

**The Effects of Historically Restricting Tidal Flow  
on Productivity, Decomposition and Nutrient Cycling  
In the  
Great Sippewissett Salt Marsh System**

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## Abstract

This study seeks to determine the impact of historic tidal restrictions on the basic functioning of salt marsh systems by comparing fundamental ecosystem characteristics, including primary productivity, rate and pathway of respiration (with a focus on the anaerobic processes of sulfate reduction and methanogenesis), and rate of mineralization to a natural reference site. Given the current interest in restoring tidal flow to historically impounded areas, this study also considers how restoration might impact the rate and pathway of respiration. I also explore the potential of tidal restoration to liberate large stores of ammonium from the impounded marsh sediments.

The results clearly show that tidal restriction changes the fundamental carbon dynamics of salt marsh system by significantly increasing the rate of primary production while simultaneously decreases rates of respiration, but increasing the methanogenesis pathway by orders of magnitude. These results have implications for atmospheric chemistry as tidal restriction changes the carbon sequestration potential of salt marshes and significantly increases their production of a potent green house gas, methane. In the event of tidal restoration, the data suggests that respiration processes will return to those experienced by the natural marsh site. Furthermore, the results show that tidal restoration has the potential to effectively liberate ammonium stores from historically impounded sediments with the possibility of causing eutrophication in adjacent water bodies.

**Key words:** Salt marsh, tidal restrictions, primary production, respiration, sulfate reduction, methanogenesis, eutrophication

## Introduction

Until a few decades ago, wetlands were considered wastelands, to be drained, dyked, and filled at our leisure in order to control mosquitoes, build railroads and create “useful” land. In New England, for instance, by the mid 1970’s half of the region’s salt marshes were dyked or filled (Nickerson 1978; Niering & Bowers 1966). Because tidal influence is a cornerstone of salt marsh ecology and biogeochemistry, the presence of tidal restrictions dramatically change salt marsh characteristics (Mitsch and Gosselink 1986).

Today, with the insights of basic research, we understand the tremendous value provided by salt marsh ecosystems. Besides providing important habitat for birds, salt marshes provide key “ecosystem services,” including protecting coastal areas from storm surge and sea level rise, protecting the water quality of adjacent estuaries by acting as a biological filter, and serving as nursery habitat for many commercial fish species (Day et al. 1989). The realization of these “ecosystem services” has recently provoked keen interest in the restoration of tidally restricted salt marshes (Portnoy and Giblin 1997a). Restoration efforts are time and cost intensive undertakings. Understanding how certain fundamental dynamics of salt marsh systems have

changed with tidal restriction and being able to predict responses to restorative actions is vital for meeting restoration goals.

Although many studies have examined how characteristics induced by tidal restriction affect the species composition and habitat value of salt marshes less has been done to understand changes in fundamental metabolic processes and internal nutrient cycling (Portnoy and Giblin 1997a; Magenheimer 1996). Changes in the rate and pathway of microbial respiration in the decomposition of organic matter influence rates of nutrient cycling and primary production. The interaction of these changes affects salt marsh impact on atmospheric chemistry and their ability to keep pace with sea level rise. In terms of the outcome of tidal restoration, recent work by Portnoy and Giblin raises the concern that restoration could mobilize large quantities of ammonium stored in impounded sediments and result in the eutrophication of adjacent coastal waters (Portnoy and Giblin, 1997b).

This study seeks to answer a number of basic but important questions concerning how historic tidal restrictions have affected fundamental ecosystem processes in salt marshes and how restricted areas may respond to tidal restoration. The primary questions posed are as follows: a) How has tidal restriction changed species composition, rates of primary production, rates and pathways of respiration (specifically sulfate reduction versus methanogenesis), and rates of mineralization? b) How will the rate and pathway of respiration change with tidal restoration? c) Will tidal restoration induce ammonium mobilization from marsh sediments?

The questions were studied in the Great Sippewissett Marsh system, Cape Cod, Massachusetts where portions of the marsh have been tidally restricted for several decades by the construction of the rail road system across the marsh running parallel to coastline. This study is timely as plans are underway to restore natural tidal range to these restricted areas in 2007 (personal communication, Mr. J. Costa).

## **Study Sites**

Four study sites were selected at the Great Sippewissett Marsh, one in the unaltered portion of the salt marsh and the remainder in three tidally restricted marsh areas directly inland from the rail road tracks (outlined and shaded red in the low portion of figure 1) The only connection between the restricted marsh systems and the natural (unaltered) salt marsh are small culverts identified as FA28 & FA28a (associated with site A), FA20 (associated with site B), and FA21 (associated with site C) in figure 1. The condition and size of these culverts varied creating different characteristics at each of the impounded sites. The culverts at Site A were widest and in the best condition allowing this site to be the best drained, their elevation, however, prevents regular tidal influence (Buzzards Bay National Estuary Program). The culverts at Site B and C, on the other hand, were small and in poor condition. At site B this resulted in extreme water logging with the water table elevated about 12 cm (4.7 inches) above the marsh sediment. At site C slight water logging occurred.

## Methods

At all four sites I selected one representative 1Mx 1M study plot 4-5 meters away from a main tidal creek in which I conducted all parts of this study. To obtain an estimate of relative productivity, I collected the end of season standing and fallen biomass in each of the 1M x1M study plots. I thoroughly dried the harvested biomass in a drying oven and subsequently weighed it, assuming half the dry weight as carbon biomass. I assigned this value as the primary production per square meter per growing season (per year).

In order to attain measurements of total respiration I measured the flux of carbon dioxide ( $\text{CO}_2$ ) from two sediment cores collected at each site. I measured methanogenesis by the flux of methane ( $\text{CH}_4$ ) from these cores. The sediment cores collected for respiration measurements were 10.2 cm in diameter and on average 17 cm deep. I kept the cores at room temperature under anaerobic conditions by sealing the core tubes and flushing the headspace with  $\text{N}_2$  gas. Within a week of core collection, I sampled the core headspaces for the concentration of  $\text{CO}_2$  and  $\text{CH}_4$  over a total of 14 hours at the following time intervals (0, 1.7, 3.7 & 14 hours). I used 20 ml plastic syringes to sample the gases by first injecting 20 ml of  $\text{N}_2$  gas at atmospheric pressure, actively equilibrating the gases in the headspace, and withdrawing 20 ml of gas. In determining the concentration of  $\text{CO}_2$  and  $\text{CH}_4$ , I analyzed the samples with the thermal conductivity detector and flame ionization detector of a gas chromatogram respectively. I converted the concentrations of  $\text{CO}_2$  and  $\text{CH}_4$  to  $\text{gC/m}^2$  by normalizing to the volume of the core headspace and dividing by the surface area of the core. I determined the rate of total respiration as the change in the absolute amount of  $\text{CO}_2$  (expressed as  $\text{gC/m}^2$ ) over time. For the purposes of estimating the contribution of methanogenesis to total respiration, I assumed the dominant pathway of methanogenesis to be the breakdown of acetate. As such, I determined the rate of methanogenesis as the change in the absolute amount of  $\text{CH}_4$  (expresses as  $\text{gC/m}^2$ ) over time multiplied by two as only  $\frac{1}{2}$  mole of methane is produced for every mole of organic matter decomposed by this pathway. To determine the effect of tidal restoration on the rate and pathway of respiration I likewise collected two additional sediment cores from each impounded site and slowly flushed them with 16 litres (L) of low nutrient sea water collected from Woods Hole, Massachusetts. I determined the rate of total respiration and methanogenesis as previously described.

I measured the rate of mineralization, defined as the conversion of organic nitrogen (N) to inorganic  $\text{NH}_4^+$ , by the change in ammonium content of marsh sediments over 23 days of incubation at room temperature. I performed potassium chloride (KCl extractions) on homogenized sub-samples of the 0-4 cm and 8-12 cm sediment depth intervals of two small "initial" sediment cores (3.7 cm in diameter and on average 20 cm deep) taken at each site and determined the concentration of extracted ammonium. Based on the volume of wet sediment used for the KCl extractions I converted the measured ammonium concentrations to an amount of nitrogen-ammonium per  $\text{cm}^3$  of sediment, integrated this value over a 17cm depth interval, and normalized to a per meter square basis. I repeated this process on sub cores taken from the large sediment cores incubated at room temperature and expressed the rate of mineralization as the change in ammonium content per meter square over the incubation time.

To determine the mobilization potential of mineralized N with tidal restoration I studied how the ratio of free (dissolved in pore water) to total (dissolved in pore water plus sorbed to sediment particles) compared before and after saturation with Woods Hole sea water. To do this, I sectioned small sediment cores into 0-6 cm, 6-12 cm, and 12-18cm depth intervals and each interval vertically into three equal portions. I used one portion to determine total ammonium content, the second free ammonium content under ambient conditions, and the third free ammonium content after saturation with Wood Hole sea water. As baseline information for cross site comparison, I determined the average “*insitu*” concentration of pore water “free” ammonium by removing a sediment core from each impounded site, allowing the pore water from the surrounding sediments to slowly fill the void and determining the ammonium concentration of a mixed sample. In sites that were inundated, overlying surface water was first removed by hand pumping water out of an enclosed area.

## Results

The result of historic tidal restriction in Great Sippewissett Marsh has been to effectively create a freshwater marsh system on the inward side of the railroad tracks. Salinity of pore water measured at the three impounded sites was consistently 0ppt. A tidal marsh is considered a freshwater marsh when salinities are below 0.5 ppt (Odum 1988). In contrast, pore water salinity at the natural marsh was 26ppt, within the range (25-32 ppt) observed for other Cape Cod salt marshes (Portnoy and Giblin 1997b). Marsh productivity increased significantly (2 to 3 times) in the impounded marsh sites as indicated by consistently higher end of season biomass (673 gC/m<sup>2</sup> to 407 gC/m<sup>2</sup>) as compared to the natural marsh (194 gC/m<sup>2</sup>). Productivity increased steadily across impounded marshes by 1.3 times at each site from C to A (figure 2). A dramatic change in species composition has also resulted with dominance by *Phragmites australis* (Common reed) in impounded marsh sites as opposed to *Spartina alterniflora* (Smooth cordgrass) and *Spartina patens* dominant in the natural marsh area

Historic tidal restriction has a notable effect on the rate and pathway of respiration/decomposition in marsh sediments. The rate of respiration was significantly higher in the natural marsh site (1.1gC/m<sup>2</sup>/d) versus the impounded sites (0.3-0.4 gC/m<sup>2</sup>/d), a 68% reduction (figure 3). Microbial respiration in the natural marsh is clearly dominated by sulfate reduction as the rate of methanogenesis was considerably low (7 x10<sup>-4</sup> gC/m<sup>2</sup>/d) accounting for only 0.06% of total respiration. Although sulfate reduction remained important in the impounded marsh sites, the importance of methanogenesis increased significantly, by an order to two orders of magnitude in all cases (figure 4). Rates of methanogenesis were 5.5 x 10<sup>-3</sup> gC/m<sup>2</sup>/d, 5.5 x 10<sup>-2</sup> gC/m<sup>2</sup>/d, and 1.2 x 10<sup>-2</sup> gC/m<sup>2</sup>/d and accounted for 1.6%, 18.6%, and 2.8% of total respiration at impounded sites A, B, and C respectively (table 1).

In all cases, when impounded marsh sites were flushed with sea water, rates of methanogenesis decreased one to two orders of magnitude to 2.9 x 10<sup>-4</sup>, 1.4 x 10<sup>-3</sup> and 2.6 x 10<sup>-4</sup> gC/m<sup>2</sup>/d at site A, B, and C respectively (figure 5). At sites A and C this meant rates reverted to the same order of magnitude as that measured in the natural marsh. Despite the order of magnitude decrease observed in site B, the rate of methanogenesis remained an order of magnitude above that

measured in the natural marsh. The rate of respiration was not statistically different before and after the impounded marsh sites were flushed with sea water (t-test,  $p=0.06$ ). Rates of respiration in the flushed marsh sites ranged from 0.2-0.35  $\text{gC/m}^2/\text{d}$  (figure 6).

The results of the mineralization study were surprising. The rate of mineralization in the natural marsh system was low,  $8 \times 10^{-3} \text{ gN/m}^2/\text{d}$  ( $8\text{mg N/m}^2/\text{d}$ ). Interestingly, all impounded marsh sites displayed immobilization of ammonium as opposed to the expected mineralization at rates ranging from  $1.3 \times 10^{-2}$  to  $3.9 \times 10^{-2} \text{ gN/m}^2/\text{d}$  (figure 7).

Flushing impounded marsh sediments with seawater clearly mobilizes ammonium sorbed to cation exchange complexes in the sediment. Averaged over the three impounded sites, the percentage of total ammonium that was free (dissolved in pore water) increased from 57% to 98% after saturation with sea water, an almost doubling (figures 8 and 9). Although there was variation among sites and along the sediment depth profile, in the clear majority of cases, the percentage of free ammonium increased when the sediment was flushed with sea water. Furthermore, free ammonium concentration of pore water collected from salt sediments showed variation among sites. The natural marsh site had 4-10 times the concentration of free ammonium versus impounded sites. Among impounded sites, concentrations increased fairly steadily (by 1.6 – 1.7 times) from site C to B and B to A respectively (figure 10).

## Discussion

### *The Effect of Tidal Restriction on Relative Productivity*

Although end of season biomass does not account for production for the entire year and thus does not give an absolute rate of primary production it does serve as a good proxy. The main factor responsible for the 2 to 3 times increase in marsh productivity in restricted areas is the change in species composition from dominance by *Spartina alterniflora* to dominance by *Phragmites australis*, a species with an inherently faster growth rate (Windham and Lathrop, 1999). The dramatic change in species composition can be attributed to the freshening of the marsh sediments as a result of impoundment.

The differences in productivity among impounded sites can be explained by a combination of the other factors mentioned. Most notable is that both productivity and pore water ammonium concentration increase steadily from site C to A. While this observation does not prove a cause effect relationship, it does suggest that ammonium availability exerts a degree of control on productivity. In marsh ecosystems, ammonium is the primary form of nitrogen available for plant growth (Mitsch and Gosselink 1986) and pore water ammonium would be the most readily accessible for plant uptake. Localized heterogeneity in ammonium inputs via groundwater due to the spatial distribution of nearby septic tanks and differences in sediment type may have created the pattern in pore water concentrations. The sediment at site C for instance was considerably more sandy than that at A and B; sandy soils are known to have a lower nutrient content than more silty soils (Day et al. 1989). Water logging at sites B and C is likely also important in explaining the reduced productivity at these sites. Water logging decreases the availability of oxygen to plant roots which is needed for respiration and growth (Day et al. 1989).

### ***The Effect of Tidal Restriction on Rates of Respiration and Methanogenesis***

This study focused on the anaerobic pathways of sulfate reduction and methanogenesis. Salt marsh sediments are primarily anaerobic, save the first few millimeters and thin films surrounding plant roots (Valiela 1995; Jorgensen 1980). Respiration, however, by sulfate reduction and methanogenesis can continue down to 2m and below. In a New England Salt Marsh, sulfate reduction has been measured to account for 53.7% of total respiration and methanogenesis 0.7%. The other important pathway was aerobic respiration (44.9%) (Valiela,1995). Although this study does not account for aerobic respiration, the comparison of total respiration by anaerobic pathways is fair. Aerobic respiration is not expected to vary significantly in tidally restricted marshes except those that have suffered severe drainage and thus sediment aeration as a result of tidal restriction. Of the study sites chosen, even sediments of site A (the most well drained site) were saturated to the surface.

A major finding of this study is that rates of respiration and thus organic matter decomposition significantly decrease when salt marshes are impounded. The 68% reduction in respiration can be attributed to a decrease in the importance of sulfate reduction as a metabolic pathway due to the significant decline in sulfate concentrations at these sites. The concentration of sulfate in marsh pore water is controlled by site salinity. We have seen that the effect of impoundment has been to essentially turn the sites from tidal into freshwater marsh systems. Whereas marine systems experience sulfate concentrations of 20mM or more, freshwater systems experience concentration around 0.1 mM (Valiela, 1995). Although the decrease in sulfate reduction resulted in an increase in methanogenesis, it was obviously not sufficient enough to compensate for the decline in sulfate reduction. The pathway of sulfate reduction is more efficient at respiring/decomposing organic matter than methanogenesis perhaps because sulfate reducers (although limited in substrate compared to aerobic decomposers) can utilize a wider variety of carbon substrates than methanogens and the energy yield of sulfate reduction is more favorable (9.7 kcal/mole organic matter versus 6.6 kcal/mole) (Fenchel et al. 1998; Valiela 1995).

### ***What Does Tidal Restriction Mean for Net Ecosystem Production? – What are some broader implications?***

Looking at the rate of primary production and respiration simultaneously, we see that the impact of impounding salt marshes can be to significantly increase rates of primary production while significantly decreasing rates of organic matter decomposition. The combined effect is an increase in net ecosystem production. In reality this means that the amount of carbon in the form of organic matter remaining in the system each year increases. According to another study, a switch in salt marsh species composition from dominance by *Spartina* to dominance by *Phragmites* increased the rate of carbon accumulation in high marsh peat by as much as 5 times (Windham 2001). This translates into two significant results; impoundment can increase the carbon sequestration ability of salt marshes and increase rates of sediment accretion.

Interestingly, both these consequences tie into different aspects of global climate change. With global warming being a central topic in environmental science, a particular focus of ecological research has been the carbon sequestration ability of various ecosystems. Although the total acreage of salt marshes is small as compared to other ecosystems, on a per area basis, marshes

and swamps are the most productive ecosystems (Schlesinger 1991). Therefore, for their size, they have a disproportionate potential to sequester carbon. Marshes and swamps together produce 2.2 Gt C yr<sup>-1</sup> as biomass (NPP). This level of production is comparable to other ecosystems with much greater total acreage including temperate evergreen forests (2.9 Gt C yr<sup>-1</sup>), woodland and shrublands (2.2 Gt C yr<sup>-1</sup>), and temperate grasslands (2.0 Gt C yr<sup>-1</sup>) (Schlesinger 1991). A very conservative estimate of average global carbon sequestration by salt marshes is 210 g CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup> (Chmura et al. 2003). On this order of magnitude, carbon storage by salt marsh ecosystems can have regional significance. In the Bay of Fundy, for instance, restoration of salt marsh systems could sequester additional carbon equivalent to 4-6% of Canada's reduction target under the Kyoto Protocol (unpublished manuscript by Chmura 2004. The Global Carbon Sink in Tidal Salt Marshes). Thus, although impounding marshes decreases other ecosystem values, it increases the ability of the system to remove carbon dioxide from the atmosphere and sequester it as organic matter on long time scales until it is very slowly decomposed.

A primary concern with global climate change is sea level rise. Since the 1950s, average global sea level has been rising at a rate of 1.75 mm/yr (BBC News). With continued warming of the earth's atmosphere, this rate is expected to further increase (BBC News). The rate of peat accretion in natural marsh sediments is slow, on the order of 3.1 mm/yr in *Spartina alterniflora* dominated systems of Massachusetts (Mitsch and Gosselink 1986). There is, therefore, understandable concern that in the future, accelerated sea level rise will inundate salt marsh ecosystems and eliminate their high ecological and economic value (Warren and Niering 1993). This has already been ongoing to a large extent on the Gulf Coast of America (Mitsch and Gosselink 1986). An increase in accretion rate as a consequence of impoundment may be the needed edge to buffer marsh systems against sea level rise.

#### ***Effect of Tidal Restriction on the Rate and Relative Importance of Methanogenesis***

Another finding of this study with far reaching implications is that impounding not only changes the rate of respiration, but also induces fundamental changes in the pathways involved. Methanogenesis was able to increase one to two orders of magnitudes in impounded sites, a noteworthy change. Sulfate reducers and methanogens compete for acetate, a product of fermentation and a primary substrate for both metabolic pathways (Jorgensen 1980). Sulfate reduction has an inherently higher energy yield than methanogenesis, allowing sulfate reducing bacteria to out-compete methanogens for the majority of acetate substrate (Valiela 1995; Fenchel et al. 1998). Therefore, in the high sulfate concentrations of the natural marsh, the sulfate reducing bacteria are able to flourish while the methanogen population is severely depressed. In the impounded marsh areas, low sulfate concentrations release some competitive pressure from sulfate reducers, allowing the methanogen population and the role of methanogenesis to significantly increase. Sulfate reduction still remains an important process in these impounded areas, however, based on the credible assumption that the difference between total respiration and methanogenesis is largely attributable to a mix of sulfate reduction and fermentation. The presence of sulfate reducers does not necessarily exclude methanogens in organic rich sediments as noted by Holmer and Kristensen (1994) as the two types of bacteria can occupy different micro niches. Nonetheless, studies have reported sulfate as the dominant factor limiting methanogenesis in salt marsh sediments (Magenheimer et al. 1996); the findings of this study support those results. The importance of competition with sulfate reducers is clear as the rate of

methanogenesis and the percentage contribution to total respiration increased across sites according to increasing degree of tidal restriction (that is natural marsh < site A < site C < site B). The effect was particularly noteworthy in site B where it appears that tidal influence has been completely removed, creating a more advantageous environment for methanogens.

Putting these results in a global context, this means that impounding salt marshes has the potential to increase methane flux from marsh sediments one to two orders of magnitude. While this results in a high methane flux from the impounded sites studied, the rates of methane production measured at the Great Sippewissett Salt Marsh are small compared to other freshwater marsh areas (Magenheimer et al. 1996). Therefore, the increase in methane flux due to salt marsh impoundment could be substantially greater in some systems. We care about methane fluxes to the atmosphere as it is a potent greenhouse gas with 21 times the warming capacity as carbon dioxide (IPCC). The flux of methane from wetlands (including salt marshes) is responsible for 22% of global emissions making salt marsh ecosystems somewhat important to atmospheric chemistry (IPCC). In increasing methane emissions by the scale described we increase the net impact of wetlands and decrease the ecosystem value of salt marshes specifically.

#### ***How Will Tidal Restoration Impact Rates of Total Respiration and Methanogenesis?***

The one to two orders of magnitude reduction in methanogenesis as a result of flushing impounded sediments with sea water highlights the vulnerability of the methanogen population in saline environments. The dramatic reductions observed were perhaps induced by salinity shock in addition to increased competition as the population of sulfate reducers increased. In this experiment, the reduction of methane production was immediate to flushing with seawater. In the event of tidal restoration, however, we can expect to see reductions of the same magnitude, but perhaps over a time scale of a few hydroperiods to allow for saline waters to penetrate the deeper marsh sediments.

Rates of total respiration did not increase as anticipated when impounded sediments were flushed with sea water. The expectation was that flushing would trigger a significant increase in sulfate reduction leading to accelerated rates of respiration comparable to that of the natural marsh. The fact that results were not as expected in this experiment does not invalidate the hypothesis. Mostly likely, the sediment cores had not incubated long enough after sea water flushing to allow the sulfate reducer population to increase to the point of seeing increased respiration rates. The fact that flushing decreased the methanogen population so severely and that the sediments of impounded areas are high in organic matter provides every reason to assume that rates of respiration will return to those of the natural marsh area and that the dominant pathway will be sulfate reduction.

#### ***Effect of Tidal Restriction on Rates of Mineralization***

The immobilization observed in the impounded sites is likely not a real phenomenon but an artifact of technical problems incurred during the experiment. In the course of collecting and handling the incubated cores some pore water was lost, likely representing a large pool of ammonium. The idea of immobilization being ruled out in the impounded areas is also based on

the depressed rates of mineralization observed in the natural marsh site. Even if a hypothesis was generated to support why immobilization occurred across the impounded sites, there is no solid reason to expect suppressed rates of mineralization in the natural marsh site. An intensive study of Great Sippewissett Salt Marsh determined re-mineralization rates of 14.9-16.3 gN m<sup>-2</sup> yr<sup>-1</sup> in natural *Spartina alterniflora* areas much higher than the 3 gN m<sup>-2</sup> yr<sup>-1</sup> determined in this study. (Schlesinger 1997) Theoretical rates of decomposition calculated based on total respiration rates and C/N ratio of plant material resulted in realistic rates of remineralization for the natural marsh. I assume these calculated values also reasonable for impounded sites.

### ***Will Tidal Restoration Cause Ammonium Liberation from Historical Impounded Marsh Sediments?***

The results of this study support previous work done by Portnoy on historically impounded salt marshes in the finding that tidal restoration will liberate ammonium sorbed to the cation exchange complexes of sediments. Sea water has high concentrations of sodium and lower concentrations of magnesium, cations of the appropriate charge density to effectively displace ammonium from these exchange complexes as clearly expressed in the near doubling of free ammonium concentration with sea water flushing. Further evidence that the presence of sea water increases the percentage of ammonium that exists dissolved in pore water as opposed to bound to exchange complexes comes directly from sampling pore water collected in the field. While the impounded site A had about double the total store of ammonium than the natural marsh site (8.3 versus 4.8 ug NH<sub>4</sub><sup>+</sup>/cm<sup>3</sup> sediment), the pore water concentration of “free ammonium” obtained was four times greater in the natural marsh site as seen in figure X. This must mean that a larger portion of the total pool in the natural marsh site exists dissolved in pore water.

Ammonium mobilized by tidal restoration has basically two fates: a) it could be taken up by plants during the growing season, or b) it could be exported from the system during tidal inundation. This sudden release of large amounts of stored ammonium has the potential to cause eutrophication in the creeks of the marsh itself or in adjacent coastal estuaries. The symptoms of eutrophication include among others algae blooms, loss of submerged aquatic vegetation, anoxia and resultant fish kills (Valiela 1995). This potential impact should be considered carefully in restoration efforts, especially given that a primary interest of restoration is to regain lost nursery habitat for fish species. Although the eutrophication potential has a finite life, because of large organic nitrogen stores that have built up over the course of impoundment the time scale is likely to be on the order of years as opposed to months or weeks as the organic nitrogen store is continuously mineralized to ammonium.

### **Conclusion**

It is clear from this study that impounding salt marshes dramatically alters the carbon dynamics of the system. In the Great Sippewissett Salt Marsh system, the result of impoundment has been to significantly increase the rate of primary production while simultaneously decreasing the rate of microbial respiration/decomposition. The net of these two processes is an increase in the carbon sequestration ability and accretion rate of impounded sites. These consequences are significant on a large scale in the face of global climate change and sea level rise. While these

results are applicable beyond the Great Sippewissett Marsh system, they may not be relevant to all cases of tidal restriction in salt marsh ecosystems. Portnoy and Giblin (1997b), for example, found that where impoundment of salt marshes leads to drained sediments, the result was increased rates of decomposition via aerobic respiration and consequent subsidence of the sediments. The pros and cons of impoundment, therefore, vary given site specific characteristics.

This study also showed that impoundment significantly increased the rates of methane production, a potent green house gas. Based on the fundamental mechanisms involved, we can expect this to be a result with universal applicability. In terms of the impact on atmospheric chemistry, it is hard to say whether the benefits of enhanced carbon sequestration outweigh the cost of increased methane production.

Finally, while restoring salt marsh ecosystems is important for regaining extremely valuable habitat for bird and fish species, we must also be vigilant of the potential for eutrophication of adjacent surface waters due to ammonium liberation with tidal restoration. To ensure that the benefits of tidal restoration are not negated by the symptoms of eutrophication, one approach might be to phase the restoration process as to stage the export of mobilized ammonium.

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## Figures and Tables

**Figure 1.** Map of study sites selected at the Great Sippewisset Marsh System.

**Figure 2.** Effect of impoundment of rates of primary productivity.

**Figure 3.** Effect of impoundment on the rate of total respiration.

**Figure 4.** Effect of impoundment on rates of methanogenesis.

**Table 1.** Effect of impoundment on the contribution of methanogenesis to total respiration

**Figure 5.** Effect of tidal restoration on rates of methanogenesis in impounded marsh sites.

**Figure 6.** Effect of tidal restoration on rates of respiration in impounded marsh sites.

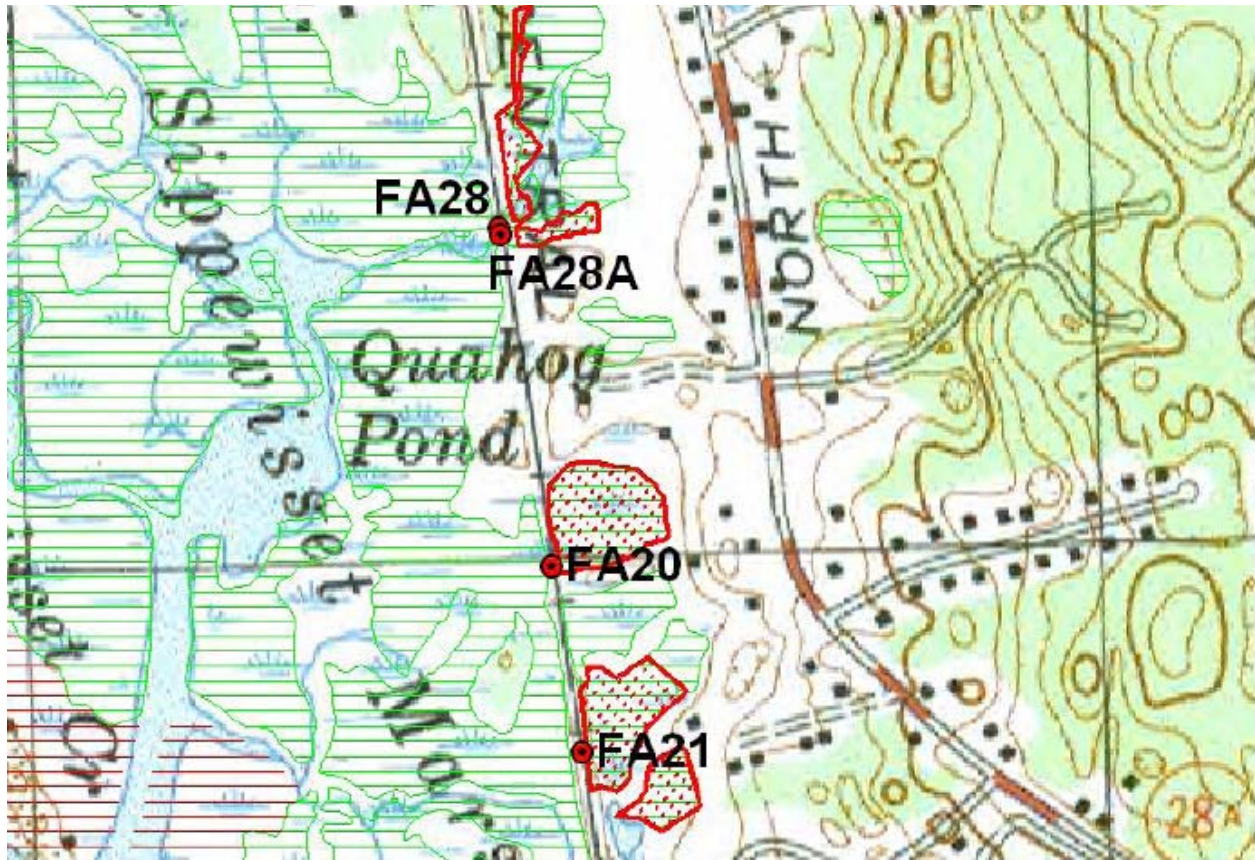
**Figure 7.** Effect of impoundment on rates of mineralization in marsh sediments

**Figure 8.** Percentage of ammonium that exists as free versus exchangeable form in the sediments of impounded sites (under present/ambient conditions)

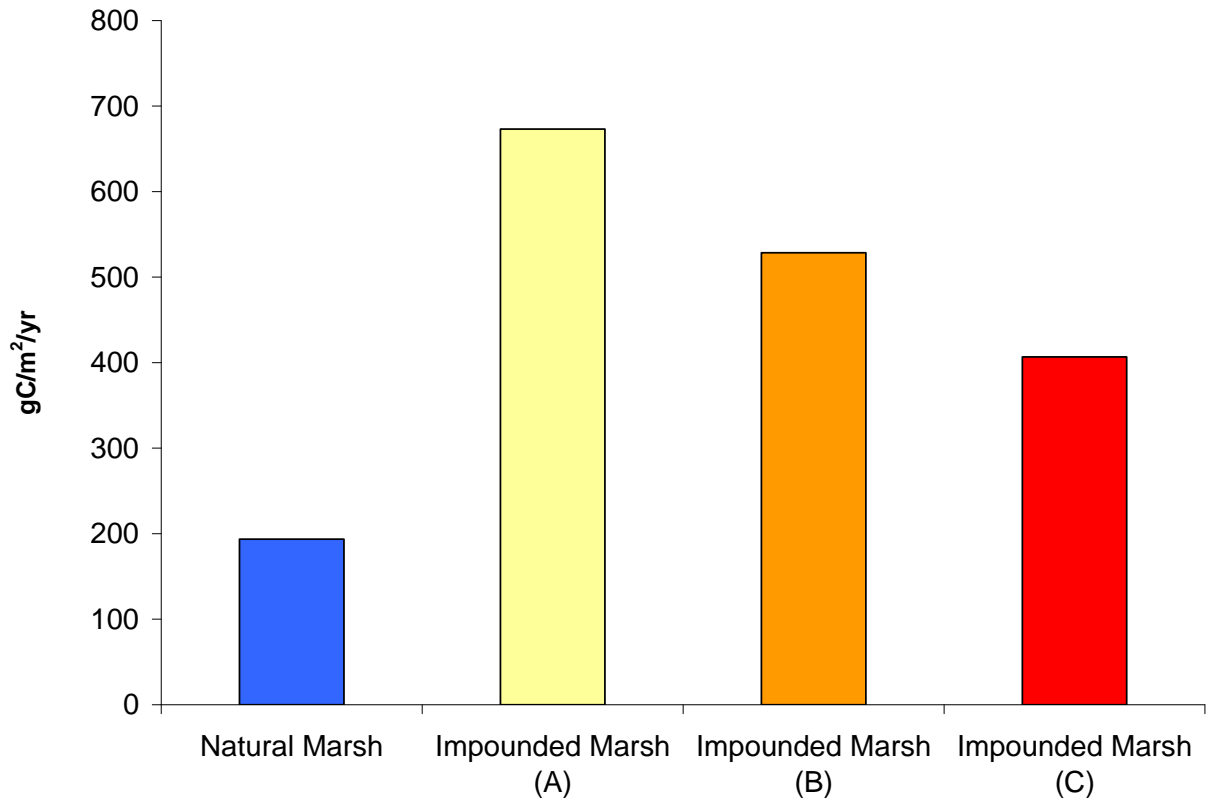
**Figure 9.** Percentage of ammonium that exists as free versus exchangeable form in the sediments of impounded sites after saturation with sea water.

**Figure 10.** Effect of impoundment on concentrations of pore water “free” ammonium.

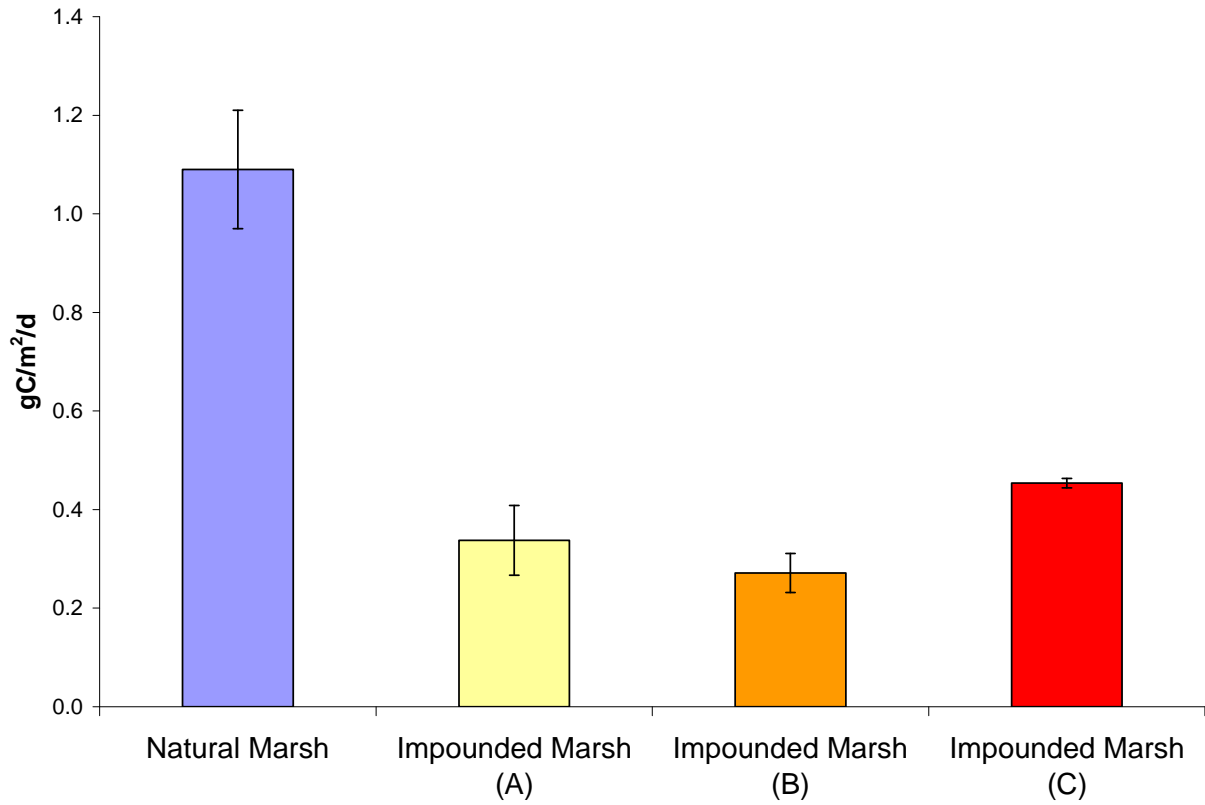
**Figure 11.** Effect of impoundment on net ecosystem production (carbon storage).



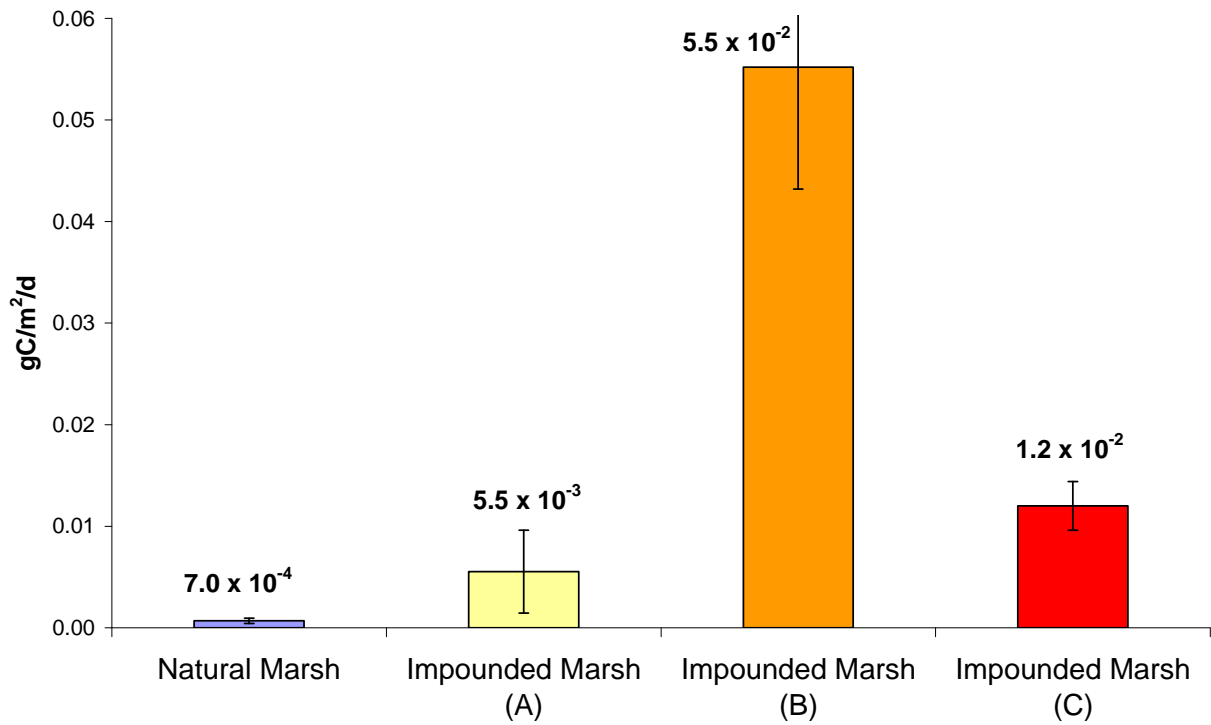
**Figure 1.** Map of study sites selected at the Great Sippewissett Marsh System. The natural marsh site is located left of the rail road tracks that is flanked by three historically impounded sites (indicated in red and designated Sites A, B, C from top to bottom).



**Figure 2.** Effect of impoundment of rates of primary productivity. The increased productivity in the impounded sites is a function of a switch in species composition from dominance by *Spartina* spp. to *Phragmites*.



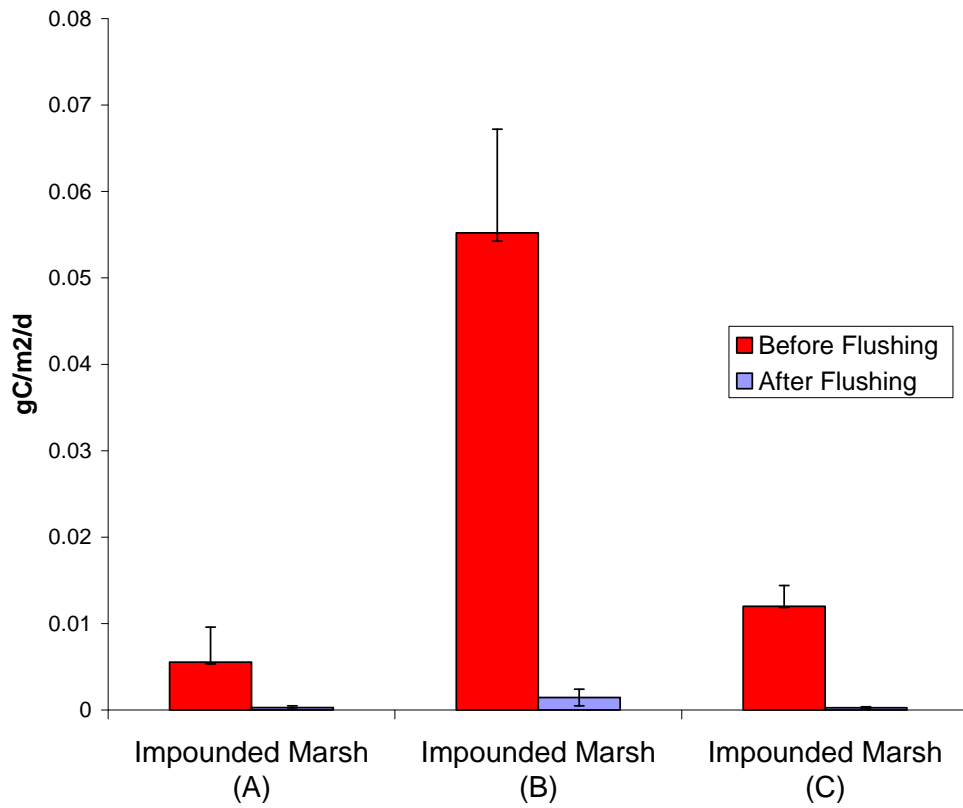
**Figure 3.** Effect of impoundment on the rate of total respiration. The decrease in sulfate reduction in freshwater environments is responsible for the 68% decrease of rates in impounded sites.



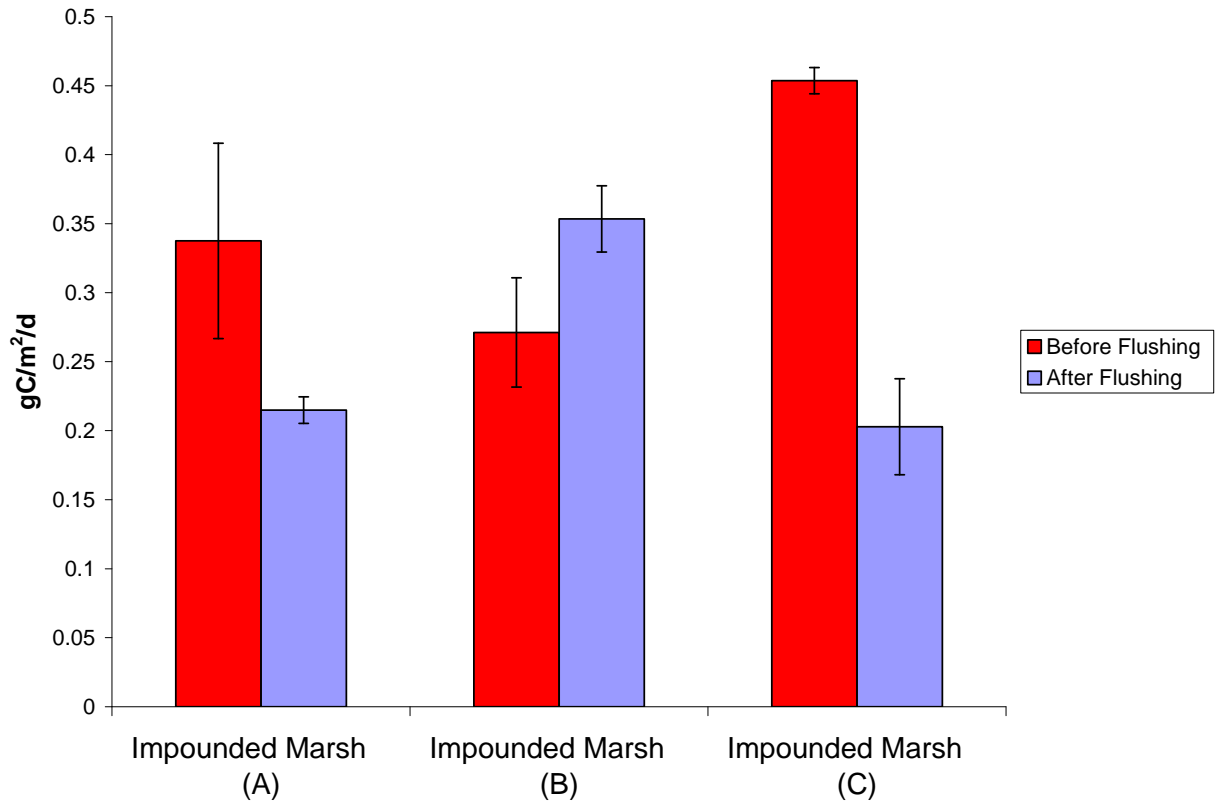
**Figure 4.** Effect of impoundment on rates of methanogenesis. Rates increase orders of magnitude as a result of decreased competition from sulfate reducers.

**Table 1.** Effect of impoundment on the contribution of methanogenesis to total respiration

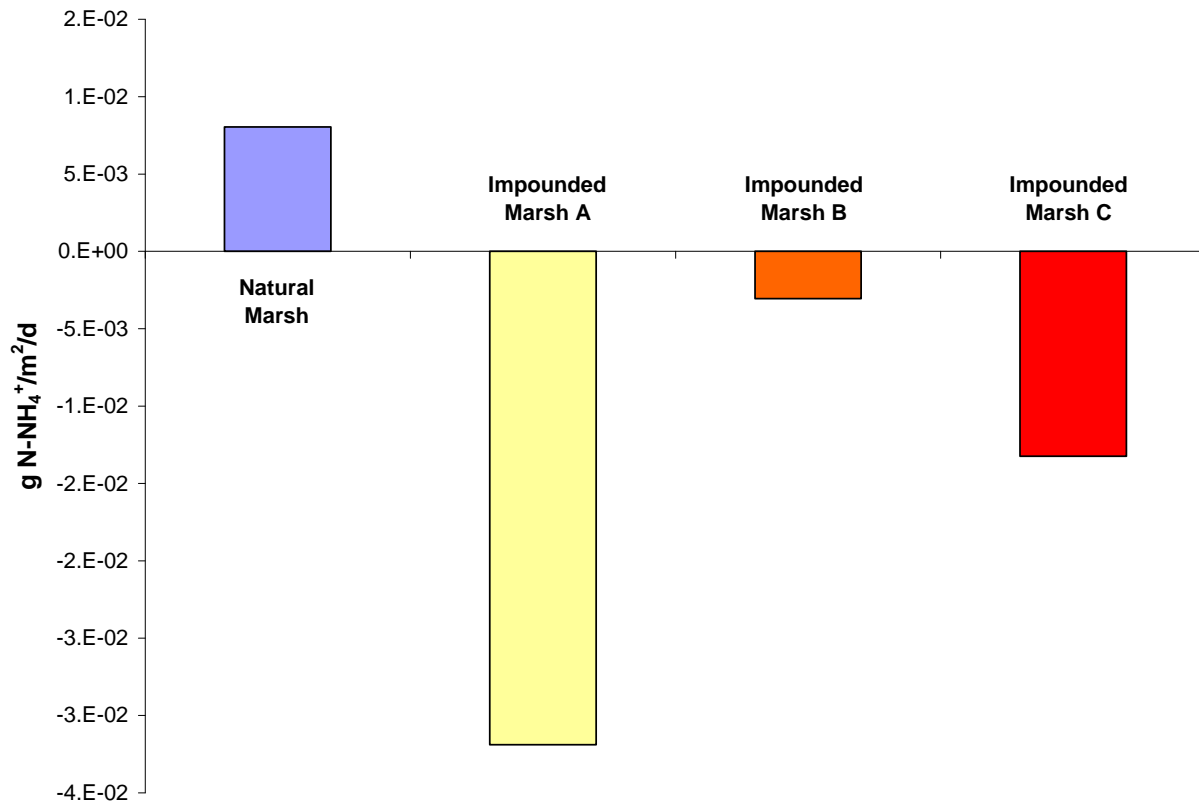
<b>Site</b>	<b>Percentage (%) of Total Respiration that is Methanogenesis</b>
<b>Natural Marsh</b>	<b>0.1</b>
<b>Impounded Marsh (A)</b>	<b>1.6</b>
<b>Impounded Marsh (B)</b>	<b>20</b>
<b>Impounded Marsh</b>	<b>2.7</b>



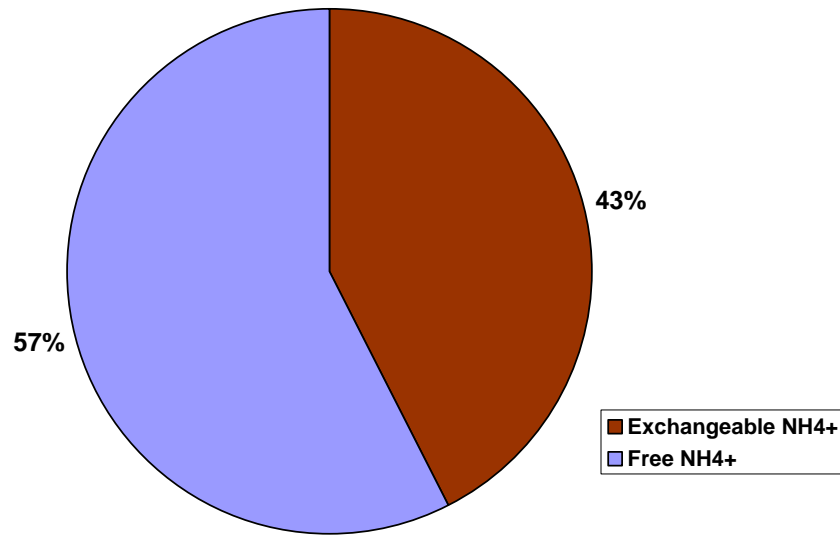
**Figure 5.** Effect of tidal restoration on rates of methanogenesis in impounded marsh sites. Rates significantly decrease due to a combination of salinity shock and increased competition from sulfate reducers.



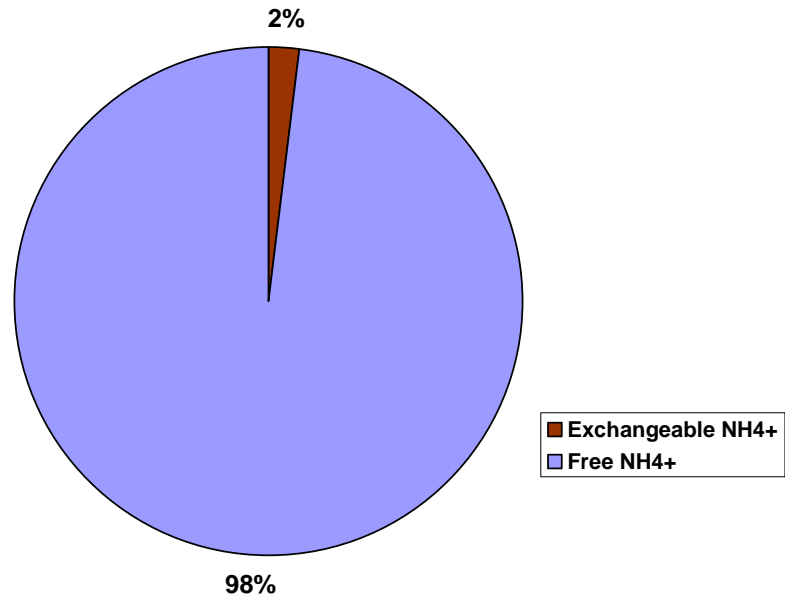
**Figure 6.** Effect of tidal restoration on rates of respiration in impounded marsh sites. The sampling time was too soon to observe the expected increase in respiration.



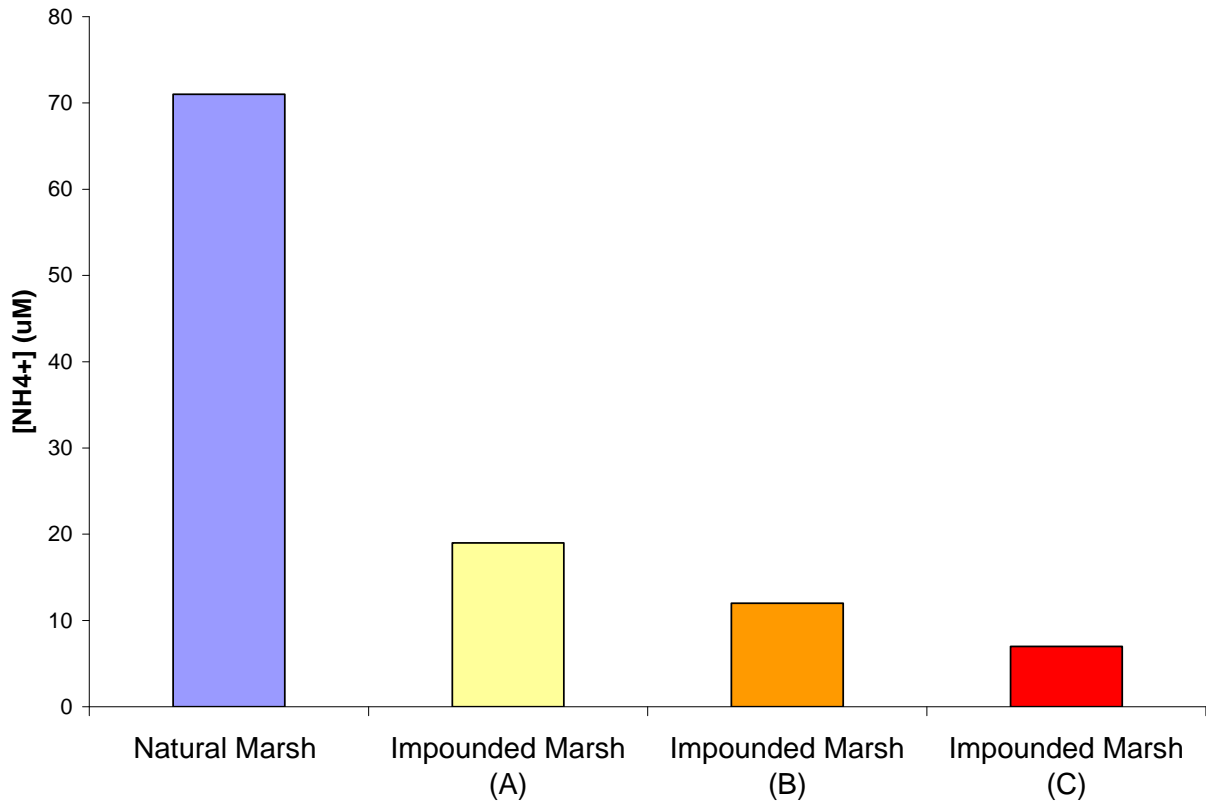
**Figure 7.** Effect of impoundment on rates of mineralization. The immobilization and low rate of mineralization are thought to be a real phenomenon, but an artifact of technical difficulties during the experiment.



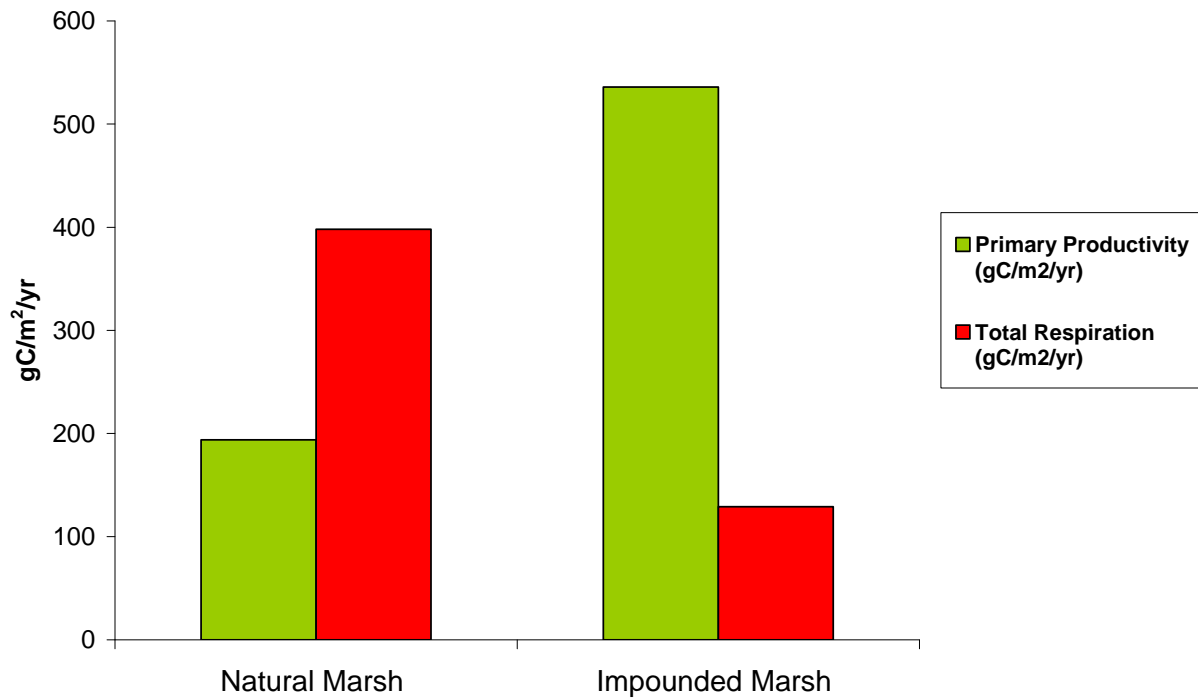
**Figure 8.** Percentage of ammonium that exists as free versus exchangeable form in the sediments of impounded sites.



**Figure 9.** Percentage of ammonium that exists as free versus exchangeable from in the sediments of impounded sites after saturation with sea water. The increase in the percentage of free ammonium is due to the presence of cations in sea water (sodium and magnesium) that displace exchangeable ammonium from the cation exchange complexes.



**Figure 10.** Effect of impoundment on concentrations of pore water “free” ammonium. Concentrations are highest in the natural site likely the presence of sea water cations that “compete” with ammonium for cation exchange sites on sediment particles.



**Figure 11.** Effect of impoundment on net ecosystem production (carbon storage). In reality rates of respiration are not higher than rates of primary production. The result is as shown only because end of season biomass was taken as a proxy for rates of primary production, but is inevitably an underestimate. Furthermore, rates of respiration were measured under room temperature – thereby producing optimal rates most times not experienced in the field.

