Biogeomorphodynamics of Coastal Ecosystems under Conditions of Climate Change and Nutrient Enrichment

By

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Thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Science in Environment
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ABSTRACT

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Abstract

At a given time, tidal landforms inhabit one of three alternate elevation-determined stable states: salt marsh, sub-tidal platform, or tidal flat. The balance between soil production and sea level rise controls transitions between states. Due to increasing anthropogenic inputs, CO_2, the sea level, and nutrient enrichment rates are rising. What effect will this have on the evolution of tidal landforms? The present thesis recognizes that (1) nutrient enrichment tends to decrease below-ground biomass production, thus potentially reducing the organic soil contribution to accretion, (2) nutrient enrichment promotes above-ground biomass productivity, thus potentially increasing sediment trapping, and (3) elevated CO_2 causes an increase in total biomass production. Through use of point- and one-dimensional models, the present thesis addresses the individual and joint effects of the above mechanisms and finds that: (1) nutrient enrichment decreases accretion and increases suspended sediment requirements necessary to maintain the salt marsh state, (2) elevated CO_2 increases accretion and thus decreases the suspended sediment requirements necessary to maintain the salt marsh state, and (3) the increase in accretion effected by CO_2 addition is greater in magnitude than the decrease effected by nutrient enrichment. Thus we can infer that in a future scenario including increasing CO_2 and nutrient enrichment the

effect of CO_2 will dominate. This net increase in accretion may thus partially or completely balance the expected general reduction in sediment delivery to the coasts.

Dedication

This work is dedicated to my grandfather Andrew Knight Foy. Grampy, you showed me that a life lived for others is the truest wisdom, that intelligence and kindness are not mutually exclusive, and that confidence and humility are a tricky but worthwhile balancing act.

Contents

List of Figures

Acknowledgements

This work could not have been completed, or for that matter, even begun, without the constant uplifting love of my friends and family. Thank you to my mother Andrea Margida, for her seemingly unlimited capacity for emotional support, to my father Dr. Anthony Margida, for his never-ending attention to the practicalities of my life (which I so frequently neglected while working on my thesis), and to my brother Gregory Margida, for injecting my day-to-day existence with a steady stream of humor and fun; to my friends Dr. Kyle Bradbury and Justin Migacz for their patient and kind MATLAB tutoring; to my role-model and hero, Dr. Norm Christensen for showing me that there will always be a place in academia for the kindhearted; to Dr. Gaby Katul for helping me to figure out the mystery of my academic future; to Katherine Murray and Anna Braswell for their dedication and clever problem solving; to Dr. Massimiliano Ignaccolo for his helpfulness, kindness and wonderfully intuitive coding; and finally, to Dr. Marco Marani for believing in me against the odds. "Nothing we do, however virtuous, can ever be accomplished alone. Therefore, we are saved by love" – Reinhold Neibuhr.

1. Introduction

This thesis deals with the coupled dynamics of sediment, water, and biota controlling the fate of costal lagoons and estuaries in response to direct and indirect anthropogenic forcing. In particular, I ask the following questions: (1) How will increasing atmospheric carbon dioxide levels due to climate change and (2) how will nutrient enrichment resulting from increased development and agricultural practices affect the biogeomorphodynamics of coastal ecosystems; (3) how will species zonation change as a result and what effect does biodiversity have on resilience.

1.1 Background

1.1.2 Biogeomorphodynamics in the tidal frame

The study of biogeomorphodynamics is rooted in the disciplines of biology, geology, morphology, and dynamical systems. Simply put, it is the area of research primarily occupied with the effects of life on landform, and vice versa. This thesis is concerned with the biogeomorphodynamics of the intertidal zone, hereafter referred to as the *tidal frame*. The tidal frame is the strip of land located at the ecotone between terrestrial and marine ecosystems and is characterized by periodic tidal flooding. Within the tidal frame, there exist three accessible elevation-determined stable states: salt marsh, sub-tidal platform, and tidal flat (Marani 2007). Transitions between these states are controlled by the balance between accretion to the marsh floor and the rate of relative sea level rise.

Accretion is defined as soil production and accumulation. It is comprised of organic productivity, sediment deposition, and trapping of suspended sediments. Of those three terms, organic accretion and trapping are both functions of halophyte productivity; specifically, belowground biomass contributes to organic accretion and aboveground biomass controls trapping.

1.1.2 Salt marsh ecology & sustainability

The salt marsh is the vegetated stable state located between mean sea level and mean high tide. Marshes are intermittently flooded by the tides and are colonized by halophytes, vegetation species adapted to hypersaline and hypoxic soil conditions. Salt marshes are ecologically valuable and benefit humans in several ways. Among other important ecosystem services, they mediate the effects of disturbances, contributing to flood control and to reducing storm surges (Craft *et al.* 2009). Furthermore, due to their high capacity for nutrient filtration, they are instrumental in waste treatment. Marshes also provide a valuable habitat for important species and are home to ecologically important nurseries and fisheries (Craft *et al.* 2009). Finally, salt marshes play an essential role in the global carbon cycle as they are characterized by the highest rate of carbon uptake per unit area among terrestrial/transitional biomes. This carbon is incorporated into biomass, much of which is subsequently permanently incorporated into the soil due to highly reducing conditions, and thus enters long-term storage. For these reasons and others, salt marshes are of high ecological significance and their preservation, in the face of sea level rise and of other anthropogenic interferences, is an important issue. Therefore, much can be gained from examining the effects of projected future carbon dioxide and nutrient enrichment levels on salt marsh accretion.

1.2 On nutrient enrichment

Since the middle of the 20th century the anthropogenic impact on the global nitrogen cycle has increased dramatically. From 1970 to 2005, world population grew by 78% and reactive nitrogen input to the environment increased by 120%-- and it continues to rise yearly (Galloway 2008). Humans have developed industrial processes to reduce N2 to NH4+, created innovative agricultural practices to boost crop yields, and grown in dependence on fossil fuel combustion. Worldwide, atmospheric transport and deposition have become the dominant pathways for reactive nitrogen within the environment. However, research increasingly shows that due to an effect known as the "nitrogen cascade," nitrogen loading problems within separate systems are linked by multiple pathways that transport nutrients across system boundaries. In 1860, an estimated 34 Tg N per year was produced as NOx and NH3 and then deposited to earth's surface as NOy and NHx; 1995 saw an increase in nitrogen emission to 100 Tg N per year; it is currently projected that by 2050, 200 Tg N per year will be created (Galloway 2008).

Additionally, crops add a large new source to the global nitrogen cycle. Cultivation-induced nitrogen fixation contributes about 2.4×10^{12} mol/year to the global nitrogen balance, primarily from nitrogen-fixing legume crops (Canfield 2010). The Haber-Bosch process of NH4+ creation produced 9.5×10^{12} mol in 2008, while the burning of fossil fuels supplied another 1.8×10^{12} mol (Canfield 2010). Combined, atmospheric transport from anthropogenic sources contributes to doubling the background rate of nitrogen fixation on earth and supply about 45% of the total amount of fixed nitrogen produced annually (Canfield 2010). In the absence of anthropogenic contributions, the natural rate of nitrogen deposition to the environment is, at most, 0.5 kg N/ha/yr (Galloway 2008). Humans have driven this number up to an average of 10 kg N/Ha/yr in many regions of the world—an increase greater than an order of magnitude from background nitrogen deposition rates (Galloway 2008). In the future, this figure is expected to double by the year 2050 (Galloway 2008). Some regions are projected to reach deposition rates of 50 kg N/Ha/yr, with some landscape-level inputs being in fact much larger (i.e. forest ecosystems) (Galloway 2008). It is widely acknowledged that nitrogen deposition in excess of critical loads has detrimental effects on receiving systems (Galloway 2008, Canfield 2010).

Global use of nitrogen-based fertilizers also increased dramatically from 1960 to 2000—by approximately 800% (Canfield 2010). Corn, rice, and wheat crops comprise about 50% of this use: all crops whose nitrogen use efficiency is generally below 40% (Canfield 2010). Poor nitrogen use efficiency means that most of the fertilizer that is applied will wash out of the root zone or become subject to denitrification, thus avoiding assimilation into biomass. This overuse of nitrogen-based synthetic fertilizers is expensive both economically and environmentally speaking—globally, nearly 90% of nitrogen fertilizer is made of NH_4^+, which can be converted by nitrifying bacteria to the more mobile compound NO_3^- (Canfield 2010). This form of nitrogen can readily leach into rivers, lakes, and aquifers, resulting in nitrogen loss and cultural eutrophication of coastal environments.

Under varying conditions of relative sea level rise, the long-term sustainability of the salt marsh state depends on the native macrophytes, which maintain a relatively constant elevation of their habitat within a narrow part of the intertidal frame (Morris 2002). The elevation of the marsh floor dictates the length and frequency with which these environments are covered by the tides. This duration and regularity of tidal submersion is critical to a vast array of organisms, not least of all the macrophytes, which are termed "foundation species" because of their ability to modify the morphology of their habitat, their controls on other species interactions and the availability of necessary resources, and their overall effect on the structure of the marsh community (Morris 2002). Salt marsh macrophytes regulate a distinct community of organisms that is in sharp contrast to the tidal mud flat community that would take over in their absence. The marsh plants' success in controlling their environment, however, is contingent on a variety of variables, among which are relative sea level rise and sediment supply. There are documented cases of the salt marsh environment's ability to maintain an elevation in equilibrium with the changing local sea level for 1000 years by accretion of inorganic sediment and organic matter to the marsh floor (Morris 2002). For these reasons, the effect of nutrient enrichment on macrophyte primary production will be a central topic of discussions on marsh sustainability.

It is generally acknowledged that nutrient availability is a significant control on plant composition, growth, and overall productivity (Darby & Turner 2008, Morris et al. 2002, Drake 2009). Plants have been known to adapt to their current nutrient foraging requirements by demonstrating shifts in root, rhizome, and shoot morphology and mass (Darby & Turner 2008). For example, plants native to terrestrial grasslands develop lower root to shoot ratios by mass as soil nutrient availability rises, aboveground biomass production increases, and belowground biomass production decreases.

Fertilized marshes have demonstrated enhanced rates of soil respiration. This change can likely be attributed to an increase in the lability of belowground macroorganic matter due to elevated nitrogen concentration in the tissue of macrophyte roots, rhizomes, and litter resulting in rising rates of decomposition. Alternatively, it is probable that enhanced nutrient availability to local microbial populations also increases rates of decomposition. As such, nutrient enrichment alters the distribution of soil carbon stores in two key ways: by altering the decay rate of labile organic carbon as well as promoting a shift in allocation of carbon to aboveground plant biomass (Wigand 2009).

1.3 On elevated atmospheric carbon dioxide

Global atmospheric carbon dioxide concentration is projected to reach values between 500 and 900 ppm by the year 2100, causing significant climate change (IPCC 2008). However, there remains uncertainty in terms of the geographic distribution of projected warming, the future rate of carbon dioxide increase, and the implications global warming will entail for other climate factors, including sea level rise. Amid this uncertainty, however, there is a considerable degree of agreement within the scientific community that elevated carbon dioxide concentrations increase plant growth. This fertilization effect is a result of the fundamental response of all green plants to elevated carbon dioxide-- competitive inhibition of the oxidase activity of Rubisco promotes increased photosynthetic carbon assimilation. Rubisco's oxidase activity increases faster with temperature than with carboxylation, so promotion of increased photosynthetic rates with rising atmospheric carbon dioxide is expected to be more significant in warmer than in cooler climates. It stands to reason, then, that increasing global temperatures will also enhance this effect. The enhanced production caused by increased carbon dioxide is also affected by environmental factors that alter the CO_2 sink capacity. However, extensive studies give strong evidence that elevated atmospheric carbon dioxide does indeed stimulate plant growth (Kimball 1983, Cure and Acock 1986).

In order for the CO_2 fertilization effect to result in a net enhancement in productivity, it is necessary that the macronutrients essential for photosynthesis—nitrogen, phosphorus, and potassium-- be available in sufficient quantity. The limitation of any one of these nutrients may constrain the CO_2 fertilization effect. Marine environments tend to be nitrogen-limited (Raalte *et al.* 1974); that is, the scarcity of bioavailable nitrogen is known to result in photosynthetic inhibition and in some cases physical symptoms of nitrogen deficiency, such as stunted growth and chlorosis (Howarth 1988). Therefore, as atmospheric CO2 concentration increases, a concurrent increase in availability of primary macronutrients must take place, with nitrogen in particular being a significant control on the potential for enhancement of productivity.

That said, elevated atmospheric carbon dioxide could affect coastal wetlands in one of two ways: directly, via a fertilization effect which would enhance production; or indirectly, by contributing to sea level rise via global warming (IPCC 2001). The understanding of the joint effect of these two change mechanisms is clearly of great importance to our understanding of coastal dynamics. Stressors such as salinity and flooding, which are associated with sea level rise, are known to limit the fertilization effect of atmospheric carbon dioxide, and in doing so, they affect the long-term sustainability of these tidal systems. In steady state coastal marsh surface elevation must remain constant relative to sea level rise; this equilibrium is maintained through complex physical and biological processes. Sedimentation, erosion, and subsidence are examples of physical controls on accretion and compaction, whereas production-decomposition dynamics affect soil volume and contribute biogenically to the elevation of the tidal frame. The latter dynamic is thought to be the largest, and most uncertain, contributing factor to the sustainability of coastal marshes under relative sea level rise. As systems once reliant on a constant influx of sediment begin to receive reduced sediment flows, these biological contributions to accretion become increasingly important. As such, changes in plant production, which include those brought about by increased atmospheric carbon dioxide concentrations, affect the marsh's sustainability potential.

Production and decomposition of marsh plants is not only influenced by locally and regionally variable factors, however; global forcings such as eustatic sea level rise and elevated atmospheric carbon dioxide will also have an effect. Increased atmospheric carbon dioxide enhances plant shoot density and productivity, both in the short- and long-term. Additionally, elevated carbon dioxide contributes significantly to increased belowground inputs to accretion via enhanced root biomass.

Of the two types of photosynthetic pathways seen in marsh halophytes, C3 species response to carbon dioxide has been found to be greater than C4 species (Cherry *et al.* 2009, Curtis *et al.* 1990, Drake 1992). These differential responses to increased atmospheric carbon dioxide may lead to a decrease in biodiversity and a shift in species distribution. Changes in litter quality and decomposition rates will co-occur as a result of elevated carbon dioxide, indirectly affecting organic accretion to the marsh floor. In combination with the increased flooding and salinity of sea level rise, and with elevated nutrient loading or other local factors, these effects may interact to further affect above- and below- ground biomass partitioning, and thus organic matter accumulation.

Much work has been done to analyze perennial halophytes response to increasing atmospheric carbon dioxide and thus better understand the ecological consequences of this phenomenon. Such studies have shown that halophytic plants exhibit a range of morphological and physiological responses to elevated carbon dioxide, and that these effects can impact the accumulation of both aboveground and belowground biomass (Cherry *et al.* 2009, Curtis *et al.* 1990, Drake 1992, Kathinlankal *et al.* 2008). The effects of increasing carbon dioxide on aboveground carbon allocation and photosynthetic processes are well understood. However, belowground responses have not been studied to the same degree and as such there remains much to learn about carbon allocation to root growth, and about the belowground component of the carbon economy of marsh plants in general.

As one of the most biochemically active ecosystems on the planet, wetlands are vital to the global carbon cycle. In particular, tidal ecosystems can sequester carbon at a rapid rate as they accrete and bury organic-rich sediments as the elevation profile of the tidal frame evolves. There has been much work done to improve the scientific community's understanding of carbon dioxide cycling in both terrestrial and marine ecosystems (Cherry *et al.* 2009, Kathinlankal *et al.* 2008); however, there is still considerable uncertainty about the precise nature of the controls on coastal wetland carbon cycling. Limited information about the net carbon dioxide exchanges in tidal ecosystems is largely derived from chamber experimentation, and from regional and global carbon budgets. Past work of this kind shows that salt marshes have a high capacity for carbon sequestration; *Spartina alterniflora,* or smooth cordgrass, is the dominant plant species on North America's east coast and has a tendency to form monoculture stands in tidal ecosystems. These environments are highly vulnerable to relative sea level rise, or RSLR. RSLR, tidal changes, and coastal development and engineering all contribute to changes of equilibrium state within the tidal frame. Tidal systems have been maintaining equilibrium over the past 4000 years with RSLR by vertical accretion, but projected rates of RSLR are faster than some marsh systems are able to keep pace via such processes and can threaten the long-term viability of these ecosystems. Increasing RSLR is known to possibly result in loss of the marsh equilibrium state (Morris *et al*. 2002, Marani *et al.* 2007). If vertical accretion to the marsh floor does not keep up with changes in relative sea level, then these valuable tidal systems can be transformed into barren mud flats. In order for native plant production to counter the effects of relative sea level rise; the marsh must function as a net sink for carbon dioxide (Kathilankal et al. 2008).

1.4 On biodiversity and stability

Due to development, fragmentation, and urban runoff, global species diversity is in decline-- sensitive species die off, while a few hardier species persist at the expense of others. Biodiversity, however, is important for ecosystem functioning; certain species are critical for performing essential ecosystem services; and the functions of those keystone species are necessary for ecosystem sustainability (Zelder *et al.* 2001).

Much work has been done to explore the importance of species richness, in the form of several biodiversity experiments which involved planting randomly drawn assemblages of herbaceous plants and gauging their productivity, largely by measuring the accumulation of biomass. This work has largely been done in terrestrial grasslands and not tidal marshes, though similarities in terrestrial and marsh species lead us to believe that similar effects may occur in marsh environments. Overall, it has been found that increasing plant biodiversity increases productivity (Naeem *et al.* 1998) and contributes to increased resilience of the system(Tilman and Downing 1994). Hector *et al.* (1999) conducted a series of experiments in eight countries (thus, largely removing regional bias) which found that reducing biodiversity by 50% resulted in an aboveground biomass decline by 10-20 percent. In reviewing current literature on the biodiversity of plants, it is confirmed that many functions increase with a rise in the number of species present (Schwartz *et al.* 2000); however, it is not yet understood whether there exists a continual, linear relationships between species diversity and function.

Studies do show, however, that the two are positively related within the salt marsh (Schwartz *et al.* 2000, Tilman and Downing 1998, Hector *et al.* 1999). One possible reason is that all of the species are needed, each to provide a specific function for the system. According to Zelder *et al.* (2001), different plant species are specialized to perform different functions best. In summary, species-rich communities enhance salt marshes by increasing canopy complexity and biomass (Naeem *et al.* 1998, Tilman and Downing 1998, Hector *et al.* 1999). Note that work by Naeem, Tilman, and others focuses on diversity within a given area (generally terrestrial grasslands). Salt marshes, however, are notoriously simple and species diversity is largely a matter of elevation-determined zonation. As such, it remains to be seen whether grassland-specific findings will be generalizable to coastal ecosystems.

2. Methods

2.1 Literature review and data interpretation

2.1.1 Carbon dioxide data

Cherry *et al.* 2009 examined the effects of carbon dioxide on biological processes influencing elevation change in coastal wetlands experiencing stress due to relative sea level rise. In order to investigate these effects, they chose a typical North American brackish marsh in order to gain a generalizable understanding of the processes at work. They began collecting samples from the site in 2005. The sods collected were roughly a 50:50 mix of C4 and C3 halophyte species—specifically, the cores were dominated by *Spartina patens* and *Schoenoplectus americanus*.

The conclusion of Cherry *et al.* 2009 was that elevated carbon dioxide enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea level rise, such as salinity and flooding. They conclude that the combined effect of increased atmospheric carbon dioxide concentration and increased salinity due to relative sea level rise on C3 halophytic vegetation is an increase in elevation of the marsh floor. This study utilized Cherry *et al*.'s 2009 results (Fig. 1) to model the relationship between organic accretion and elevated carbon dioxide.

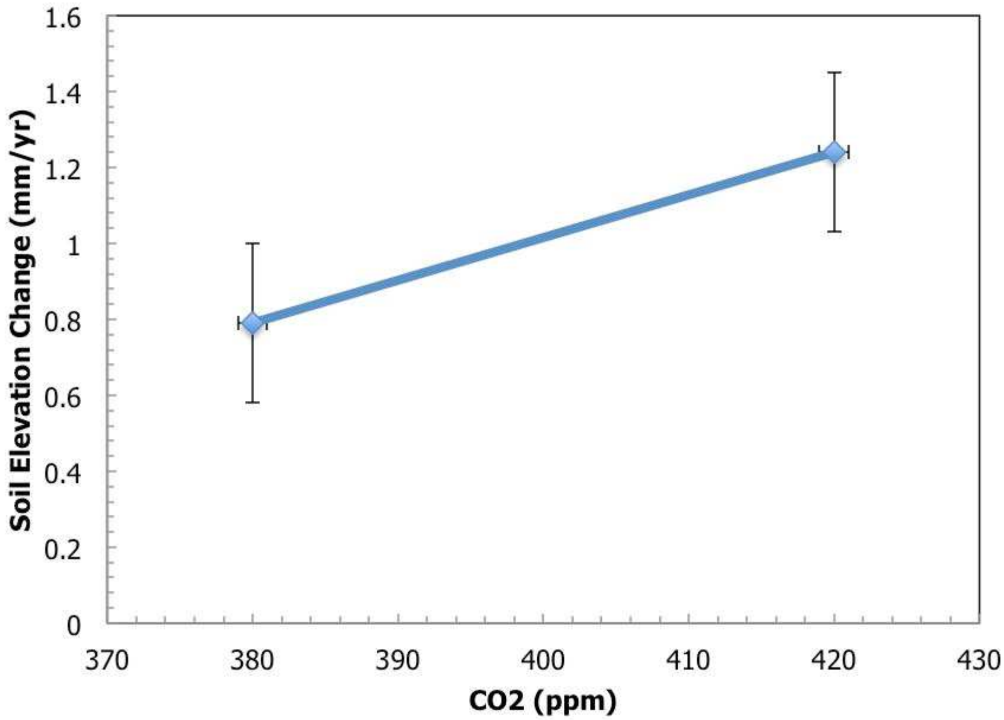

Figure 1: Cherry et al.'s (2009) results show that with the addition of carbon dioxide to the atmosphere, organic accretion increases.

The experimental results in Fig. 1 were used to determine a parameterization of the increased organic soil production as $Q_o=f(CO_2)\cdot Q_{o,b}$, where $Q_{o,b}$ is the baseline organic soil production under current climatic conditions, and $f(CO_2)$ is a function of atmospheric CO_2 concentration, which is here assumed to be a linear function obtained from interpolating the experimental points in Figure 1:

$$f(CO_2) = 0.012975 \times CO_2 - 3.9305$$

where CO_2 is expressed in ppm.

Drake *et al.* 1989 grew *S. olneyi*, *S. patens*, and a mixed community of the two species + *d. spicata* (a C4 grass) in chambers at two CO_2 levels, ambient and elevated. C3 sedge *S. olneyi* root dry mass increased significantly, while C4 grass *S. patens* and mixed community root dry mass increased only slightly.

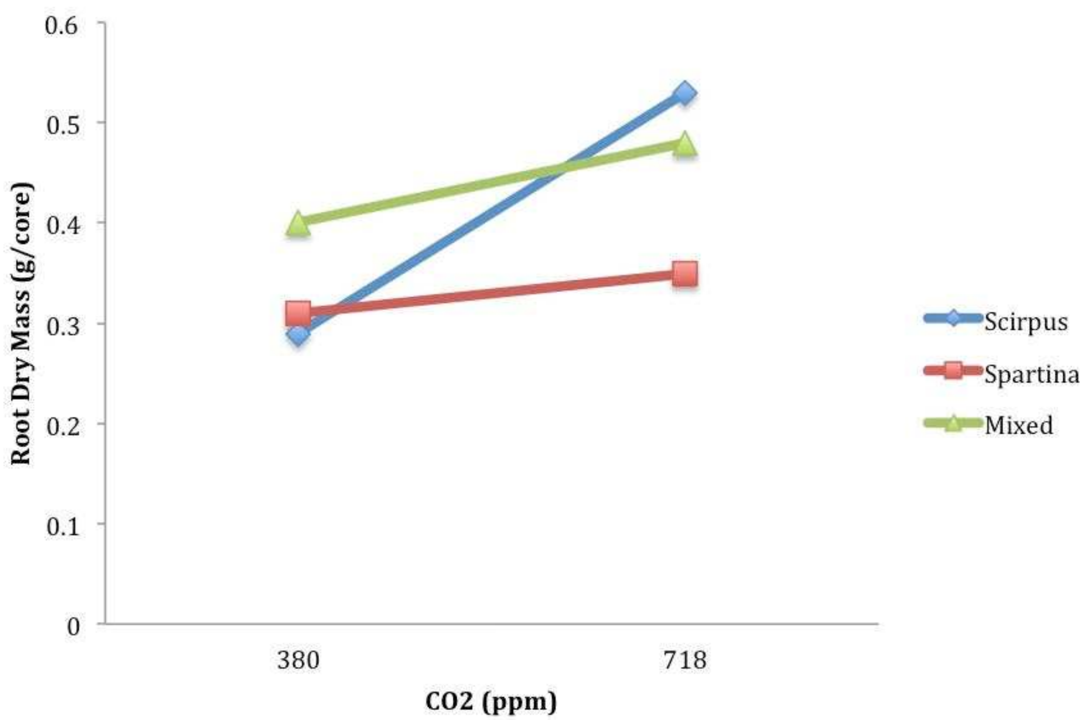

Figure 2: Drake et al.'s (1989) results show that with the addition of carbon dioxide to the atmosphere, belowground biomass production increases.

2.1.3 Nutrient enrichment data

Morris et al. (2002) analyzed the effects of nutrient addition on above- and below-ground biomass production in a marsh environment at Goat Island, within South Carolina's North Inlet estuary. This site was selected mainly because of the long observation record available since 1984. This particular marsh has transgressed inland over a beach ridge so that approximately 0.4 m of organic-rich sediment overlies tightly packed beach sands.

The conclusions of Morris et al. (2002) are threefold: 1) the addition of nutrients causes a decrease in belowground biomass (Fig. 3); 2) the addition of nutrients causes an increase in aboveground biomass production (Fig. 4); and 3) the addition of nutrients promotes marsh floor accretion (Fig. 5). Since it is known that belowground biomass contributes more significantly to organic accretion than aboveground biomass, Morris *et al.* (2002) conclude that the accretion increase observed under nutrient enrichment must be due to the enhanced trapping effect promoted by increased aboveground biomass which more than compensates for the diminished organic sediment production.

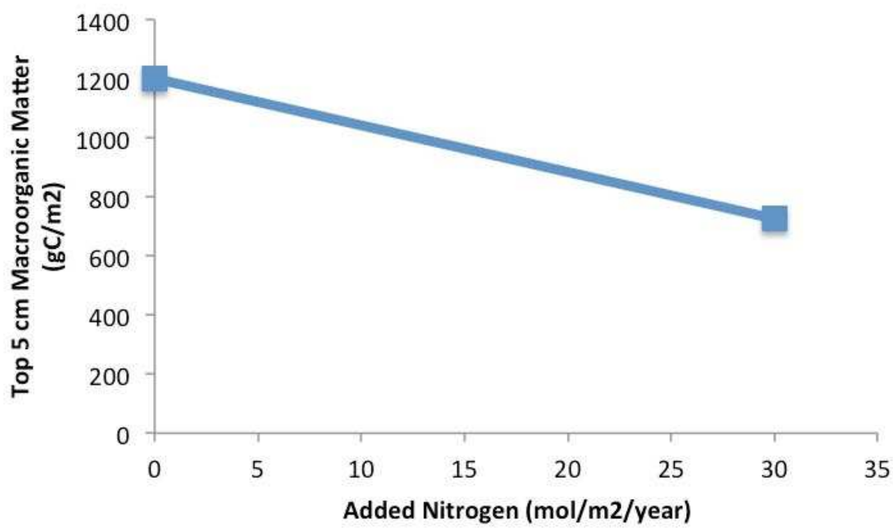

Figure 3: Morris et al. (2002) show that belowground biomass production decreases as nutrient treatment increases.

We use here the results by Morris et al. (2002) to derive a parameterization of the increase in belowground biomass as a function of nutrient level as $Q_o = G(N) \cdot Q_{o,b}$, where N is the nutrient addition above current conditions (in mol/m^2/yr) and G(N) is a function obtained from the linear interpolation of the data points in Figure 3:

$$G(N) = 0.01318 \times N + 1$$

where N is added nitrogen in mol/m^2/year.

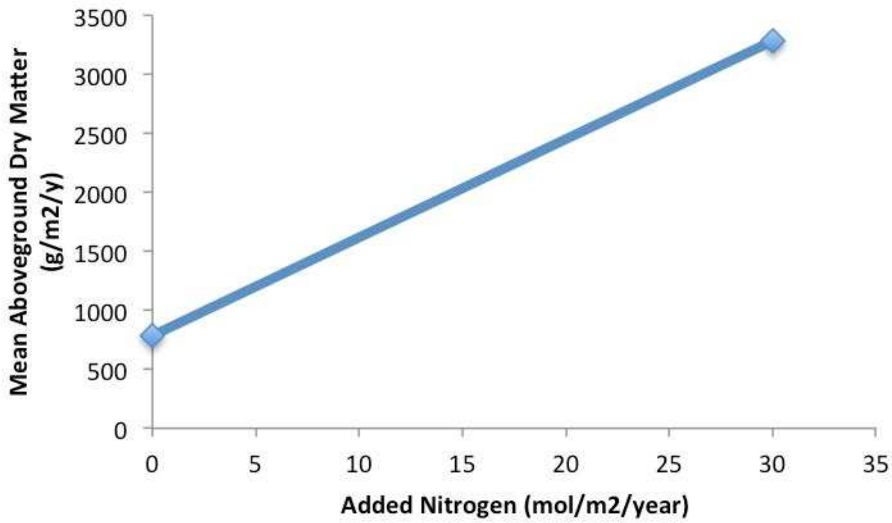

Figure 4: Morris *et al.* observed that production of aboveground biomass increases with nutrient treatment.

As above, we use here the results by Morris et al. (2002) to derive a parameterization of the increase in the aboveground biomass as a function of nutrient level as Q_o=G(N)· $Q_{o,b}$, where N is the nutrient addition above current conditions (in mol/m^2/yr) and G(N) is a function obtained from the linear interpolation of the data points in Figure 4:

$$G(N) = 0.1068 \times N + 1$$

where N is once again added nitrogen in mol/m^2/year.

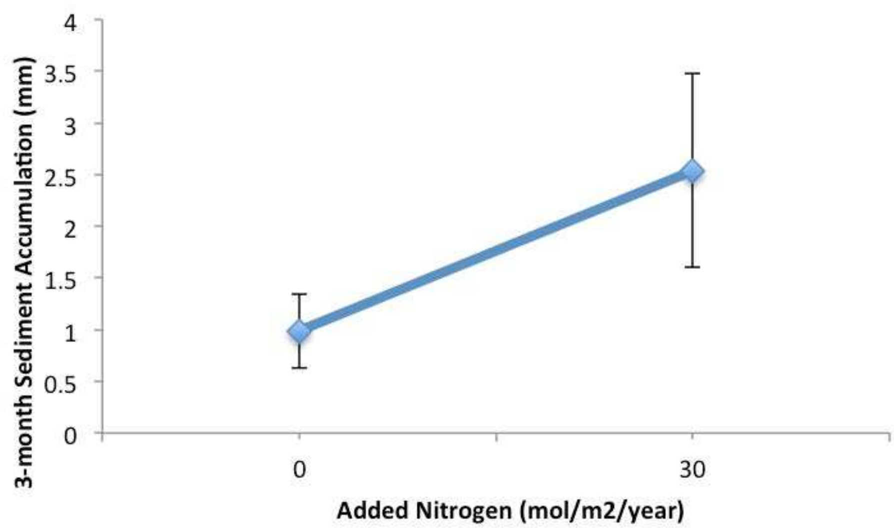

Figure 5: Morris *et al.*'s results show that with nutrient addition, vertical accretion to the marsh floor increases, as measured by three months worth of sediment accumulation.

Morris *et al.* (2002) found that vertical accretion at the North Inlet study site increased with nutrient loading. The direct relationship of belowground biomass to vertical accretion is acknowledged (Darby and Turner 2008, Morris 1999, Morris *et al.* 2002); the aboveground contribution is less well understood. However, it is known that an increase in aboveground biomass productivity promotes increased trapping in the presence of adequate suspended sediment availability. A possible explanation for Morris *et al.*'s results, then, is the enhanced trapping capacity promoted by increased canopy (aboveground) biomass production.

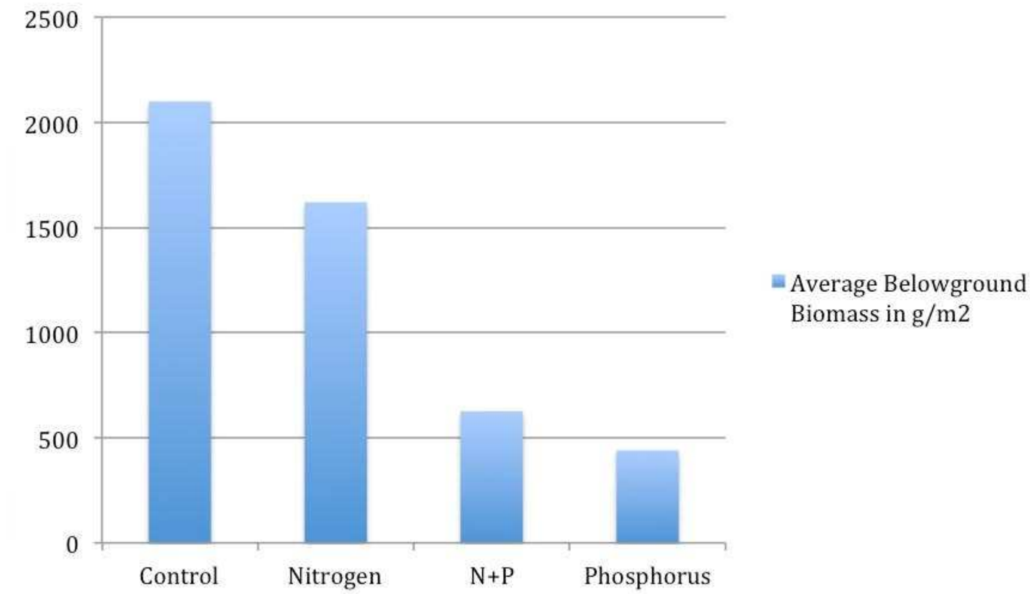

Figure 6: Darby and Turner 2008's results show that belowground biomass production decreases with nutrient treatment.

Darby and Turner's finding support the statement that in more nutrient-poor environments, plants have greater belowground biomass. This phenomenon may imply that the inverse is also true-- that marshes subject to nutrient loading will perhaps be less sustainable/ resistant to relative sea level rise due to decreased production of belowground biomass.

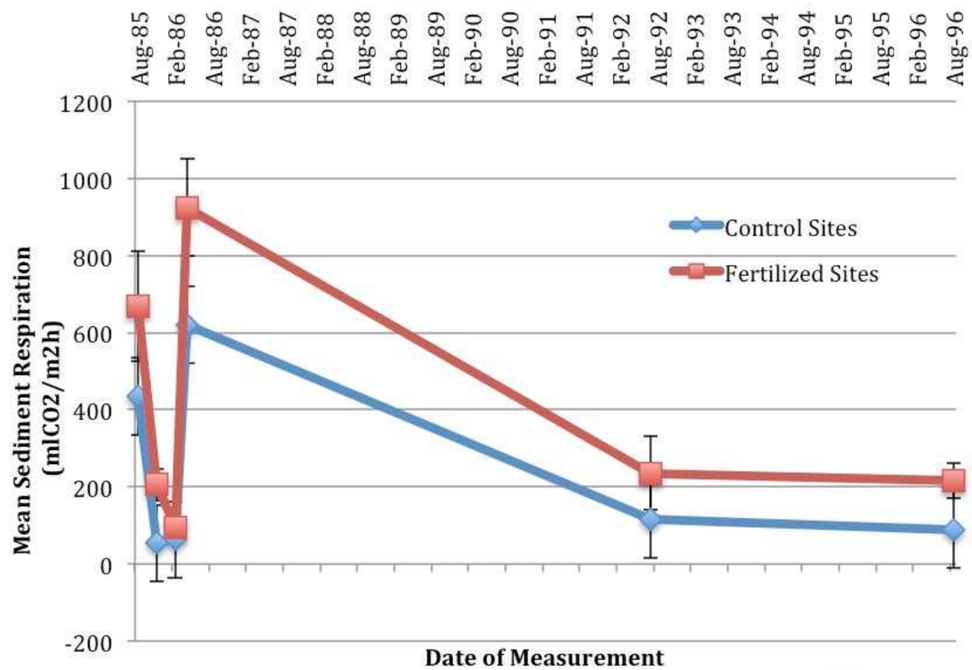

Figure 7: Morris and Bradley 1999 found that soil respiration is consistently higher in fertilized sites, meaning that carbon storage capacity is decreased.

In a study done by Morris & Bradley in 1999 it was observed that when compared to unfertilized salt marsh sites, sites that had been fertilized for 12 years showed elevated soil respiration by 36% and diminished soil carbon accumulation by 40 g C/m^2/year. Nonetheless, they noted a significant rise in elevation of the marsh platform, possible attributable to the enhanced contribution of the aboveground biomass to "trapping"—the process by which inorganic materials are accreted. Morris & Bradley's 1999 study took place in South Carolina in a marsh relatively rich in suspended sediments. The increased surface elevation they observed would likely be much less probable in sediment-poor environments.

Combined with Morris *et al*.'s results presented in Fig. 5 which show increased accretion under nutrient loading conditions, Morris and Bradley's findings here suggest that increased soil production dominates over increased soil respiration; hence, the addition of nutrients to the tidal system results in a net increase in accretion.

2.2 Descriptions of models

2.2.1 Point model

This project builds on the model developed by Marani et al. (2007), which effectively describes the complex dynamics that control and regulate the elevation of a tidal platform as well as the biomass of the macrophyte population and the microphytobenthic colonies. The model, and by extension, the model used here, makes two assumptions: that the area of the tidal platform is either (1) large enough such that the sample of scales of heterogeneity involved is statistically significant (i.e. topographies, vegetation, sedimentation, etc.) or (2) small enough such that the correlation scales of heterogeneity can be assumed to be consistent within the tidal frame encompassed by the model. As such, the model utilizes either spatially averaged or point platform properties, respectively, and assumes local spatial gradients to be insignificant. The following figure illustrates the model framework (Marani *et al.* 2007):

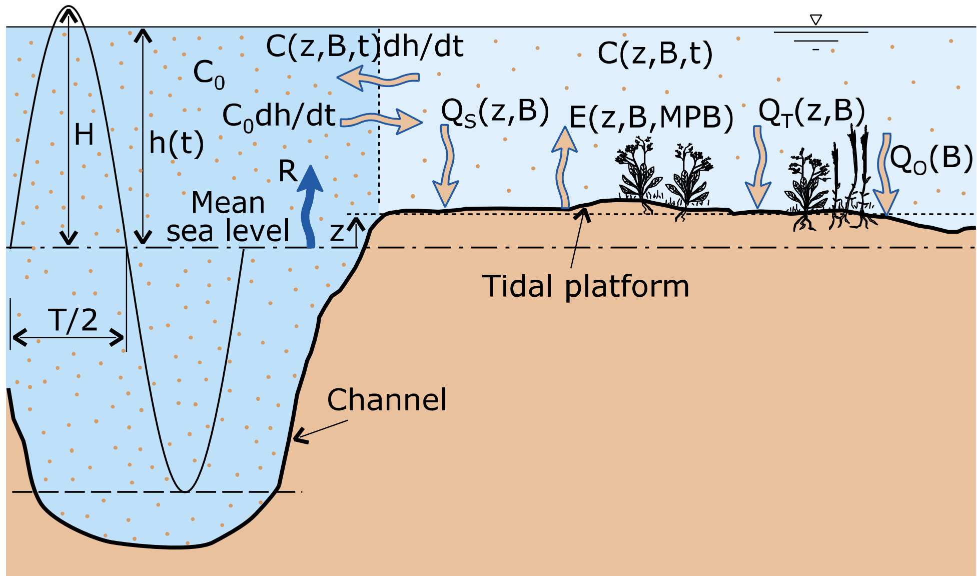

Figure 8: point modeling framework including sediment fluxes contributing to and working against accretion to the marsh floor.

Long-term evolution of the tidal frame is depicted by the following sediment balance equation, which is a version of Exner's equation and expresses variations in soil elevation relative to mean sea level (Marani 2010):

$$\frac{dz}{dt} = Q_s(z,B) + Q_T(z,B) + Q_O(B) - E[z,B,MPB(z)] - R$$

With Qs = deposition due to settling, Qt = deposition due to trapping, Qo = organic accretion, E = erosion, R = relative sea level rise, z = elevation of the marsh platform, B = biomass, and MPB = microphytobenthos (Marani 2010).

Marani *et al.* and D'Alpaos *et al.* (2010) originated this equation and have integrated it over space in order to analyze the time progression of the mean elevation of a tidal platform. To describe the parameterization of hydrodynamic flows and sediment transport, which describes the water and sediment fluxes between the channel and the tidal platform, in greater detail, see the following equation, which implements this parameterization:

$$\frac{d}{dt}(DC) = -w_s C - \propto B^{\beta} C + C\frac{dh}{dt}$$

where h(t) is the instantaneous tidal elevation with respect to local mean sea level, D(t)=h(t)-z is the instantaneous water depth, and C(z,B,t)=C_0 when dh/dt>0, while C(z,B,t)=0 when dh/dt<0; $h(t) = Hsin \cdot (\frac{2\pi t}{T})$ where H is the tidal amplitude and T=12 hours is the main tidal period; $w_s \cdot C(t)/\rho_b$ represents instantaneous settling flux and $\alpha \cdot B^{\beta} \cdot C(t)/\rho_b$ is the instantaneous trapping flux. The instantaneous settling flux and trapping flux, when integrated over all yearly tidal cycles, produce the annual mean total inorganic flux from the water column to the surface, which is denoted Q_s (t). Marani *et al.* assumed that the settling velocity w_s=0.2 mm/s. This settling velocity is typical for a sediment size of 20 μm and has been retained for the continued implementation of the model; α and β account synthetically for suspended sediment trapping capacity of the halophyte canopy (Marani *et al.* 2010). The bulk density of the sediment after compaction is denoted ρ_b+ρ_s(1-p), with ρ_s= 2650 kg/m^3 and porosity p=0.5. Due to the wave energy dissipation and the stabilizing effect associated with the presence of vegetation within the marsh, erosion E is assumed to be zero for vegetated equilibrium states. Otherwise it is denoted E (B,x,t)α(τ(z,t)- τ_c (MPB)), with τ_c (MPB) being a function of the presence of microphytobenthos (which produce a stabilizing biofilm) representing the threshold shear stress above which erosion starts. E (B, x, t)=0 when τ (z, t)< τ_c (MPB). τ (z, t) denotes the wave-induced bottom shear stress that is a function of the locally variable wind velocities and of water depths that vary with time (Marani *et al.* 2013).

Vegetation response time scales are shorter than typical response times for geomorphological processes (Marani *et al.* 2010). Therefore, instead of utilizing a complete dynamical equation for the time evolution of biomass, it is assumed to be in equilibrium with elevation of the tidal landform and is denoted B(z). From field data used in Marani *et al.* 2010, it is assumed that the production of biomass is an increasing function of elevation, utilized in the multi-species case: B (z)=B_0 (2)(z/(Hz)) where B_0 = 1 kg/m^2, z>0). Data gathered from *Spartina*-dominated environments, which are typical of North American marshes, yield a biomass productivity function that decreases with elevation: B (z)=B_0 (2)(H-z)/(2H-z).

These assumptions yield an organic accretion function which is denoted Q_o(z)=γB(z) where γ incorporates the characteristics of typical marsh halophytes and the density of the organic soil they produce after compaction and decomposition processes and is equal to 2.5x10^{-6} m^3/year/g.

The deposition and erosion fluxes within the model, therefore, are dependent only on elevation and the system displays a set of stable and unstable fixed points whose actual accessibility is dictated by spatially-varying initial condition and RSLR forcings. Assuming a constant rate of RSLR in space and time, the equilibrium states can be identified by determining the values of z for which dz/dt = 0 . The following figure (from Marani *et al.* 2013) illustrates the stable states:

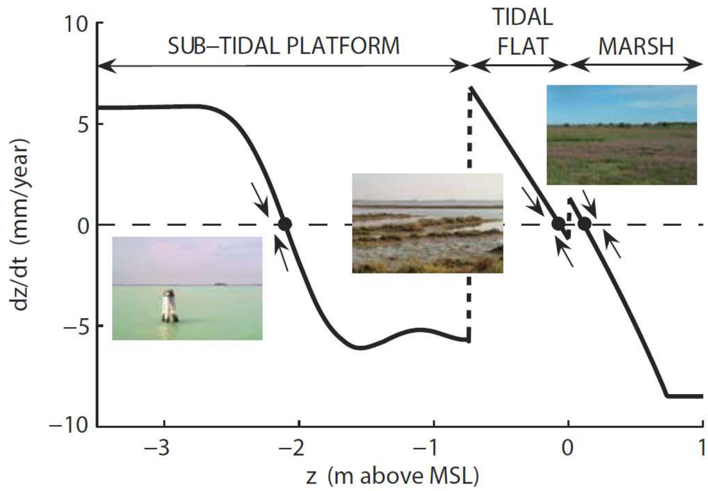

Figure 9: a depiction of the three accessible alternative stable states within the tidal frame, accompanied by a photographic example of each environment.

The present work is concerned with the effects of nutrient loading and atmospheric carbon dioxide increase on marsh platform soil accretion, and those effects can be best understood through studying macrophyte responses to nutrient enrichment. Hence, we introduce further important dependencies for aboveground and belowground biomass contributions to organic accretion:

The belowground biomass contribution is manipulated by multiplying the background rate of organic deposition by a belowground multiplying factor that is a function of nutrient addition and is derived from Morris 2002 data which show that with nutrient treatment, belowground biomass production decreased from 1201 to 726 g/m²/year that takes into account the belowground biomass contribution to organic accretion. The function is implemented as a multiplier for organic accretion and is written as follows:

$$G(N) = 0.01318 \times N + 1$$

Where N=nutrient addition. Similarly, the increased atmospheric carbon dioxide trials also make use of this function by implementing the parameterization derived from Cherry *et al.* 2009 data described in the previous section and written as follows:

$$f(CO_2) = 0.012975 \times CO_2 - 3.9305$$

The aboveground biomass contribution (trapping) is manipulated by multiplying the background rate of trapping by an aboveground nutrient enrichment-dependent function, which incorporates the aboveground biomass contribution to trapping, which is derived from the Morris 2002 data that found that nutrient addition created an increase in aboveground biomass production from 780 to 3280 g/m²/yr. This function is implemented as a multiplier for trapping within the model and defined as follows:

$$G(N) = 0.1068 \times N + 10$$

Where N=nutrient addition as before. Likewise, increased atmospheric carbon dioxide trials utilize this function by once again implementing the parameterization derived from Cherry *et al.* 2009 which showed that elevated carbon dioxide increases aboveground biomass production and therefore also trapping, written as follows:

$$f(CO_2) = 0.012975 \times CO_2 - 3.9305$$

2.2.2 One-Dimensional Model

The one-dimensional model is able to incorporate space, and thus species distribution, in order to enhance understanding of tidal system biogeomorphological evolution. Zonation, a spatial pattern in which patches composed of single species or of mixtures of species with approximately fixed composition display sharp transitions in the seeming absence of appreciable topographic gradients, is a well-known trait of marsh vegetation species distribution. Through use of the one-dimensional model, it is shown that zonation is a biogeomorphological property of the salt marsh environment and not merely a result of biological factors. It is also shown that species distribution is evidence of the acknowledged feedbacks between biomass productivity and vertical accretion to the marsh floor. Marani *et al*. 2013 originated this approach, the framework of which can be visualized with the aid of the following figure (from Marani *et al.* 2013):

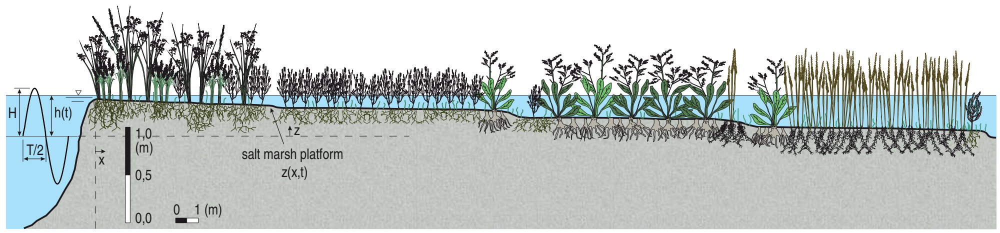

Figure 10: one-dimensional modeling framework schematic featuring the incorporation of species zonation along the marsh platform elevation gradient.

The environment is described in one dimension by coupling a space-dependent exner equation, enforcing sediment mass conservation, and an equation for sediment transport across the marsh. As before, the erosion flux is negligible due to dominance of marsh vegetation and its stabilizing effect, while vegetation competition is linked to a fitness-function description of vegetation adaptation to the local elevation conditions.

In order to calculate the rate of local inorganic sediment deposition, the modelintegrates the instantaneous settling flux over a year and thus computes the mean annual settling flux rate. Next, the instantaneous suspended sediment deposition flow velocities are needed in order to calculate the settling flux. These are obtained by assuming an advective-dispersive sediment transport process that is solved for short time scales:

$$\frac{\partial yC}{\partial t} + \frac{\partial}{\partial x}\left(uCy - k_d y \frac{\partial C}{\partial x}\right) = -w_s C$$

where $y(x, t) = z_w(t) - z(x, t)$ is the water depth, $z_w(t)$ is the elevation of the free surface, k_d is the dispersion coefficient [assumed to be a constant value, $k_d = 1.5$ m^2/s, characteristic of the small flow velocities typical in marshes], and $u(x, t)$ is the fluid advective velocity.

The latter is computed from the water continuity equation (in a quasi-static propagation of tidal levels assumption) by assuming a sinusoidal fluctuation of the tidal level $z_w(t) = H \cdot \sin(2t/T)$ (with T = 12 h and H = 0.5 m typical of microtidal settings). Sediment erosion is neglected because of the effective wave dissipation by aboveground biomass on the marsh surface. To assess the competitive dynamics of different vegetation species and thus predict the emerging zonation patterns, the model gives the local organic accretion rate as a function of the species-specific fitness function. This fitness function delineates which species will colonize the site at each time step. It also specifies the degree of adaptation of the species to each elevation increment, and represents the actually-produced fraction of the maximum rate of biomass production characteristic of the species under optimal growing conditions; as previously noted, marsh species are acknowledged to attain maximal productivity within specific elevation ranges.

In addition to elevation specialization of each species, ecological competition for space is an important control on the distribution of vegetation species. Marsh halophytes have an array of competition strategies that are similar to those of terrestrial plants, largely involving the investment of energy and carbon into the acceleration of reproductive rates, and production of physiological structures that increase plant survival odds such as aerenchyma (Adam 1990). It follows that these competitive advantages reach their fullest potential when a plant is growing in its species-specific optimal habitat conditions (Marani *et al.* 2010).

This mode utilizes a fittest-takes-all representation of competition mechanisms. The distribution of species throughout the tidal frame is updated with each time step, which allows for the analysis of alternative stable states within an "ideal tidal system"—one in which stochastic heterogeneities in the environment, as well as other organisms which affect the outcome of plant species competition, are discounted.

In summary, the system evolves in time through the following steps: (1) Computation over a tidal cycle of flow velocity, suspended sediment concentration and inorganic deposition rates for the current topographic profile. The yearly average deposition rate at year t_j is evaluated as $Q_S(x_k, t_j) = n_T/T \cdot \int w_S \cdot C(x_k, t)dt$ [n_T being the number of tidal cycles in 1 year, C (x_k, t) the local instantaneous suspended sediment concentration, and w_S = 0.2 mm/s a typical settling velocity of fine intertidal sediments]. (2) Computation of $Q_O(x_k, t_j) = \gamma \cdot B_0 \cdot f_i(z(x_k, t_j))$, where $\gamma \cdot B_0$ = 2.5 mm/year, i being the species currently occupying coordinate x_k. (3) Computation of $\partial z/\partial t = Q_s(x_k, t_j) + Q_o(x_k, t_j) - R$ and update of the topography at each site as $z(x_k, t_j + \Delta_t) = z(x_k, t_j) + \delta z/\delta t(x_k, t_j) \cdot \Delta_t$ ($\Delta_t = 1y$). (4) Update of the species distribution throughout the transect using the fittest-takes-all competition mechanism (Marani *et al.* 2013).

2.3 Model simulations

2.3.1 Point model

The point modeling approach is used to show the effects of nutrient addition, elevated atmospheric carbon dioxide, and varying suspended sediment availability on the elevation profile of the tidal landform, as well as on the accessibility of the salt marsh equilibrium state. This was accomplished by running the following simulations:

1. Baseline scenario—keeping nutrient addition equal to 0 mol/m^2/year, suspended sediment availability constant at 20 kg/m^3 (typical of a relatively sediment-starved environment, such as the Venice lagoon) and atmospheric carbon dioxide levels ambient at 380 ppm.
2. Varying nutrient addition level between 0 and 30 mol/m^2/year while keeping suspended sediment availability constant at 20 kg/m^2.
3. Varying nutrient addition level between 0 and 70 mol/m^2/year while simultaneously allowing suspended sediment concentration to vary between 0 and 10 kg/m^3.
4. Varying atmospheric carbon dioxide level between 380 and 700 ppm while keeping suspended sediment availability constant at 20 kg/m^2.
5. Varying atmospheric carbon dioxide level between 380 and 430 ppm while simultaneously allowing suspended sediment concentration to vary between 0 and 10 kg/m^3.

2.3.2 One-dimensional model

1. Three species “no trapping” 5000 year scenario—keeping nutrient addition equal to 0 mol/m^2/year, suspended sediment availability

constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.

2. Three species "no trapping" 5000 year scenario with doubled sea level rise-- keeping nutrient addition equal to 0 mol/m^2/year, suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.
3. Three species moderate nutrient addition 5000 year scenario-- setting nutrient addition equal to 1 mol/m^2/year (chosen to maintain consistency with nutrient loading values reported in Darby and Turner 2008), keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.
4. Three species moderate nutrient addition 5000 year scenario with doubled sea level rise-- setting nutrient addition equal to 1 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.
5. Three species high nutrient addition 5000 year scenario-- setting nutrient addition equal to 1.7 mol/m^2/year (once again chosen to maintain consistency with nutrient loading values reported in Darby and Turner

2008), keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.

6. Three species high nutrient addition 5000 year scenario with doubled sea level rise-- setting nutrient addition equal to 1.7 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.
7. Six species “no trapping” 5000 year scenario—keeping nutrient addition equal to 0 mol/m^2/year, suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.
8. Six species “no trapping” 5000 year scenario with doubled sea level rise-- keeping nutrient addition equal to 0 mol/m^2/year, suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.
9. Six species moderate nutrient addition 5000 year scenario-- setting nutrient addition equal to 1 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.

10. Six species moderate nutrient addition 5000 year scenario with doubled sea level rise-- setting nutrient addition equal to 1 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.
11. Six species high nutrient addition 5000 year scenario-- setting nutrient addition equal to 1.7 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 3.5 mm/year.
12. Six species high nutrient addition 5000 year scenario with doubled sea level rise-- setting nutrient addition equal to 1.7 mol/m^2/year, keeping suspended sediment availability constant at 20 kg/m^3, atmospheric carbon dioxide levels ambient at 380 ppm, and relative sea level rise equal to 7 mm/year.

3. Results

3.1 Point model

The results of the point model simulations are shown here in two formats: the tidal frame equilibrium curve (Figures 11, 12, 13) and the suspended sediment concentration (C0) “threshold curve” (Figures 14 and 15). The tidal frame equilibrium curve indicates what alternative stable states are potentially accessible by the system . Of particular interest to this thesis is the salt marsh equilibrium state, which is indicated by the equilibrium point that is furthest to the right.

By plotting the change in elevation over time against elevation itself a characteristic tidal equilibrium pattern emerges (Figure 11).

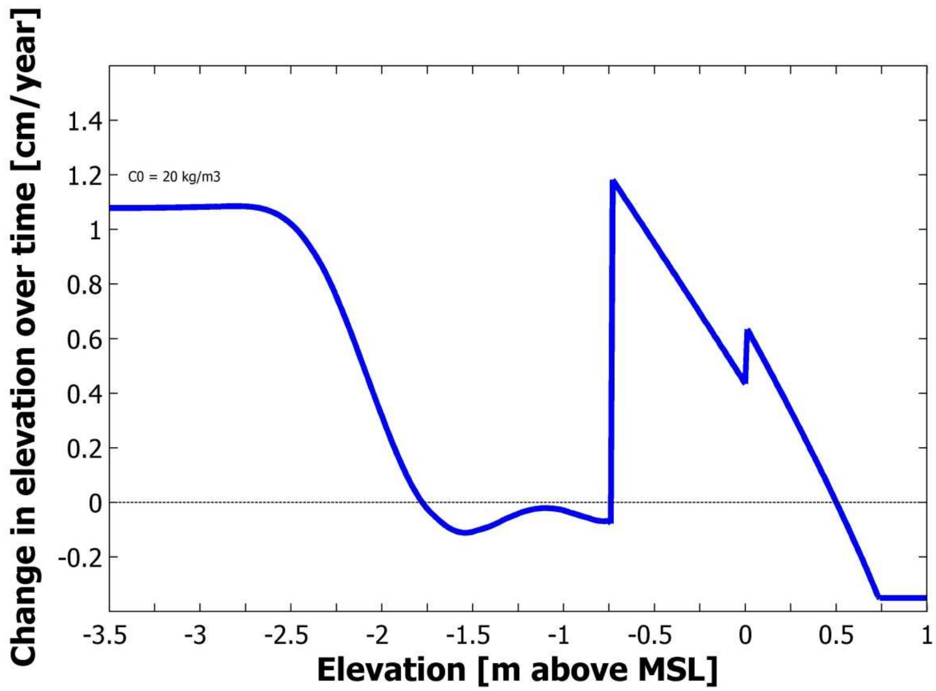

Figure 11: The characteristic tidal equilibrium curve when suspended sediment is set to 20 kg/m³.

The point model experiments show that the result of adding nutrients in concentrations up to 70 mol/m²/year is a downward elevation shift of the salt marsh equilibrium state from approximately 0.6 to 0.4 m above mean sea level (Figure 12):

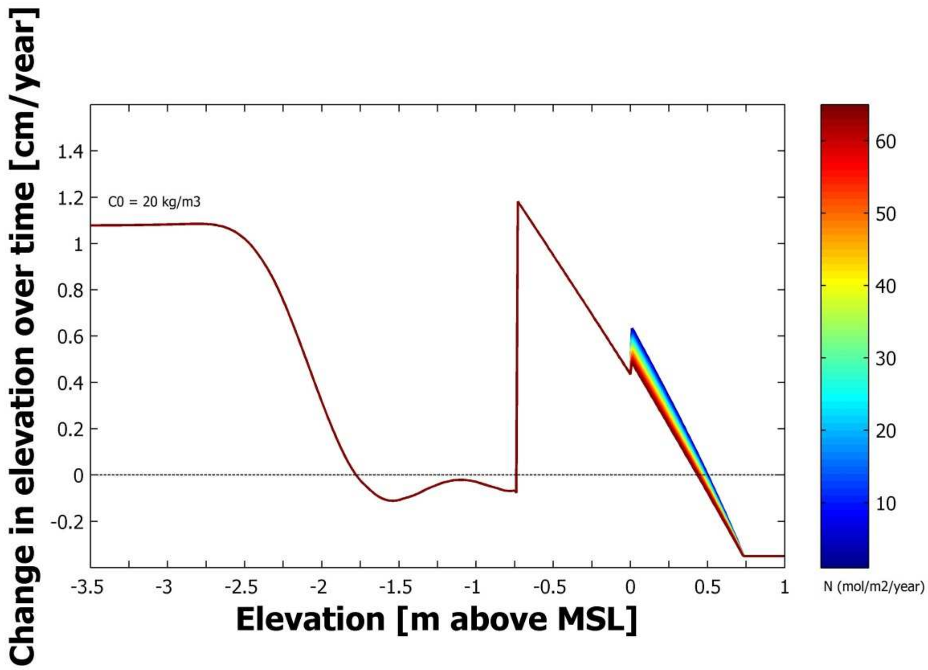

Figure 12: as the level of nutrient enrichment is increased, the salt marsh equilibrium elevation decreases.

The point model simulations further show that the result of increasing atmospheric carbon dioxide from 380 to 700 ppm is an upward elevation shift of the salt marsh equilibrium state from approximately 0.5 to 0.75 m above mean sea level (Figure 13):

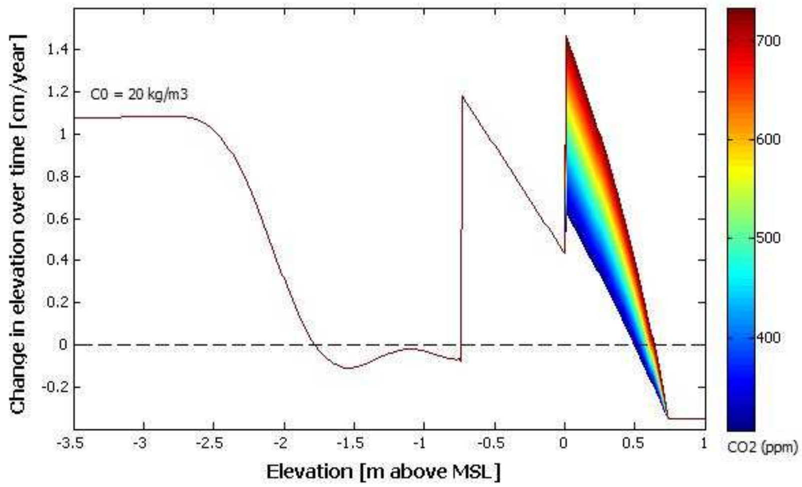

Figure 13: as the level of atmospheric carbon dioxide is increased, the tidal frame equilibrium curve shifts to higher elevations within the salt marsh elevation zone.

It is also shown that with the addition of nutrients from 0 to 70 mol/m^2/year, suspended sediment requirements for sustainability of the marsh increase from approximately 3.8 to 8.4 kg/m^3 (Figure 14). In the present global context, in which sediment delivery to the coast tends to be reduced worldwide, these results indicate a decreased resilience of marsh equilibria as nutrient concentrations increase.

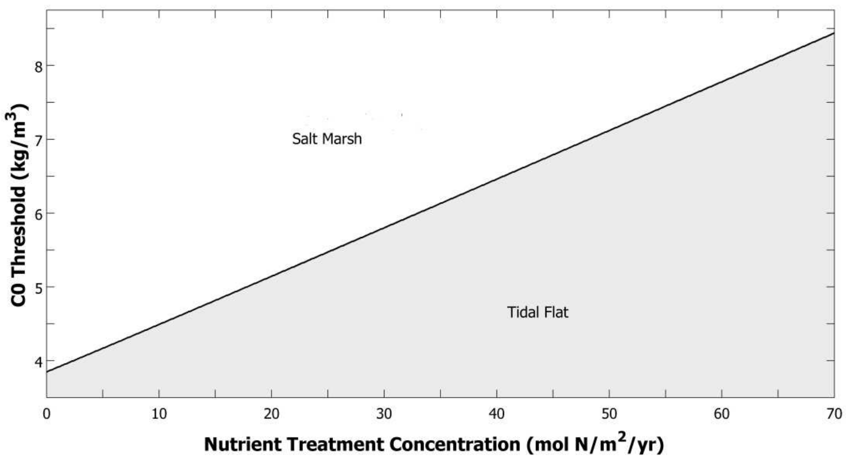

Figure 14: with increasing nutrient enrichment, suspended sediment availability must also increase in order to maintain the salt marsh equilibrium state.

On the contrary, elevating atmospheric carbon dioxide from 380 to 430 ppm results in decreasing requirements for suspended sediment availability from approximately 3.8 to 0.5 kg/m^3 (Figure 15).

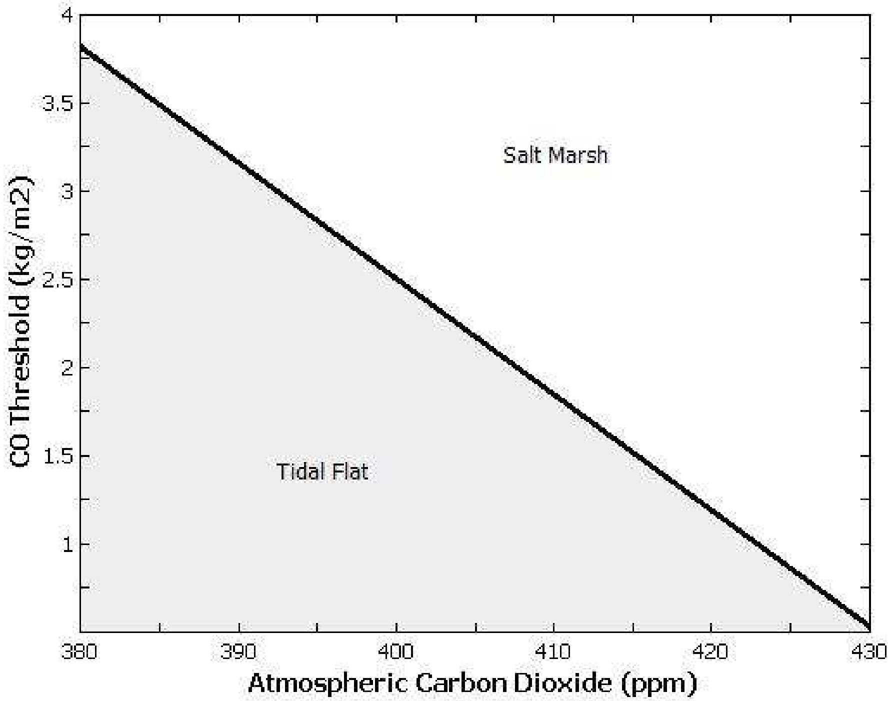

Figure 15: with increasing carbon dioxide, the suspended sediment availability required to maintain accessibility of the salt marsh stable state decreases.

3.2 One-dimensional model

The results of the one-dimensional simulations are shown here in the form of plots that show the spatial marsh profile. As the system is perturbed in different ways (nutrient addition, sea level rise, and species number are manipulated), these graphs show the effects of those perturbations on species and elevation distributions in space. Figures 16 and 17 show the effects of varying nutrient addition and relative sea level rise on the elevation and zonation of a three-species system over 5000 years.

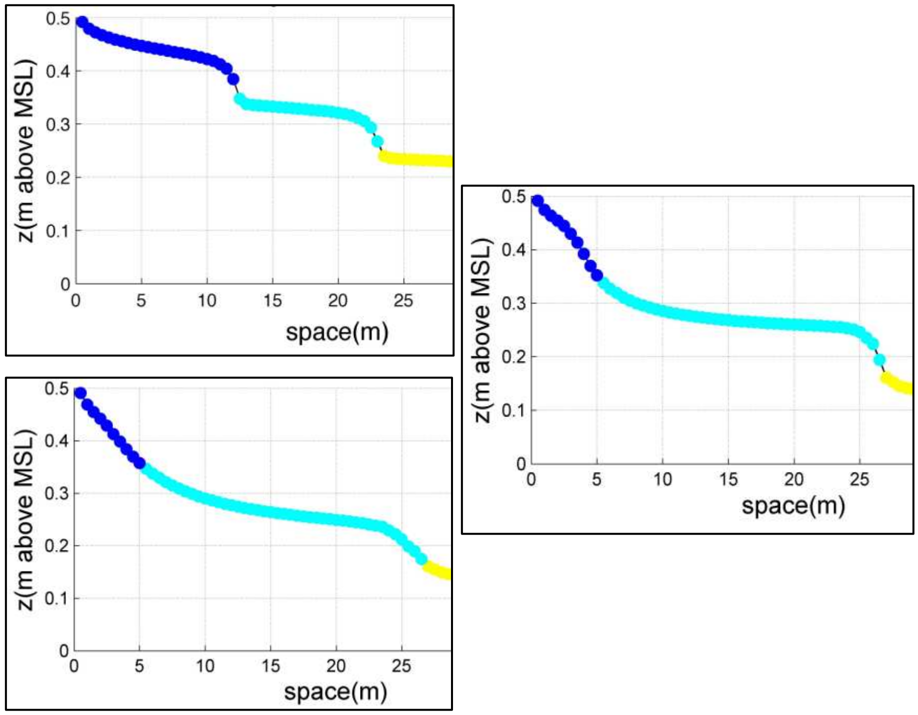

Figure 16: three-species system elevation profiles after 5000 years; clockwise from top left nutrients = 0, 1, and 1.7 mol/m²/year, RSLR=3.5 mm/year.

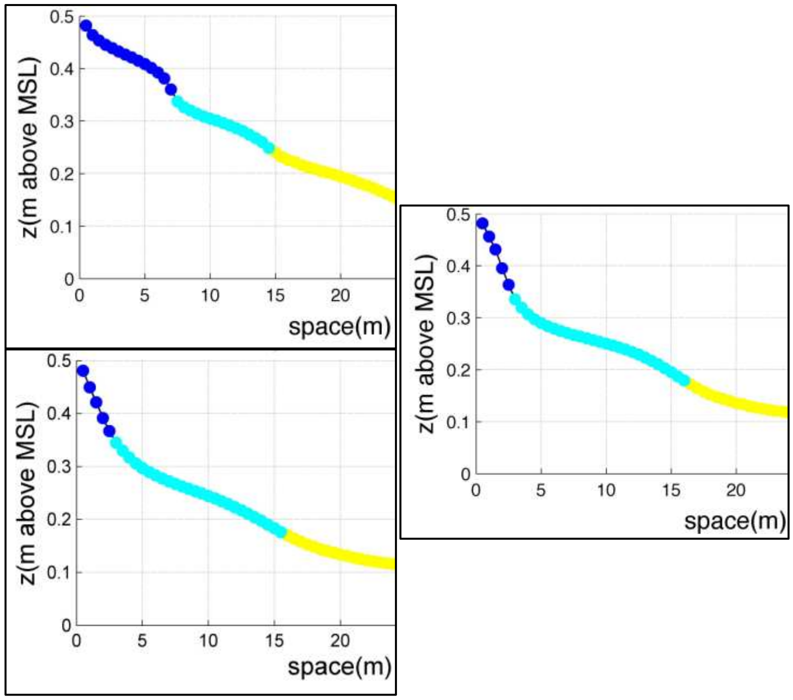

Figure 17: three-species system elevation profiles after 5000 years; clockwise from top left nutrients = 0, 1, and 1.7 mol/m²/year, RSLR=7 mm/year.

Uniformly and regardless of nutrient addition status, when relative sea level rise is increased from 3.5 to 7 mm/year, the spatial structure of the marsh experiences a collapse and the characteristic “terraced” profile flattens out, meaning that the species zonation becomes less distinct as the system experiences elevation change due to relative sea level rise. Additionally, this thesis finds that nutrient addition decreases the overall elevation of the three- species tidal frame.

Figures 18 and 19 show the effects of varying nutrient addition and relative sea level rise on the elevation and zonation of a six-species system over 5000 years:

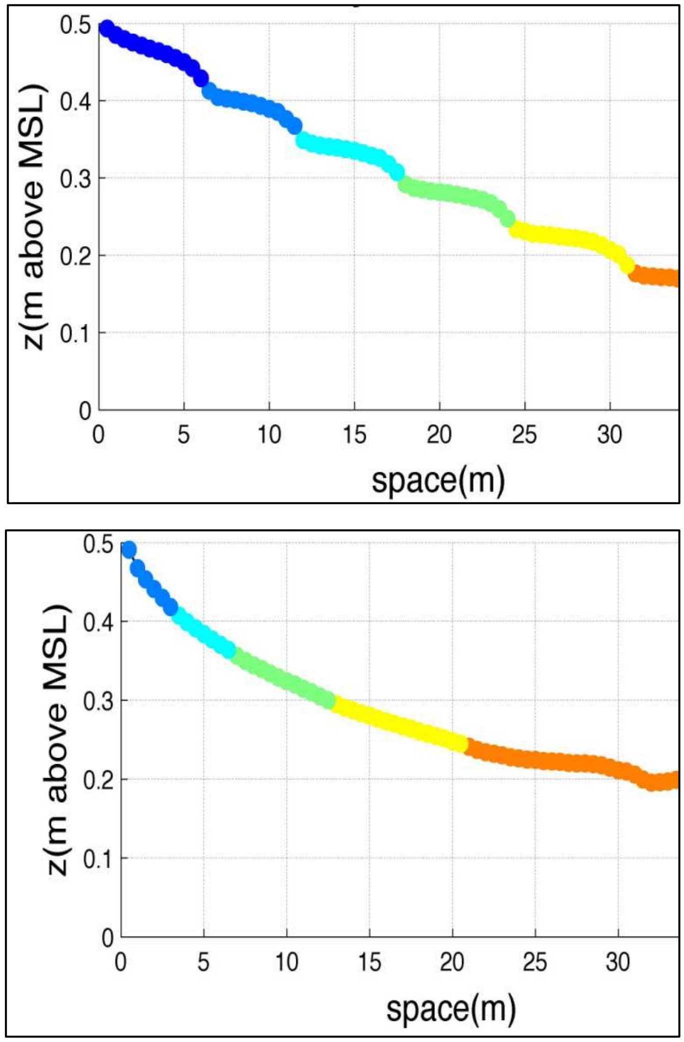

Figure 18: six-species system elevation profiles after 5000 years; nutrients = 0 at top and 1.7 mol/m²/year at bottom; RSLR=3.5 mm/year.

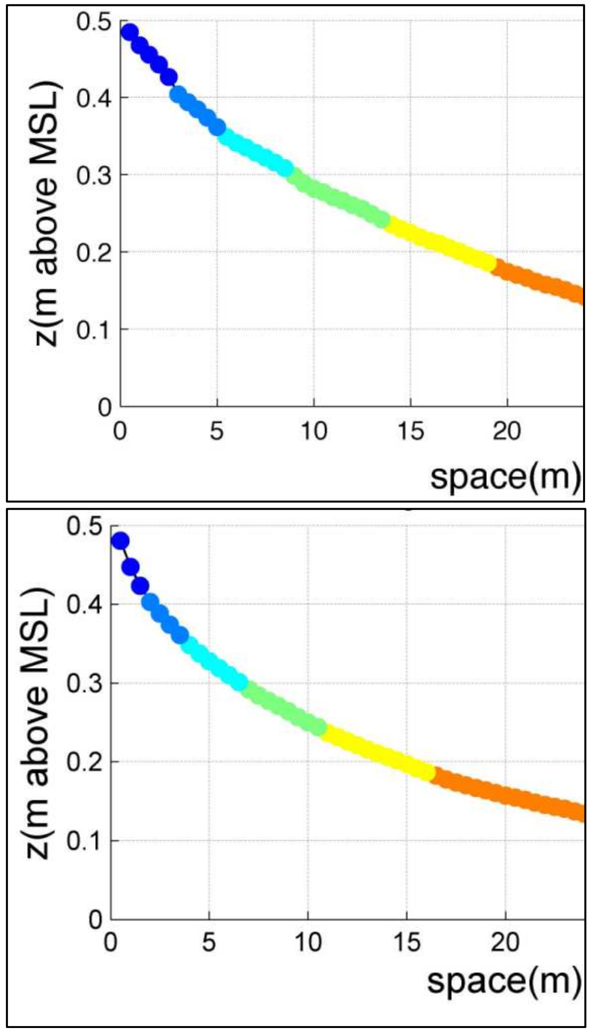

Figure 19: six-species system elevation profiles after 5000 years; nutrients = 0 at top and 1.7 mol/m^2/year at bottom, RSLR=7 mm/year.

Note that biodiversity (as measured by species number) does not promote a significant elevation difference between the way that three- and six- species systems respond to relative sea level rise (See Figure 17 for comparison).

Similarly to in the three-species system, when relative sea level rise is increased from 3.5 to 7 mm/year, the spatial structure of the marsh experiences a collapse and the characteristic “terraced” profile flattens out. Additionally, this thesis finds that nutrient addition decreases the overall elevation of the six- species tidal frame.

4. Conclusions

4.1 With regard to nutrient enrichment

4.1.1 Nutrient enrichment decreases accretion under background SSC

Figure 9 shows that as nutrients are added to the tidal system, the equilibrium curve within the salt marsh elevation zone is forced to lower elevations when the suspended sediment concentration is held constant at 20 kg/m^3. This means that in sediment poor environments, nutrient addition will effectively reduce the marsh's resilience to relative sea level rise.

4.1.2 Marshes subject to increased nutrient loads require higher SSC

This thesis has shown that in coastal environments with high nutrient loading, it is necessary also to have high suspended sediment availability in order to maintain the salt marsh equilibrium (Fig. 11). Without high suspended sediment availability, marshes with high nutrient loading will experience a shift in productivity from belowground to aboveground biomass production but the accompanying trapping potential will not be actualized. However, if suspended sediment availability is high enough to meet these increasing requirements for sustainability, nutrient addition could increase marsh resilience to relative sea level rise.

4.2 With regard to carbon dioxide enrichment

4.2.1 Elevated carbon dioxide increases accretion under background SSC

Figure 10 shows that as atmospheric carbon dioxide increases within the tidal system, the equilibrium curve within the salt marsh elevation zone is forced to higher elevations when the suspended sediment concentration is held constant at 20 kg/m^3. This means that in sediment poor environments, carbon dioxide will effectively promote the marsh's resilience to relative sea level rise.

4.2.2 Marshes subject to elevated atmospheric CO2 have lower SSC requirements

It has been shown in this thesis that under conditions of elevated atmospheric carbon dioxide, the suspended sediment concentration required to maintain the salt marsh stable state decreases (Fig. 12). In the absence of high suspended sediment availability, marshes with elevated atmospheric carbon dioxide will experience an increase in belowground biomass production and therefore will accrete more rapidly regardless of suspended sediment availability.

4.2.3 Accretion change due to CO_2 elevation is greater than change due to nutrient enrichment

We can make this statement with considerable certainty for two reasons: (1) the largest projected nitrogen loading rates to marine environments are on the order of 1.7 $mol/m^2/yr$ (Darby & Turner 2008), while the amounts added in the simulations here were orders of magnitude greater (up to 70 $mol/m^2/yr$) and still affected only a small decrease in accretion; (2) current IPCC atmospheric carbon dioxide concentration projections range between 500 and 900 ppm—in some cases greater even than the values used in our simulations (up to 700 ppm), which as we have demonstrated, effected large increases in accretion.

4.3 With regard to biodiversity

Terrestrial grasslands with greater biodiversity have been demonstrated to be more productive and resilient than less species-rich systems (Naeem *et al.* 1994, Tilman and Downing 1994). Tilman and Downing (1994) further state that with increased biodiversity there is increased ecosystem stability. With increased biodiversity, these systems also experience increased productivity and ecosystem functionality (Tilman and Downing 1994), which leads us to believe that more species-rich marsh environments will be able to achieve higher rates of organic accretion. However, Figures 16 and 18 show that under current relative sea level rise conditions (3.5 mm/year) and nutrient addition, six-species systems maintain elevation relative to sea level rise no better than three-species systems do—i.e., the change in elevation between the two systems is not significant. Therefore, we cannot state that marshes featuring mixed communities are more resilient to relative sea level rise than monoculture communities. This discrepancy between the current results and Naeem *et al.* (1998), Tilman and Downing (1994) and others may be attributable to the ecological differences between salt marshes and terrestrial environments. Salt marshes tend to feature simple patterns of vegetation colonization, where species diversity is largely a matter of elevation-determined zonation. As such, a perfect comparison cannot be drawn between these environments and terrestrial systems.

4.4 Regarding future salt marsh sustainability

It is difficult to predict how coastal wetlands will respond to global forcings such as increased atmospheric carbon dioxide and nutrient loading, given the complexity of interactions among biological and environmental factors as synthesized in this thesis. Modeling approaches will always be guilty, to some extent, of oversimplification. However, the models utilized here incorporate data-based parameterizations that realistically reproduce observed behaviors. Sustainability of coastal wetlands in response to climate change and nutrient loading will be characterized by high local variability and will be dictated by a variety of locally variable factors such as suspended sediment availability and local rates of nutrient loading. This thesis provides a foundation for the scientific community's understanding of salt marsh responses to climate change as well as a comprehensive model uniquely situated for further investigation as more current data and climate change projections are made available.

4.5 Summary and future research

Elevated atmospheric carbon dioxide levels, nutrient loads to coastal wetlands, changing biodiversity patterns due to development, and increasing relative sea level rise—that is what the future holds for salt marshes. This thesis has elucidated the relative role of some of the mechanisms that will regulate biogeomorphodynamic responses of tidal systems to anthropogenic pressures. In general, carbon dioxide increases organic accretion, nutrient loading decreases elevation, and increasing relative sea level rise requires marshes to "keep up" -- to accrete at a rate at least equal to that of rising ocean waters. Additionally, the results of this thesis indicate that marshes with carbon-dioxide rich atmospheres will have decreased requirements for suspended sediment, while nutrient-loaded marshes will require more suspended sediment in order to maintain access to the marsh equilibrium state.

However, some questions remain. First, how will these factors interact? IPCC predictions clearly state that some large degree of carbon dioxide rise is inevitable; therefore, it would be useful to know how carbon dioxide and nutrient loading jointly affect salt marsh halophytes, and whether there is any interaction between the two forcings.

Second, the results of this thesis indicate that biodiversity may promote resilience to sea level rise. However, is it necessary that the bio diverse community also possess what Zelder *et al.* (2000) refers to as "biocomplexity" That is, is a community of slightly different species sufficient to promote resilience, or must the species be drastically different (i.e. different photosynthetic pathways such as C3 and C4, which we know respond differentially to elevated carbon dioxide)? It is likely that the latter is the case, but this question will be best answered through future studies—either field studies that identify mixed communities and compare their productivity and resilience to relative sea level rise over time, or chamber studies in the style of Morris *et al.* (2002).

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