware Estuary Living Shoreline Initiative (DELSI). Poster presentation at the 11<sup>th</sup> International Conference on Shellfish Restoration, Charleston, SC, November 2008.
- Cargill, S.M. and R.L. Jefferies. 1984. Nutrient limitation of primary production in a sub-arctic salt-marsh. *Journal of Applied Ecology* 21:657-668.
- Franz, D. R. 1997. Resource allocation in the intertidal salt marsh mussel *Geukensia demissa* in relation to shore level. *Estuaries*. 20:134-148.
- Franz, D. R. 2001. Recruitment, survivorship, and age structure of a New York ribbed mussel population (*Geukensia demissa*) in relation to shore level – a nine-year study. *Estuaries*. 24:319-327.
- Friedrichs, C. T., and J. E. Perry. 2001. Tidal salt marsh morphodynamics: A synthesis. *Journal of Coastal Research Special Issue* 27: 7-37.
- Hart, A.M., F.E. Lasi, ans E.P. Glenn. 2002. SLODS<sup>tm</sup>: slow dissolving standards for water flow measurements. *Aquaculture Engineering*. 25: 239-252.
- Jokiel, Paul L. and Janice I. Morrissey. 1993. Water Motion on Coral Reefs: Evaluation of the 'Clod Card' Technique. *Marine Ecology Progress Series*. 93: 175-181.
- Jordan, T. E. and I. Valiela. 1982. The nitrogen budget of the ribbed mussel, *Geukensia demissa*, and its significance in nitrogen flow in a New England salt marsh. *Limnology and Oceanography.* 27: 75-90.
- Koch, M. S., and I. Mendelssohn. 1989. Sulphide as a soil phytotoxin: Differential responses in two marsh species. *Journal of Ecology* 77:565-578.

- Koch, M. S., I. A. Mendelssohn, and K. L. McKee. 1990. Mechanisms for hydrogen sulfide-induced growth limitation on wetland macrophytes. *Limnology and Oceanography* 35: 399-408.
- Kreeger, D. A. and R. I. E. Newell. 1996. Ingestion and assimilation of carbon from cellulolytic bacteria and heterotrophic flagellates by the mussels *Geukensia demissa* and *Mytilus edulis* (Bivalva, Mollusca). *Aquatic Microbial Ecology*. 11L: 205-214.
- Kuenzler, E. J. 1961. Structure and energy flow of a mussel population in a Georgia salt marsh. *Limnology and Oceanography*. 6: 191-204.
- Leonard, L. A., and M. E. Luther. 1995. Flow hydrodynamics in tidal marsh canopies. *Limnology and Oceanography* 40: 1474-1484.
- Luckenbach, M. W., L. D. Coen, P. G. Ross, Jr., and J. A. Stephen. 2005. Oyster reef habitat restoration: relationships between oyster abundance and community development based on two studies in Virginia and South Carolina. *Journal of Coastal Research* Winter Special Issue. 40:64-78.
- Lunn, D.J., Thomas, A., Best, N., and Spiegelhalter, D. (2000) WinBUGS -- a Bayesian modelling framework: concepts, structure, and extensibility. *Statistics and Computing*, 10:325--337.
- McCaffrey R.J. and J. Thomson. 1980. A record of accumulation of sediment and trace metals in a Conneticut salt marsh. Pages 129-164 in B. Saltzman (ed.), *Estuarine Physics and Chemistry: Studies in Long Island Sound. Advances in Geophysics* 22.
- McLaren, J.R. and R.L. Jefferies. 2004. Initiation and maintenance of vegetation mosaics in an Arctic salt marsh. *Journal of Ecology*. 92: 648-660.
- Meyer, David L., Edward C. Townsend, and Gordon W. Thayer. 1997. Stabilization and erosion control value of oyster cultch for intertidal marsh. *Restoration Ecology*. 5(1): 93-99.
- Morris, J.T. 1982. A model of growth responses by *Spartina alterniflora* to nitrogen limitation. *Journal of Ecology*. 70:25-42.
- Nepf, H. 1999. Drag, turbulence and diffusivity in flow through emergent vegetation. *Water Resources Research* 35: 479-489.
- Newell, Roger I. E. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding Bivalve Molluscs: A review. *Journal of Shellfish Research*. 23 (1): 51-61.

- Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21<sup>st</sup> century: Changes under the SERES climate and socio-economic scenarios. *Global Environmental Change* 14:69-86.
- Nicholls, R.J., E. Hoozemans, and M. Marchand. 1999. Increasing flood risk and flood risk due to global sea level rise: regional and global analysis. *Global Environmental Change*9: S69-S88.
- Piazza, Bryan P., Patrick D. Banks, and Megan K. La Peyre. 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. *Restoration Ecology*. 13(3): 499-506.
- Porter, Elka T., Lawrence P. Sanford, and Steven E. Suttles. 2000. Gypsum Dissolution Is Not a Universal Integrator of 'Water Motion'. *Limnology and Oceanography*. 54(1): 145-158.
- Redfield, A.C. 1972. Development of a New England salt marsh. *Ecological Monographs*. 42:201-237.
- Schwimmer, R.A. 2001. Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, USA. *Journal of Coastal Research* 17: 672-683.
- Spiegelhalter DJ, Best NG, Carlin BP and Van der Linde A, "Bayesian Measures of Model Complexity and Fit (with Discussion)", Journal of the Royal Statistical Society, Series B, 2002 64(4):583-616.
- Turner, R.E., J.J. Baustian, E.M. Swenson and J.S. Spicer. 2006. Wetland sedimentation from Hurricanes Katrina and Rita. *Science*. 314: 449-452.
- Turner, R.E., E.M. Swenson and C.S. Milan. 2000. Organic and inorganic contributions to vertical accretion in salt marsh sediments. Pages 583-595 in M.P. Weinstein and D.A. Kreeger (eds.) Concepts and Controversies in Tidal Marsh Ecology. Dordrecht: Kluwer Academics.
- Valiela, I., J. M. Teal and N. Y. Persson. 1976. Production and dynamics of experimentally enriched salt marsh vegetation: Belowground biomass. *Limnology* and Oceanography. 21: 245-252.
- Wilson, D.J. and R.L. Jefferies. 1996. Nitrogen mineralization, plant growth and goose herbivory in an Arctic coastal ecosystem. *Journal of Ecology* 84: 841-851.
- Yokoyama, Hisashi, Misa Inoue, and Katsuyuki Abo. 2004. Estimation of the assimilative capacity of fish-farm environments based on current velocity measured by plaster balls. *Aquaculture* 240; 233-247.

Variable	Description	Samples per Transect
Final Transect Length (cm)	The change in initial 1m transect length after one year	1
Percent Mussel Cover	Percent cover of mussels in a 25cm2 quadrat at beginning of study	1
Percent Spartina alterniflora cover	Percent cover of <i>Spartina</i> <i>alterniflora</i> in a 25cm <sup>2</sup> quadrat at beginning of study	1
Mass Transfer Rate (g/hr)	Dissolution rate of plaster- o-paris hemisphere during two neap and two spring tides over course of study	4

 Table 1: Data collected at transect level.

Variable	Description	Samples per Site
<b>Final Transect Length</b>	The change in initial 1m	31
( <b>cm</b> )	transect after one year	51
Percent Mussel Cover	Percent cover of mussels in a 25cm <sup>2</sup> quadrat at each transect at beginning of study	31
Percent Spartina alterniflora cover	Percent cover of Spartina alterniflora in a 25cm <sup>2</sup> quadrat at each transect at beginning of study	31
Mussel Density (#/25cm <sup>2</sup> )	Numbers of mussels present in a 25cm <sup>2</sup> quadrat excavated to 10cm deep	15
Below Ground Biomass (g)	Dry weight of below surface vegetation present in a 25cm <sup>2</sup> quadrat excavated to 10cm deep	15
Mass Transfer Rate (g/hr)	Dissolution rate of plaster-o-paris hemisphere during two neap and 2 spring tides, at each transect, over course of study	124
Total Kjeldahl Nitrogen (%)	Percent total of organic nitrogen, ammonia (NH <sub>3</sub> ), and ammonium (NH <sub>4</sub> <sup>+</sup> ) in the chemical analysis of soil sample	1
Inorganic Nitrogen- Nitrate (ppm)	Amount of Inorganic Nitrogen- Nitrate NO <sup>-</sup> <sub>3</sub> in the chemical analysis of soil sample	1
Phosphorous (lb/acre)	Amount of Phosphorous in the chemical analysis of soil sample	1

**Table 2:** Data collected at Site level.

**Table 3:** Results of the two-way Bayesian Factorial analysis. If the value zero is contained within the range defined by val2.5pc and val97.5pc (i.e., the 95% Credible Interval), then zero is an acceptable value for the respective model coefficient and there is not enough evidence to support that metric or interaction as influencing the response variable, change in transect length. Highlighted values indicate.....

Model Coefficient	Mean	Standard Deviatio n	MC_Err or	val2.5p c	Median	val97.5 pc	Description of Coefficient
β <sub>0</sub>	94.700	51.770	3.497	-0.594	90.800	205.100	General
$\beta_1$	- 136.20 0	72.840	4.520	- 285.100	-135.600	0.382	River 2
$\beta_{1,4}$	75.150 0	47.150	2.767	-14.870	75.420	167.500	River 2*Site 2
$\beta_{1,5}$	57.090	48.600	2.902	-35.550	56.830	154.700	River 2*Site 3
$\beta_{1,6}$	104.60 0	110.900	6.793	- 106.100	105.000	327.300	River 2*Mass Transfer Rate
β <sub>1,7</sub>	0.034	0.313	0.005	-0.586	0.037	0.644	River 2*Percent Mussel Cover
$\beta_{1,8}$	0.079	0.388	0.012	-0.678	0.073	0.842	River 2*Percent Spartina Cover
β <sub>2</sub>	45.320	44.100	2.615	-43.770	46.960	129.700	River 3
β <sub>2,4</sub>	-1.123	30.020	1.710	-58.760	-1.639	59.660	River 3* Site 2
β <sub>2,5</sub>	-19.610	29.680	1.747	-76.520	-20.210	39.940	River 3* Site 3
$\beta_{2,6}$	- 165.70 0	102.600	4.694	- 365.500	-167.600	42.350	River 3*Mass Transfer Rate
β <sub>2,7</sub>	0.007	0.275	0.009	-0.525	0.005	0.547	River 3*Percent Mussel Cover
β <sub>2,8</sub>	0.024	0.423	0.016	-0.794	0.019	0.856	River 3*Percent Spartina Cover
β <sub>3</sub>	96.710	49.770	2.884	-0.255	96.650	195.600	River 4

β <sub>3,4</sub>	-53.660	27.700	1.498	- 108.700	-53.430	-0.577	River 4*Site 2
β <sub>3,5</sub>	-39.430	31.860	1.780	- 103.400	-39.240	22.660	River 4* Site 3
β <sub>3,6</sub>	- 397.80 0	102.100	5.354	- 599.400	-395.900	- 201.300	River 4*Mass Transfer Rate
β <sub>3,7</sub>	0.926	0.230	0.007	0.476	0.926	1.379	River 4*Percent Mussel Cover
β <sub>3,8</sub>	-0.795	0.469	0.018	-1.708	-0.797	0.131	River 4*Percent Spartina Cover
$\beta_4$	-25.650	46.300	2.887	- 115.500	-24.130	60.260	Site 2
β <sub>4,6</sub>	7.309	90.360	4.782	- 174.600	8.117	180.500	Site 2* Mass Transfer Rate
β <sub>4,7</sub>	0.638	0.302	0.013	0.051	0.633	1.239	Site 2*Percent Mussel Cover
$\beta_{4,8}$	-0.164	0.480	0.023	-1.079	-0.165	0.768	Site 2*Percent Spartina Cover
β5	-43.080	48.600	3.123	- 143.500	-41.560	49.280	Site 3
β <sub>5,6</sub>	231.00 0	105.100	5.561	24.750	228.000	448.400	Site 3*Mass Transfer Rate
β <sub>5,7</sub>	0.335	0.335	0.014	-0.308	0.330	1.015	Site 3*Percent Mussel Cover
β <sub>5,8</sub>	-0.193	0.480	0.023	-1.113	-0.197	0.740	Site 3*Percent Spartina Cover
β <sub>6</sub>	-83.510	88.560	5.782	_ 274.300	-76.960	80.850	Mass Transfer Rate
β <sub>6,7</sub>	1.784	0.905	0.050	0.096	1.768	3.645	Mass Transfer Rate*Percent Mussel Cover
β <sub>6,8</sub>	0.214	1.517	0.078	-2.753	0.197	3.234	Mass Transfer Rate*Percent Spartina Cover
β <sub>7</sub>	-0.791	0.543	0.030	-1.913	-0.778	0.227	Percent Mussel Cover

β <sub>7,8</sub>	-0.008	0.009	1.88E-04	-0.025	-0.008	0.009	Percent Mussel Cover*Percent Spartina Cover
$\beta_8$	0.184	0.845	0.047	-1.495	0.198	1.795	Percent Spartina Cover

**Table 4:** Results of pair-wise comparisons from the Bayesian Hierarchical Model showing which sites differed from each other in the analysis. Comparison of **DC**-Dividing Creek; **OR**- Oranoaken Creek; **SJ**- St. Jones River; **MR**- Maurice River. Numbers describe position of site within river: **1**- at mouth of river; **2**- around first meander; **3**-as far upriver as mussels are present. X = discernable difference via pairwise comparison. O = identical site. Blank = no discernable difference detected.

Site	DC	DC	DC	OR	OR	OR	SJ	SJ	SJ	MR	MR	MR
Sile	1	2	3	1	2	3	1	2	3	1	2	3
DC 1	0						Χ	Χ	Χ	X	X	X
DC 2		0					Χ	Χ	Χ	Χ	Χ	Χ
DC 3			0				Χ	X	Χ	Χ	Χ	Χ
OR 1				0			Χ	X	Χ	Χ	Χ	Χ
OR 2					0		Χ	Χ	Χ	Χ	Χ	Χ
OR 3						0	Χ	Χ	Χ	Χ	Χ	Χ
SJ 1							0			Χ		
SJ 2								0	Χ			
SJ 3									0	Χ	Χ	
MR 1										0	Χ	Χ
MR 2											0	X
MR3												0

**Table 5: FTL**- Final Transect Length; **MTR**-Mass Transfer Rate; **PM**- Percent Mussel Cover; **PS**-Percent Spartina Cover; **KN**-Kjeldhal Nitrogen; **MD**-Mussel Density; **PWDs**-Pair-Wise Differences. There are **66** possible pair-wise differences between the 12 sites for each of the six metrics referenced here. Yellow highlighted values indicate.....

Metric	Number of Pair-Wise Differences (PWDs) (A)	Percentage of occurring PWDs out of all possible PWDs for metric (A/66)	Number of FTL PWDs that also coincide with metric PWDs (B)	Percent of FTL PWDs that also coincide with metric PWDs (B/43)	
FTL	43	65%	-	-	
MTR	48	73%	30	70%	
PM	37	56%	24	56%	
PS	26	39%	20	47%	
KN	9	14%	9	21%	
MD	4	6%	4	9%	

Metric	Degrees of Freedom	Mean Sum of Squares	F value	Pr (>F)
Final Transect Length by River	3	76048.00	31.70	$2.2^{-16}$
Final Transect Length by Site	2	23092.50	7.98	$4.1^{-04}$
Percent Mussel Cover by River	3	21309.70	23.18	9.45 <sup>-14</sup>
Percent Mussel Cover by Site	2	20740.40	21.20	1.95 <sup>-09</sup>
Percent Spartina Cover by River	3	3571.00	8.96	9.66 <sup>-06</sup>
Percent Spartina Cover by Site	2	4641.30	11.57	1.35-05
Mussel Density by River	3	166795.00	4.82	2.98 <sup>-03</sup>
Mussel Density by Site	2	597838.00	19.63	1.99-08
Mussel Biomass by River	3	223603.00	5.40	$1.40^{-03}$
Mussel Biomass by Site	2	665686.00	17.78	9.17 <sup>-08</sup>
Below Ground Biomass by River	3	42113.00	6.55	3.17 <sup>-04</sup>
Below Ground Biomass by Site	2	2633.80	0.37	0.69
Mass Transfer Rate by River	3	1.96	57.03	2.20 <sup>-16</sup>
Mass Transfer Rate by Site	2	10.08	402.66	$2.20^{-16}$
Kjeldahl Nitrogen by River	3	105.00	1.05	0.42
Kjeldahl Nitrogen by Site	2	45.08	0.39	0.68
Inorganic Nitrogen by River	3	0.69	2.06	0.18
Inorganic Nitrogen by Site	2	0.33	0.74	0.50
Phosphorous by River	3	86.30	1.67	0.25
Phosphorous by Site	2	4.75	0.06	0.94

 Table 6: One-way analysis of variance (ANOVA) results



Figure 1: Locations of Delaware Bay tributaries containing study sites.



Figure 2: Schematic of study design. N = 4 Rivers, 12 sites and 372 transects overall.



Figure 3. Locations of study sites in the Maurice River.



Figure 4. Locations of study sites in Dividing Creek.



Figure 5. Locations of study sites in Oranoaken Creek.



Figure 6. Locations of study sites in the St. Jones River.



**Figure 7:** Schematic of transect design. Note: this figure is not drawn to scale in order to emphasize the quantity of transects within a study site.



**Figure 8:** Plaster-of-Paris hemisphere field placement (A) and before and after deployment comparison (B).

```
\begin{array}{l} Y = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 \\ Y = Final Transect Length \\ x_1/x_2/x_3 = River \\ River 1: x_1 = x_2 = x_3 = 0 \\ River 2: x_1 = 1, x_2 = x_3 = 0 \\ River 3: x_2 = 1, x_1 = x_3 = 0 \\ River 4: x_3 = 1, x_1 = x_2 = 0 \\ x_4/x_5 = Site \\ Site 1: x_4 = x_5 = 0 \\ Site 2: x_4 = 1, x_5 = 0 \\ Site 3: x_5 = 1, x_4 = 0 \\ x_6 = Mass Transfer Rate \\ x_7 = Percent Mussel Cover \\ x_8 = Percent Spartina alterniflora Cover \\ \end{array}
```

Figure 9: Design Matrix for factorial model. Used to differentiate between categorical and continuous data

 $Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_{1,4} x_1 x_4 + \beta_{1,5} x_1 x_5 + \beta_{1,5} x_5 + \beta_{1$  $\beta_{1.6}x_1x_6 + \beta_{1.7}x_1x_7 + \beta_{1.8}x_1x_8 + \beta_{2.4}x_2x_4 + \beta_{2.5}x_2x_5 + \beta_{2.6}x_2x_6 + \beta_{2.7}x_2x_7 + \beta_{2.8}x_2x_8 + \beta_{3.4}x_3x_4$  $+ \beta_{3.5} x_3 x_5 + \beta_{3.6} x_3 x_6 + \beta_{3.7} x_3 x_7 + \beta_{3.8} x_3 x_8 + \beta_{4.6} x_4 x_6 + \beta_{4.7} x_4 x_7 + \beta_{4.8} x_4 x_8 + \beta_{5.6} x_5 x_6 + \beta_{4.6} x_4 x_6 + \beta_{4.7} x_4 x_7 + \beta_{4.8} x_4 x_8 + \beta_{5.6} x_5 x_6 + \beta_{5.6} x_5 + \beta_{5.6}$  $\beta_{5,7}x_5x_7 + \beta_{5,8}x_5x_8 + \beta_{6,7}x_6x_7 + \beta_{6,8}x_6x_8 + \beta_{7,8}x_7x_8 + \beta_{1,4,6}x_1x_4x_6 + \beta_{1,4,7}x_1x_4x_7 + \beta_{1,4,8}x_1x_4x_8$  $+\beta_{1.5.6}x_1x_5x_6+\beta_{1.5.7}x_1x_5x_7+\beta_{1.5.8}x_1x_5x_8+\beta_{2.4.6}x_2x_4x_6+\beta_{2.4.7}x_2x_4x_7+\beta_{2.4.8}x_2x_4x_8+$  $\beta_{2.5.6}x_2x_5x_6 \ \beta_{2.5.7}x_2x_5x_7 + \beta_{2.5.8}x_2x_5x_8 + \beta_{3.4.6}x_3x_4x_6 + \beta_{3.4.7}x_3x_4x_7 + \beta_{3.4.8}x_3x_4x_8 + \beta_{3.5.6}x_3x_5x_6$  $+\beta_{3.5.7}x_3x_5x_7 + \beta_{3.5.8}x_3x_5x_8 + \beta_{1.6.7}x_1x_6x_7 + \beta_{1.6.8}x_1x_6x_8 + \beta_{1.7.8}x_1x_7x_8 + \beta_{2.6.7}x_2x_6x_7 +$  $\beta_{2,6,8}x_2x_6x_8 + \beta_{2,7,8}x_2x_7x_8 + \beta_{3,6,7}x_3x_6x_7 + \beta_{3,6,8}x_3x_6x_8 + \beta_{3,7,8}x_3x_7x_8 + \beta_{4,6,7}x_4x_6x_7 + \beta_{3,6,8}x_3x_6x_8 + \beta_{3,7,8}x_3x_7x_8 + \beta_{3,6,7}x_4x_6x_7 + \beta_{3,6,8}x_3x_6x_8 + \beta_{3,7,8}x_3x_7x_8 + \beta_{4,6,7}x_4x_6x_7 + \beta_{4,6,7}x_4x_6x_7 + \beta_{3,6,8}x_3x_6x_8 + \beta_{3,7,8}x_3x_7x_8 + \beta_{3,6,7}x_4x_6x_7 + \beta_{3,6,8}x_3x_6x_8 + \beta_{3,7,8}x_3x_7x_8 + \beta_{3,6,7}x_8x_8 + \beta_{3,7,8}x_8x_8 + \beta_{3,7,8}x_8 + \beta_{3,7,8}x_8x_8 + \beta_{3,7,8}x_8x$  $\beta_{4,6,8}x_4x_6x_8 + \beta_{4,7,8}x_4x_7x_8 + \beta_{5,6,7}x_5x_6x_7 + \beta_{5,6,8}x_5x_6x_8 + \beta_{5,7,8}x_5x_7x_8 + \beta_{6,7,8}x_6x_7x_8 + \beta_{6,7,8}x_8x_8 + \beta_{6,7,8}x_8x_8 + \beta_{6,7,8}x_8x_8 + \beta_{6,7,8}x_8 + \beta_{6,7,$  $\beta_{1.5.7.8}x_1x_5x_7x_8 + \beta_{2.4.6.7}x_2x_4x_6x_7 + \beta_{2.4.6.8}x_2x_4x_6x_8 + \beta_{2.4.7.8}x_2x_4x_7x_8 + \beta_{2.5.6.7}x_2x_5x_6x_7 + \beta_{2.4.6.8}x_2x_4x_6x_8 + \beta_{2.4.7.8}x_2x_4x_7x_8 + \beta_{2.5.6.7}x_2x_5x_6x_7 + \beta_{2.4.6.8}x_2x_4x_6x_8 + \beta_{2.4.7.8}x_2x_4x_7x_8 + \beta_{2.5.6.7}x_2x_5x_6x_7 + \beta_{2.4.6.8}x_5x_7x_8 + \beta_{2.4.7}x_8x_8 + \beta_{2.4.$  $\beta_{2,5,6,8}x_{2}x_{5}x_{6}x_{8} + \beta_{2,5,7,8}x_{2}x_{5}x_{7}x_{8} + \beta_{3,4,6,7}x_{3}x_{4}x_{6}x_{7} + \beta_{3,4,6,8}x_{3}x_{4}x_{6}x_{8} + \beta_{3,4,7,8}x_{3}x_{4}x_{7}x_{8} + \beta_{3,4,7,8}x_{7}x_{8} + \beta_{3,4,7,8}x_{8} +$  $\beta_{3,5,6,7}x_3x_5x_6x_7 + \beta_{3,5,6,8}x_3x_5x_6x_8 + \beta_{3,5,7,8}x_3x_5x_7x_8 + \beta_{1,6,7,8}x_1x_6x_7x_8 + \beta_{2,6,7,8}x_2x_6x_7x_8 + \beta_{3,5,7,8}x_3x_5x_6x_7 + \beta_{3,5,6,8}x_3x_5x_6x_8 + \beta_{3,5,7,8}x_3x_5x_7x_8 + \beta_{3,6,7,8}x_1x_6x_7x_8 + \beta_{3,6,7,8}x_1x_8 + \beta_{3,7,8$  $\beta_{3.6.7.8} x_3 x_6 x_7 x_8 + \beta_{4.6.7.8} x_4 x_6 x_7 x_8 + \beta_{5.6.7.8} x_5 x_6 x_7 x_8 + \beta_{1.4.6.7.8} x_1 x_4 x_6 x_7 x_8 + \beta_{1.5.6.7.8} x_1 x_5 x_6 x_7 x_8$ +  $\beta_{2,4,6,7,8}x_2x_4x_6x_7x_8$  +  $\beta_{2,5,6,7,8}x_2x_5x_6x_7x_8$  +  $\beta_{3,4,6,7,8}x_3x_4x_6x_7x_8$  +  $\beta_{3,5,6,7,8}x_3x_5x_6x_7x_8$  + Error **Figure 10:** Full Factorial Model with Five-Way Interactions. Y= Final Transect Length;  $x_1, x_2, x_3 =$ River;  $x_4, x_5 =$  Site;  $x_6 =$  Mass Transport Rate;  $x_7 =$  Percent Mussel Cover;  $x_8$ = Percent *Spartina* Cover;  $\beta_{\#}$  = coefficient for each term/interaction



**Figure 11:** Comparison of mean of final transect length by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 12:** Comparison of mean of final transect length by site. The data are means of the metric for each site  $\pm$  - SE. Letters above the bars denote significant differences (Tukey test p<0.05).





**Figure 13** Comparison of mean of percent mussel cover by river. The data are means of the metric for each site  $\pm$  - SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 14:** Comparison of mean of percent mussel cover by site. The data are means of the metric for each site  $\pm$  SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 15:** Comparison of mean of percent *Spartina* cover by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 16:** Comparison of mean of percent *Spartina* cover by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).

## Mussel Density By River



**Figure 17:** Comparison of mean of mussel density by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).





**Figure 18:** Comparison of mean mussel density by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).





**Figure 19:** Comparison of mean of mussel biomass by river. The data are means of the metric for each site  $\pm$ -SE. Letters above the bars denote significant differences (Tukey test *p*<0.05).





**Figure 20:** Comparison of mean of mussel biomass by site. The data are means of the metric for each site  $\pm$ -SE. Letters above the bars denote significant differences (Tukey test p < 0.05)



**Figure 21:** Comparison of below ground biomass by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 22:** Comparison of below ground biomass by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 23:** Comparison of mass transfer rate by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).





**Figure 24:** Comparison of mass transfer rate by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).


**Figure 25:** Comparison of total nitrogen by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).



**Figure 26:** Comparison of total nitrogen by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).





**Figure 27:** Comparison of inorganic nitrogen by river. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).



**Figure 28:** Comparison of inorganic nitrogen by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p<0.05).

## **Phosphorous By River**



**Figure 29:** Comparison of phosphorous by river The data are means of the metric for each site  $\pm$  - SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 30:** Comparison of phosphorous by site. The data are means of the metric for each site +/- SE. Letters above the bars denote significant differences (Tukey test p < 0.05).



**Figure 31:** Effects of River\*Mass Transport Rate Interaction on Final Transect Length. Regression lines depict trends only as a way to visualize Bayesian Factorial Model results and are not statistically significant.



**Figure 32:** Effects of Site\*Mass Transport Rate Interaction on Final Transect Length. Regression lines depict trends only as a way to visualize Bayesian Factorial Model results and are not statistically significant.



**Figure 33:** Effects of River \* Percent Mussel Cover Interaction on Final Transect Length. Regression lines depict trends only as a way to visualize Bayesian Factorial Model results and are not statistically significant.



**Figure 34:** Effects of Site \* Percent Mussel Cover Interaction on Final Transect Length. Regression lines depict trends only as a way to visualize Bayesian Factorial Model results and are not statistically significant.



**Figure 35:** Effects of Mass Transfer Rate and Percent Mussel Cover on Final Transect Length. Regression lines depict trends only as a way to visualize Bayesian Factorial Model results and are not statistically significant.