Salt Marsh Biogeochemistry and Sediment Organic Matter Accumulation

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Abstract

Sediment organic matter (OM) content varies widely among salt marshes of the USA mid-Atlantic coastline. This study examined sulfur and carbon cycle processes (sulfate reduction rates, decomposition, and root production) that influence OM accumulation in marshes.

Three treatments were established in two locations with different sediment characteristics in Phillips Creek Marsh (PCM) located at the Virginia Coast Reserve Long-Term Ecological Research (VCRLTER) site. Two of the experimental treatments were designed to alter the availability of terminal electron acceptors in sediment pore water by either removing fiddler crabs from areas with crab populations or by constructing artificial crab burrows in areas lacking crab populations. The third treatment, a reduced iron addition, was designed to lower pore-water sulfide concentrations. The results of the PCM experiments were used to explain the sediment OM content of six other marshes of the VCRLTER.

The presence of crab burrows significantly increased decomposition and decreased root production compared to the crab burrow-free treatment. Short-form *Spartina alterniflora* root growth was correlated significantly with sulfate reduction rates but not pore-water sulfide concentration. Plots with low OM generally had higher pore-water sulfide and lower pore-water sulfate concentrations than plots with more OM content. These differences could not be explained by differences in the sulfate reduction rate constants. The higher measured infiltration rates in the high OM content plots suggested that pore-water sulfide and sulfate concentrations potentially were influenced

by the effect of sediment texture on the exchange of solutes between tidal water and sediment pore water.

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Introduction

Literature Review

Salt marshes are an important ecosystem in coastal areas because they provide a wide variety of ecosystem functions. Many studies have concluded that salt marshes are a source of organic carbon for estuaries, supporting the local food web (Teal 1962; Valiela and Teal 1979; Odum 1980; Odum 1984; Hopkinson 1985; Peterson and Howarth 1987; Currin et al. 1995; Deegan and Garritt 1997). These food webs may be quite diverse. Salt marshes are used by invertebrates, fish, mammals, and birds for food and shelter (Day et al. 1989). Many commercially important fish are dependent on marshes during at least one of their life cycle stages, especially when young (Targett, 1983; Kneib, 1993; Mitsch and Gosselink 1993; Costa et al. 1994; Cattrijsse et al. 1997; Minello et al. 2003). It has been demonstrated that commercial fishery production is related to the availability of marsh area for habitat and food source (Turner 1982; Gosselink 1984; Costanza et al. 1989). Salt marshes also act as a buffer zone for upland areas. During severe storms such as hurricanes and nor'easters, marshes can contain much of the storm surge flooding, reducing upland flooding and concomitant property damage (Farber 1987). Salt marshes can also sequester carbon and may be important in mitigating CO_2 accumulation in the atmosphere (Roulet 2000).

It is therefore critical to understand how marshes respond to changes in sea level. Sea-level rise is on average 2.5mm per year world-wide (Warrick et al. 1996), but on the east coast of Virginia the relative rise in sea level has been estimated at ~3 – 3.5 mm per

year (Peltier 1985; Oertel et al. 1989; Ward et al. 1998). Without some mechanism for maintaining sediment surface elevation, marshes will disappear.

Marshes can increase surface elevation (accrete) through the import of mineral sediments and organic matter (OM) accumulation. Organic matter accumulation occurs when plant biomass adds organic matter to the sediment faster than it can decompose. It is belowground processes that are most likely to contribute to OM accumulation. In areas where short-form *Spartina alterniflora* is found, aboveground primary production is believed to be removed from the marsh surface by tide and is thus unlikely to contribute to OM accumulation in the sediment (Chalmers et al. 1985; Morris and Whiting 1986; Morris 1988; Dame 1989; Newell et al. 1989; Cifuentes 1991; Dame et al. 1991). In marshes where mineral sediment import is limited, like those of the eastern shore of Virginia, OM accumulation is the dominant mechanism for accretion (Brinson et al. 1995).

Salt marshes in the Mid-Atlantic region have a wide range of sediment OM content (Table 1). These marshes also vary in sediment texture. When sand content is high, OM tends to be low; and when clay is high, OM tends to also be high. Stribling et al. (1998) found that *S. alterniflora* leaf tissue $\delta^{34}S$ signature, an indicator of plant sulfide stress, also varies with OM and sediment texture. They reported higher $\delta^{34}S$ in sediments that were sandy and better drained; leading them to conclude that the plants were not experiencing sulfide stress, while in clay sediments with high OM the $\delta^{34}S$ was lower and indicated that the plants were sulfide stressed. These data suggest that sulfide stress and sediment texture are related and may have an effect on sediment OM content. High sand content may increase oxygen diffusion into marsh sediments, reducing sulfide stress. The

Table 1. Sediment components of Mid-Atlantic salt marshes

% Sediment OM	% Sand	% Clay	Type	Location	Source
0.5	93.9	3.5	Mainland with short *S. alterniflora*	North Carolina	(Broome et al. 1975)
4.1-6.4	5-39	15-29	Barrier Island with short *S. alterniflora*	Virginia	(Osgood and Zieman 1993)
6.0	52.4	13.2	Mainland with short *S. alterniflora*	North Carolina	(Broome et al. 1975)
6.5	57.7	11.9	Island with short *S. alterniflora*	North Carolina	(Broome et al. 1975)
7.6	76	17	Mainland with mid-height *S. alterniflora*	Maryland	(Stribling et al. 1998)
22.0	1	65	Mainland with mid-height *S. alterniflora*	Maryland	(Stribling et al. 1998)
26.4	0	45	Mainland with mid-height *S. alterniflora*	Maryland	(Stribling et al. 1998)

reduced sulfide stress may lead to a decrease in root production (Peuke et al. 1994; Ericsson 1995) and an increase in decomposition that results in a decrease in OM content.

To understand OM accumulation, it is necessary to understand decomposition and root production. Decomposition and root production can be affected by many factors including nutrient limitations, toxins (salt, pore-water sulfide), and availability of terminal electron acceptors.

Nitrogen is generally considered to be the limiting nutrient for salt marsh graminoid primary productivity (Day et al. 1989). Many studies show that the addition of inorganic nitrogen increases the aboveground growth of *S. alterniflora* (Sullivan and Daiber 1974; Valiela and Teal 1974; Gallagher 1975; Patrick and DeLaune 1976; Mendelssohn 1979). Yet, other studies show that higher sediment nitrogen content does not necessarily translate into higher aboveground primary productivity. Many have found that interior marshes have higher ammonium concentrations than at the creek bank

even though aboveground primary production is lower (Valiela and Teal 1974; Mendelssohn 1979; Valiela and Teal 1979; Buresh et al. 1980). Belowground primary production, however, is higher in the interior of marshes (Blum, 1993). Nitrogen limitation of plant productivity may be complicated by other factors such as sulfide stress.

Toxins within the sediment may be a key factor influencing OM production. During decomposition, chemicals toxic to plants are produced. The process dominating decomposition in salt marshes is sulfate reduction, which produces sulfide (Howarth and Hobbie 1982). Sulfide is toxic to organisms because it binds with the iron found in enzymes and cytoplasm inhibiting cellular function (Brock et al. 1994) such as root respiration and nutrient uptake (Mitsui 1965; Morris 1980; Koch and Mendelssohn 1989; Bradley and Morris 1990). The effect of sulfide may be especially important in the interior of the marsh where there is no subsurface exchange of water with the tidal creek (Howarth and Hobbie 1982).

Sulfide toxicity is believed to be indicated by plant tissue with a low $\delta^{34}S$ (Stribling, et al. 1998; Chambers, et al. 2001). During sulfate reduction, microbes preferentially use $^{32}SO_4^{2-}$ over $^{34}SO_4^{2-}$. Thus sulfide is significantly enriched toward the lighter sulfur isotope (Goldhaber and Kaplan 1980), enriching the pore water with isotopically lighter sulfide and heavier sulfate. When SO_4^{2-} is not limiting, *S. alterniflora* takes up sulfate, but when SO_4^{2-} is limiting *S. alterniflora* takes up sulfide so that this lighter sulfide is incorporated into its plant tissues (Carlson and Forrest 1982). Stribling et al. (1998) found that *S. alterniflora* tissue from poorly drained; organically rich

sediment had lighter isotope signatures than from irregularly flooded or sandier sites, which they attributed to sulfide toxicity in the poorly drained sites.

Sulfide may also be important in plant nitrogen uptake. For example, Bradley and Morris (1990) showed that pore-water sulfide significantly reduced *S. alterniflora*'s nitrogen uptake kinetics at concentrations as low as 0.25 mmol l^{-1}. Additionally, they found that at 2.0 mmol sulfide l^{-1} pore-water nitrogen uptake essentially ceased (Bradley and Morris 1990). If salt marsh plants behave like terrestrial plants, then the nitrogen limitation that results from the sulfide inhibition of N uptake may lead to increased root production and an increase in the root-shoot ratio (Peuke et al. 1994; Ericsson 1995). Furthermore, sulfide can be directly toxic to plant roots which may also stimulate root turnover (Carlson et al. 1994; Erksine and Koch 2000).

Decomposition is affected by the availability of terminal electron acceptors, such as O_2 and SO_4^{2-}. One of the most important factors determining the availability of electron acceptors is the permeability of the sediment. This can be affected by the texture of the sediment substrate and the presence of bioturbating animals. Oxygen, sulfate, and low molecular weight organic molecules can permeate a sandy substrate faster than a clay substrate. It has been observed that OM content of sandy sediment is significantly lower than in clay sediments (Christian et al. 1983; Ward et al. 1998) (Table 1) suggesting possibly faster decomposition in sandy sediments. Bioturbation by benthic fauna is another factor that can increase the availability of electron acceptors (Kostka et al. 2002). By creating holes in the sediment, the burrowing organisms increase the water-sediment interface allowing electron acceptors to increase contact with the upper layer of the sediment and increase infiltration (Montague 1982). The dominant bioturbating

organism in salt marsh sediments is the fiddler crab. Water within crab burrows tends to be less saline and have significantly different nutrient chemistry than the pore water (Montague 1982). Montague (1982) also found that the presence of crab burrows increased sediment respiration by 2 mg CO_2 h^{-1} per burrow compared to controls without crab burrows during July suggesting a greater rate of decomposition.

Blum (1993) found that decomposition rates between the creek bank (an area of low pore-water sulfide concentration) and interior marsh (an area of high pore-water sulfide concentration) were similar, but that root production in the interior marsh was greater than root production in the creek bank. It has been shown that stress can lead to greater root production in *S. alterniflora* (Valiela et al. 1976; Schubauer and Hopkinson 1984). Stress can result from high salinity, low redox conditions, high pore-water sulfide concentration, or nutrient limitation. Stress can also decrease the production of aboveground biomass; the plants put more energy into root production than shoot production to increase nutrient uptake and oxidize the rhizosphere (Koch and Mendelssohn 1989; Howes and Teal 1994). Overall, plant production is reduced (sum of above- and belowground), but the amount of production allocated belowground is increased. Thus, as sulfate reduction increases pore-water sulfide concentration, plants increase root production to compensate for nutrient limitation. The roots become organic matter upon death providing more material for decomposition. Decomposition in salt marsh sediments is dominated by anaerobic respiration where sulfate is the terminal electron acceptor (Howarth and Hobbie, 1982). Therefore, as decomposition proceeds as sulfate reduction, plant sulfide stress is increased leading to greater root production and concomitantly more organic matter available for decomposition. This positive feed back

between decomposition, root production, and concomitantly organic matter production may lead to an accumulation of OM in marsh sediments.

Sulfide toxicity can be mitigated by the presence of oxygen or reduced iron in the sediment. In the presence of oxygen, sulfide oxidizes quickly both spontaneously and via microbial metabolism (Brock et al. 1994). This may be of particular importance in sandy sediments, which are more permeable than clay, or in sites with crab burrows. Also, *S. alterniflora* is known to translocate oxygen through its aerenchyma tissue to its roots (Mendelssohn and Postek 1982) creating an oxidizing rhizosphere thus reducing toxicity of sulfide to the plants. Plants producing more roots would have a greater capacity to transport oxygen, thus enhanced root production when sulfate reduction is high would be a strategy that would benefit the plant. Sulfide also reacts with iron forming FeS and FeS_2 (Stumm and Morgan 1996). Thus, if reduced iron is present in salt marsh sediments, it may help mitigate sulfide toxicity (Chambers et al. 2000). For example, in *Thalassia testudinum* seagrass beds, Chambers et al. (2001) found that FeS formation was enhanced by iron addition and individual seagrass shoot growth increased.

Furthermore, there is evidence that differences in redox status and sediment iron content can impact plant tissue sulfur signatures. Currin et al. (1995) found that live *S. alterniflora* leaves from a natural marsh with higher sediment organic content and silt-clay component had remarkably lighter S isotope signatures than leaves from a transplanted marsh with lower sediment organic content and silt-clay content. They attributed this to an increased uptake and incorporation of sulfide into plant tissue (Currin et al. 1995). Similarly, Chambers et al. (2001) found that adding iron to *T. testudinum*

plots resulted in a significantly heavier $\delta^{34}S$ than in control plots indicating a reduction in sulfide toxicity as pyrite was formed.

Sulfur biogeochemistry is the driver for many of the above-mentioned processes so it is important to understand how sulfur cycles within salt marsh sediments. Sulfur is brought into the salt marsh system as sulfate (SO_4^{2-}) in the tidal water. As tidal water overlays the marsh sediment, sulfate and other solutes infiltrate the sediment pore space. The sulfate is used by plants to make proteins, sulfo-lipids and sulfate esters (Howarth 1984). Sulfate-reducing bacteria use sulfate as an electron acceptor during decomposition (Brock et al. 1994). This microbial process involves reducing sulfate to sulfide (HS^-). The fate of the sulfide is varied. It can remain in solution causing an increase in pore-water sulfide (HS^-) concentration. Sulfide can bind with metals producing various forms of metal sulfides including FeS and FeS_2 (Stumm and Morgan 1996). It also can efflux from the sediment as H_2S gas (Steudler and Peterson 1985) or efflux out of the sediment (S^{2-}, HS^- or H_2S depending on pore-water pH) into tidal water (Peterson et al. 1983). Sulfide can be taken up by plant roots and incorporated into plant biomass (Stribling et al. 1998; Chambers et al. 2001). And finally, sulfide can be oxidized to sulfate spontaneously or by sulfur-oxidizing bacteria (Howarth 1984). The metal sulfides can also be oxidized (Howarth 1984). Each of these potential pathways has an important affect on salt marsh energetics, plant biomass production, and sediment chemistry.

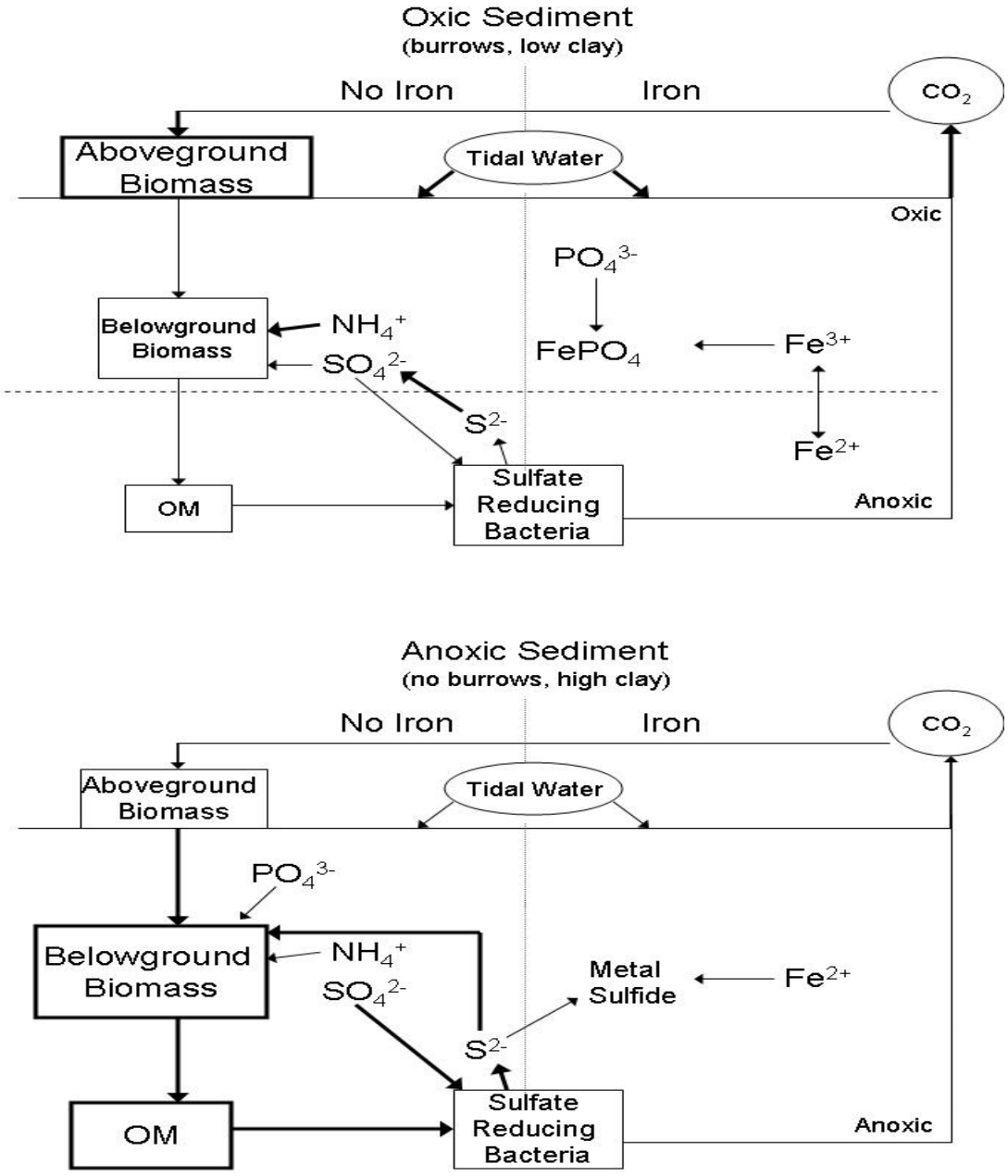
Goals of Research/Objectives

The goal of this project is to understand the combination of factors that explain why sediment organic matter content differs among mainland salt marshes on the eastern shore of Virginia. The work focused on two regions of a mainland salt marsh that are similar in age, at similar elevations above sea level, and are colonized by short-form *S. alterniflora*. The results from this salt marsh were compared to marshes in the same region to assess which marshes are most likely to accumulate sediment OM. Ultimately the results generated by this research provided information critical to understanding salt marsh response to changes in the salt water, fresh water, and land free-surfaces.

It was hypothesized that in marshes where sulfate reduction results in sulfide formation, root production will be stimulated, enhancing organic matter production and thereby allowing organic matter to accumulate. It was further hypothesized that the relationship of sediment permeability and reduced iron concentrations to biogeochemistry may lead to differences in the rate of organic matter accumulation observed in some salt marsh sediments. A conceptual model was developed to illustrate the ideas behind this experiment (Fig. 1). Specifically, the working hypothesis is:

> There exists a tolerance-limited positive feedback loop between the rates of sulfate reduction, sulfide pore-water concentration, and root production that shifts the relationship between organic matter production and decomposition to favor organic matter accumulation. This feedback loop is not realized, however, when oxygen is available as a terminal electron acceptor or when reduced iron is available in the sediments to react with sulfides produced by sulfate reduction.

Fig. 1. Conceptual model of biogeochemistry in salt marsh sediments. Thickness of arrow indicates magnitude of flow. Box outline indicates magnitude of standing stock. This figure represents the complex chemical reactions that occur under different sediment conditions. In oxic sediments, phosphate may become a limiting nutrient for plants because it binds with ferric iron, whereas in the anoxic sediment, ammonium is more likely to become limiting because of sulfide inhibition of nitrogen uptake. In oxic sediments, plants will take up sulfate, but in the anoxic sediment, plants will take up the toxic pore-water sulfide reducing its ability to take up ammonium. This will lead to a stress mechanism that causes plants to produce more belowground biomass.



The first objective of this experiment was to test the effect that enhanced terminal electron acceptor availability in sediment pore water had on root production and decomposition rates. Crab burrows were used to increase terminal electron acceptor availability (Montague 1982).

The second objective of this experiment was to test the effect reduced iron concentration had on root production. Reduced iron binds with sulfide to form FeS and FeS_2, thus reducing the toxicity of the sulfide to plants. This reduction in pore-water sulfide concentration should decrease root productivity as the plants no longer have to compensate for a decrease in root function.

The third objective of this experiment was to compare the results from the above experiments to other marshes in the region. Six marshes within the Virginia Coast Reserve (VCR) representing different levels of sediment organic matter content and crab populations were sampled once to determine if they had a similar pattern of OM accumulation as the experimental marsh.

Montague (1982) conducted a study on crab burrows and their effect on root density, pore-water solute concentrations, and sediment respiration. This study also examined those variables; however, it extends his work by examining many environmental factors that affect root production and decomposition to advance understanding of the interactions between root production and decomposition. Ultimately the results of the experiments described here were used to better understanding OM accumulation in marsh sediments.

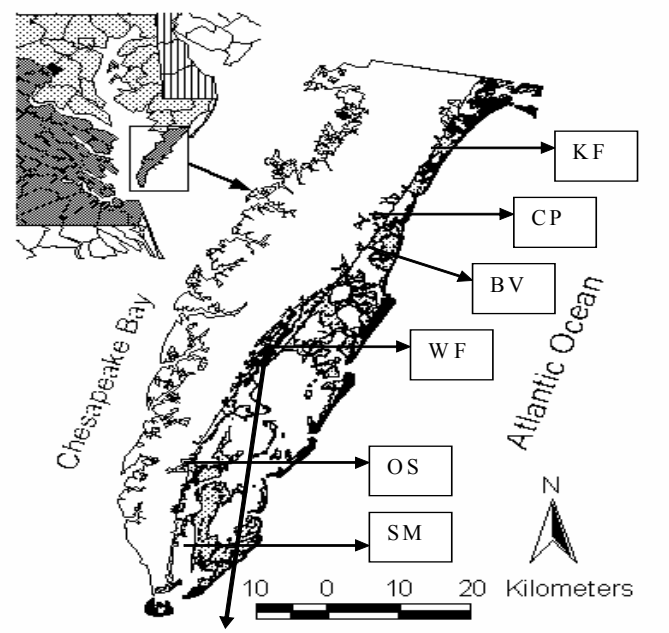
Materials and Methods

Site Description

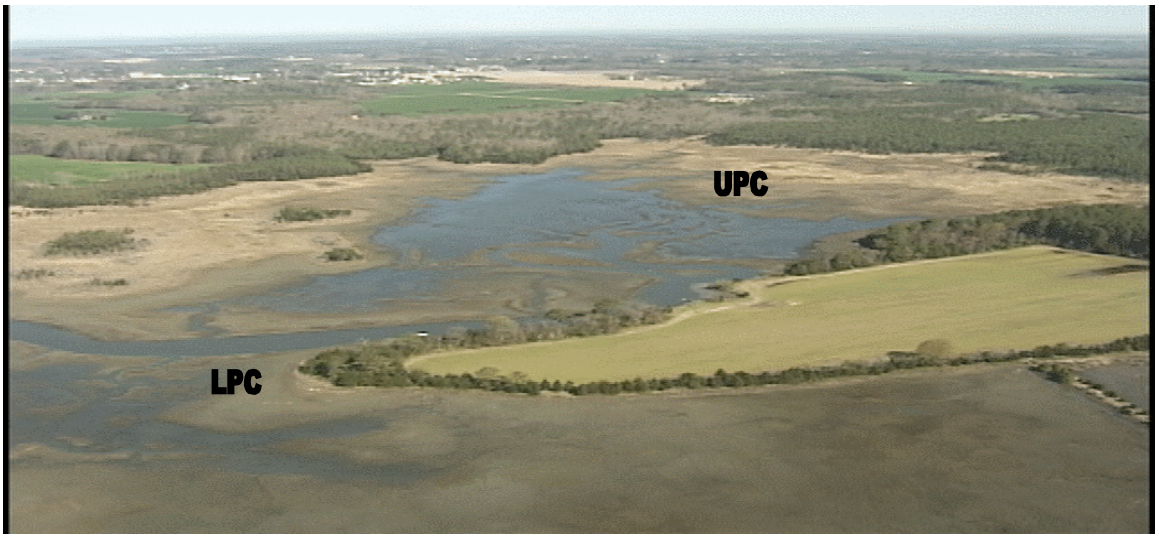
The salt marshes used in this study are located on the eastern shore of Virginia and are part of the VCR (Fig. 2). The two experimental sites were located in a marsh along Phillips Creek (37º 46' 7" N, 75º 83' 43" W) and are believed to be of similar age (Chambers et al. 1992) and receive similar inputs of new nutrients and precipitation given their close proximity along the same tidal creek (Aiosa, 1996; Tirrell 1995). Experimental plots were established in the low marsh zones of each site. The dominant vegetation at each site was short-form *S. alterniflora,* suggesting that the two sites have similar inundation frequencies (Mitsch and Gosselink 1993). There are several important differences between the two sites, however. The site designated as Lower Phillips Creek marsh (LPC) was approximately 0.6 m above mean sea level and characterized by a sandy loam sediment with 6% organic matter; roots penetrate to approximately 20 cm depth, and the sediment is similar in appearance from 0-25 cm depth. Above- and belowground biomass is low, and there are abundant fiddler crab burrows present. The aboveground density of plant stems is ~500 stems m^{-2}. The site designated as Upper Phillips Creek marsh (UPC) was approximately 0.9 m above mean sea level and characterized by sandy clay loam sediment with 33% organic matter; the top 10 cm of sediment is primarily organic; and below 10 cm, the sediment is primarily mineral with very little root penetration. Above- and belowground biomass is high, and there are no fiddler crab burrows present. The aboveground stem density is greater than 1000 stems m^{-2} (See Results section).

Fig. 2. Location of sites used in this study.

a.



b.



a. Two experimental sites are located along Phillips Creek (37º 46' 7" N, 75º 83' 43" W). Six other marshes were sampled once during the study: Steelmans Landing (SM), Oyster (OS), Woodland Farm (WF), Belleview (BV), Channel Point (CP), and Kegotank Farm (KF).
b. Upper Phillips Creek (UPC) and Lower Phillips Creek (LPC) are located approximately 700 m from one another along Phillips Creek.

Six additional marshes were sampled once to establish a regional perspective of salt marsh processes. Each of these locations was representative of the range of sediment and plant production characteristics typical of eastern shore mainland salt marshes (Ricker 1999). Fiddler crabs inhabited three of these marshes. The differences in fiddler crab presence among the marshes is directly relevant to the experiments conducted at the two sites in Phillips Creek. These marshes span the lower Delmarva Peninsula (Fig 2a.). Their associated landscapes are geomorphically different and were chosen to represent marshes with differing levels of susceptibility to sea-level rise (Ricker 1999).

Steelmans Landing (SM) is located at the southern tip of the peninsula and is adjacent to Hog Island Bay. It is a very flat and broad fringe marsh and is inhabited by fiddler crabs. Oyster marsh (OS) is located just upstream from Oyster Harbor and has a very steep slope and no fiddler crabs. It is significantly impacted by human activity. Woodland Farm (WF) is located in the middle of the peninsula along Greens Creek. It is a very flat broad marsh whose upland forest was burned in the past. It has no fiddler crabs. Bellevue (BV) is also located in the middle of the peninsula and is heavily populated with fiddler crabs. It is a small marsh with a steep slope. Channel Point (CP) is in the northern portion of the peninsula, is very organic, and has no fiddler crabs. Kegatank Farm (KF) is in the northern portion of the peninsula, has a steep slope and is inhabited by fiddler crabs.

Experimental Design

Three experimental manipulations were employed to test their impact on OM accumulation at LPC and UPC. The manipulations consisted of (1) adding reduced iron to the sediments at each site in an effort to decrease pore-water sulfide concentration and

(2) either removing crabs (and ultimately their burrows) at LPC or (3) adding artificial crab burrows at UPC to alter electron acceptor availability (Table 2). Three replicates of each treatment were done at each site (Table 3). The replicate plots were divided into subplots to accommodate the different sampling techniques employed for measuring a variety of environmental variables described below. In the "vegetation" subplot, aboveground biomass was harvested at the end of the growing season. In the "bag" subplots, decomposition and root growth litterbags were buried. The "core" subplots were used for the remainder of the analyses, such as pore-water chemistry, sulfate reduction, and sediment characteristics. The location and elevation of these plots was measured using a Trimble 4000SE GPS receiver in kinematic survey mode.

Crab Burrow Treatment

The crab burrow manipulations were begun in the summer of 2001, the first year of the study. Crab removal involved constructing exclosures around "No Crabs" and "Iron" plots (described below) at LPC and removing the crabs within these plots. The exclosures were 1.5 m^2, while the experimental plots were 1 m^2 to allow for sampling and plot maintenance within the exclosure with minimal disturbance to the plots. The exclosure frame was constructed of PVC pipe with window screening attached on four sides. The exclosure was buried 15 cm into the sediment to prevent fiddler crabs from burrowing under. Aluminum flashing was attached to the rim of the exclosure to prevent fiddler crabs from crawling over the top. Empty capture jars (large Mason jars) were also buried in the plots so that the top of the jar was flush with the marsh surface. This was to aid in reducing the number of crabs in the plot (Nomann and Pennings 1998). Plots were

Table 2. Experimental design

Site Type	No Crab Burrows	Crab Burrows	Iron Addition
Low OM	n=3	n=3	n=3
High OM	n=3	n=3	n=3

Table 3. Plot designs**.** Creek is located at top of each table.

LPC

		Iron V3		No Crabs C3	Crabs V2	No Crabs C2		
	Iron V2		Crabs B2	Crabs V3	No Crabs V2	Crabs B3	Crabs V1	
		No Crabs B1	No Crabs V1				Iron B1	No Crabs C1
Iron V1								No Crabs B3
	Iron C3						No Crabs V3	Crabs C1
								Iron B2
Iron C2							No Crabs B2	Crabs C2
							Crabs C3	
Iron C1						Crabs B1	Iron B3	

UPC

				Iron C2		Iron C3		
		Iron B3	Iron C1					Iron V1
Iron B2	Crabs B2	Crabs C1		Crabs V3			Crabs V2	
	Crabs C2		No Crabs C1		Crabs B1		No Crabs V3	Iron V2
		No Crabs C2				No Crabs V2	Crabs V1	No Crabs B1
		No Crabs C3		No Crabs B2				Iron V3
	No Crabs B3					No Crabs V1		
Iron B1		Crabs C3						
	Crabs B3							

B=litter/root growth bags 1m^2 plots
C=cores 1m^2 plots
V=aboveground End-of-year biomass 1.0 m^2 plots

monitored weekly throughout each summer and any crabs found in the exclosures were removed. Creating artificial burrow holes in the "Crabs" plots at UPC involved excavating sediment 20 cm in depth and 2 cm across with a soil auger (30 cm long, 2 cm diameter). New holes were added monthly to compensate for previous holes filling in. Approximately 50 holes per plot were present during any given month.

Iron Addition Treatment

Iron addition manipulations began in February 2002. In the iron addition treatment plots, 1.82 g $FeCl_2$ in 20 ml degassed deionized water (DIW) was added with a pore-water sampling probe and a syringe (Berg and McGlathery 2001) over a 25 cm range of depth three times over the growing season for a total addition of 600 μM $FeCl_2$ when diluted by the plot's pore water (200 μM Fe^{2+} per addition). Each addition's concentration represented enough reduced iron to react with twice the measured sulfide produced in a month as calculated from sulfate reduction measured at both LPC and UPC during the summer of 2001. Plastic barriers were buried around the iron plots to reduce iron migration out of the plots. No barrier control plots were established.

Regional Context

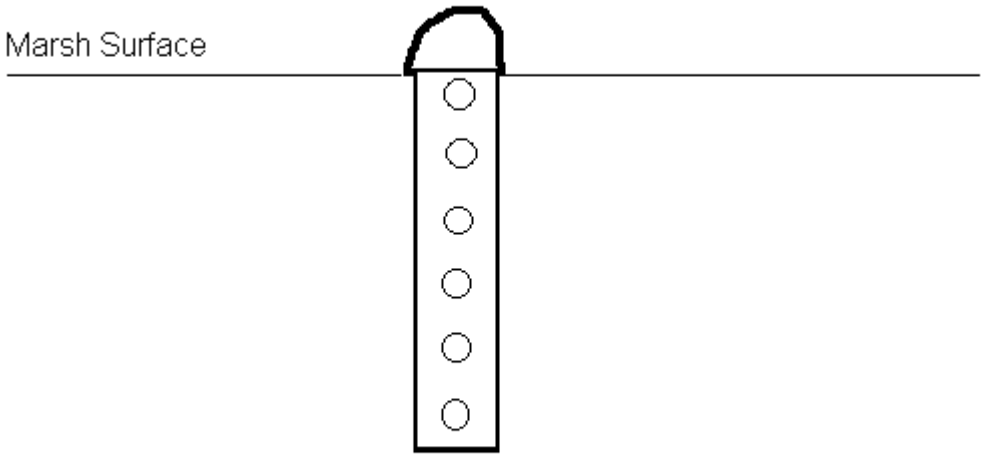
The six additional marshes were sampled once in August 2002. Three equilibrators (explained below) and three root growth litterbags (see below) were placed in each marsh in May of 2002 and samples in August. Sediment cores were also taken in August to measure sulfate reduction rates, % OM, soil composition, % H_2O, and platinum electrode potential (PtEP). Aboveground biomass was also collected at these sites in August 2002.

Measurements

Pore-water chemistry

Pore water was collected from 1, 5, 10, 15, 20 and 25-cm depths in three ways over the course of the experiment. During the summer of 2001, water was collected from sediment cores. Sediment cores were collected using a 5.2-cm diameter PVC tube. The corer was inserted into the sediment to a depth of as much as 40 cm. The cores were extruded and sliced into 5-cm increments up to 25 cm in depth and put into 50-ml polypropelene centrifuge tubes. Not all corings resulted in cores of 25 cm in length due to varying sediment conditions. The sediment-filled centrifuge tubes were stored cold and transported back to the laboratory for processing. The tubes were spun in a Sorvall RC-5B Refrigerated Superspeed Centrifuge for 30 min at 27000 x g. Supernatant was collected and aliquots of the supernatant were fixed immediately for the appropriate chemical analysis as described below. This method was abandoned because not all cores would yield sufficient water for all needed analyses. During the spring of 2002, a probe was used to collect pore water (Berg and McGlathery 2001). A long thin brass probe 40 cm long with a 1-cm interior diameter and small holes drilled at the bottom was inserted into the marsh sediment to the desired depth. A 20-ml syringe was attached to the probe by a long Nalgene tube. The syringe (and later a hand pump) was used to extract pore water. The water was filtered with a 0.2-μm Gelman 25-mm syringe filter as it entered a Vacutainer®. This method was abandoned for the same reason as above. The final and most successful method for collecting pore water was with equilibrators (Fig. 3). Sterile glass 25-ml vials were filled with degassed DIW and capped with a plastic gasket, a 0.2-μm Versapor® membrane filter cut to fit the interior of a plastic screw cap, and a plastic

Fig. 3. Equilibrator design for collecting pore water. Holes drilled into the PVC corresponded to 1, 5, 10, 15, 20, and 25-cm depth. A 25-ml glass vial filled with degassed deionized water and capped with a 0.2-µm membrane filter was inserted into each hole.



screw cap with a hole in the center. These were then inserted into a 5.08-cm diameter PVC pipe that had holes drilled into the side that corresponded to specific depths. A cap was glued over the top of the pipe to eliminate air penetration into the marsh sediment. Sediment cores were removed from the marsh and the equilibrators were placed in the resulting hole until the bottom of the cap corresponded to the surface of the marsh. The equilibrators were left in the marsh for at least 30 d to ensure complete equilibration with the pore water before sampling (Bertolin et al. 1995).

Sulfate and Chloride

Both pore-water sulfate (SO_4^{2-}) and chloride (Cl^-) concentrations were measured using a Dionex ion chromatograph with a Gelman 234 Autoinjector and a Dionex Ion Pac

AS4A 4 mm column. Eluent was composed of 1.44 mM Na_2CO_3 and 1.36 mM $NaHCO_3$. The regenerate was 0.028 N H_2SO_4. The system was pressurized by industrial grade helium gas. A Milton Roy piston mini pump pumped eluent and sample at 2 ml min^{-1}. Because of the high sample salinity, 5 µl of sample was diluted to 5.0 ml with DIW. Approximately 2 ml of the diluted sample were used for analysis. Standards used were full strength artificial seawater (24.0g NaCl, 7 g $MgSO_4 \cdot H_2O$, and 0.7 g KCl l^{-1}), half strength, one-fourth strength, and one-eighth strength seawater diluted in the above manner.

Sulfide

Pore-water free sulfide (H_2S, HS^-, S^{2-}) concentration was measured using a modified Cline's method (Cline 1969; Otte and Morris 1994). This involved fixing a 1.0-ml aliquot of sample with 1.0 ml of 4% zinc acetate (ZnAc) before analysis. To this, 0.16 ml of Cline's reagent (2.0 g N,N-dimethyl-p-phenylenediamine sulfate ($C_{16}H_{26}N_4O_4S$), 1.8 g $FeCl_3$ anhydrous, 1.2 ml H_2O, 500 ml of 50% HCl) were added. Color was allowed to develop at room temperature on the bench top for 20 min. Absorbance was read on a Milton Roy Spectronic 1001 Plus spectrophotometer at 670 nm.

Total and Reduced Dissolved Iron

Pore-water dissolved iron (Fe^{2+} and $Fe^{2+} + Fe^{3+}$) concentration was measured using the Ferrozine method (Gibbs 1979). All 1.0-ml samples were preserved with 0.02 ml of 5 N HCl. Next, for pore-water reduced iron samples, 0.05 ml of DIW was added, or for pore-water total dissolved iron samples, 0.05 ml of reducing agent (100 g hydroxylamine hydrochloride ($NH_2OH \cdot HCl$) l^{-1}) was added and allowed to sit for 5 min.

Then, 0.05 ml of ferrozine reagent (0.75g ferrozine ($C_{20}H_{12}N_4Na_2O_6S_2$) and 20 ml of 5 N HCl diluted to 1 l) and 0.125 ml of sodium acetate buffer (473 g sodium acetate trihydrate ($CH_3COONa \cdot H_2O$), 500 ml of DIW and 115 ml of glacial acetic acid (CH_3COOH) l^{-1}) were added to the samples. Color was allowed to develop for 30 min at room temperature on the bench top, and absorbance was read on a Milton Roy Spectronic 1001 Plus spectrophotometer at 562 nm.

Ammonium

Pore-water ammonium concentration was measured using the phenate method (Lagera and Blum 1997) after (Grasshoff et al. 1983). This involved adding 0.03 ml of trisodium citrate reagent (30 g of trisodium citrate dehydrate ($C_6H_5Na_3O_7 \cdot 2H_2O$), 60 ml of DIW, 2.5 ml of 0.5 N NaOH) to a 1.0-ml sample and shaking or mixing using a Vortex mixer. Immediately after, 0.03 ml of phenol reagent (10.8 ml of 88% phenol (C_6H_5OH), 100 mg of disodium nitroprusside dehydrate ($Na_2Fe(CN)_5NO \cdot 2H_2O$), diluted to 250 ml with DIW) were added and the sample mixed again. This was immediately followed by the addition of 0.03 ml of hypochlorite reagent (0.05g Trione ($C_3HCl_2N_3O_3$) in 20 ml of 0.5 N NaOH) and shaking. The samples where covered with parafilm and incubated at room temperature in the dark for at least 6 h. Absorbance was measured on a Milton Roy Spectronic 1001 Plus spectrophotometer at 630 nm.

Phosphate

Pore-water phosphate was measured using the ascorbic acid method (Lagera and Blum 1997) after (Grasshoff et al. 1983). To a 1.0-ml sample, 0.04 ml of 1 N HCl was added and the sample shaken to remove any pore-water sulfide. Then, 0.02 ml of

ascorbic acid reagent (10 g of ascorbic acid ($C_6H_8O_6$) in 50 ml of DIW, 50 ml of 4.5 N H_2SO_4) and 0.02 ml of a mixed reagent (12.5 g of ammonium heptamolybdate tetrahydrate ($(NH_4)_6Mo_7O_{24}\cdot 4H_2O$) in 125 ml of DIW added to 350 ml of 4.5 N H_2SO_4; 0.5 g of potassium antimony tartrate ($C_4H_4KO_7Sb$) in 20 ml of DIW added to above molybdate solution) were added to the sample and shaken well. Color was allowed to develop at room temperature on the bench top. Absorbance was read on a Milton Roy Spectronic 1001 Plus spectrophotometer at 880 nm after 10-30 min.

pH

The pH of all pore-water samples was measured using an Orion 720A meter and a Thermo Orion combination pH electrode. The electrode was standardized with Fisher buffer solutions of pH 4, 7, and 10.

Platinum Electrode Potential

Platinum electrode potential (PtEP) was measured by collecting sediment cores from the "core" subplots with core tubing that had small holes drilled every 1 cm in the side to a depth of 40 cm. The holes were covered with electrical tape before coring. The corer was made of extruded acrylic (5.08 cm diameter) so that the sediment surface could be seen within the tubing. A Sperry DM-350A Digital Multimeter was connected to a platinum electrode and used to measure PtEP in mV. ZoBell's solution (7.45g of KCl, 1.4066 g of $K_4Fe(CN)_6$, and 1.0964 g of $K_3Fe(CN)_6$ l^{-1}) was used to calibrate the Accumet Silver Chloride reference electrode; and creek water was used to complete the circuit. These measurements were taken immediately after the core was collected. Cores were placed back into the sediment from where they had been removed after

measurements had been taken. Cores were taken randomly from within the plots and care was taken to avoid taking cores from the same or near by location of replaced cores within the plot over the sampling season.

Decomposition

Litterbag Decomposition

Root decomposition was measured with litterbags (Blum, 1993). Decomposition litterbags contained between 1-2 g of air-dried *S. alterniflora* root material in a fine mesh (bridal organdy) bag. Root material was collected in January 2001 from the low marsh zone of UPC by extracting a large peat sample approximately 0.5 m in diameter with a shovel. The peat was placed in a cooler and returned to the lab where it was washed free of sediment, separated, and air-dried. Two litterbags were tied together; one was incubated on the marsh surface and one was buried to 10-cm depth. One group of bags from each plot was removed quarterly, gently washed and dried. The bags were examined for new root material growing into the bags. When found, these new roots were removed. The remaining litter was dried at 70ºC to a constant mass, weighed, ignited in a Thermolyne 10500 Muffle Furnace (450ºC for 24 h), and reweighed. Mass loss was determined as change in ash-free dry mass during the incubation.

Sulfate Reduction Rate

Cores were taken from the core plots and subcored with de-tipped 10-ml syringes through holes drilled in the core tubing at 2, 4, 6, 8, 10, 15, 20, and 25-cm depths. The subcores were immediately injected with 50 µl of $H_2{}^{35}SO_4$, approximately 1 µCi (Herlihy 1987 after Jorgensen 1978), capped with serum stoppers and allowed to incubate at

ambient temperature for between 1-2 h depending on the air temperature at the time of sampling. At cold temperatures, cores were incubated longer than when the temperature was warm. The subcores were frozen in an ice and ethanol bath to halt the reaction and transported to the lab for analysis.

During the summer of 2001, sulfide production was determined using the acid volatile sulfide (AVS) method (Herlihy 1987 after Jorgensen 1978). This involved liberating free sulfide (S^{2-}, HS^-, and H_2S) and FeS from a sediment slurry prepared from the subcores. Three sequentially linked 25 x 200-mm test tubes were used. The first test tube contained the ^{35}S- inoculated subcore and 2.0 ml of 12 N HCl. The other tubes served as H_2S traps. The two H_2S-trap test tubes contained 20 ml and 10 ml of 4% ZnAc, respectively. The test tubes were bubbled with N_2 gas for 1 h to strip the H_2S from the slurry. The contents of the H_2S-trap test tubes were combined, and duplicate 1.0-ml aliquots were taken for analysis. Each 1.0-ml aliquot was placed in a 20-ml scintillation vial and mixed with 10 ml of Beckman Coulter Ready Safe Liquid Scintillation Cocktail and read on a Beckman LS 6500 Multipurpose Scintillation Counter and corrected for quench.

Starting in September 2001, the total reduced inorganic sulfur (TRIS) method was employed to determine sulfide production (Fossing and Jorgensen 1989). This method allows for all fractions of sulfide formation (free sulfide, S^o, FeS, and FeS_2) to be measured in the same time frame as AVS (free sulfide and FeS) alone. For the TRIS method, $Cr^{2+}$was created by using a 100-ml glass Erlenmeyer flask containing enough 1 N HCl-rinsed “mossy zinc” to cover the bottom of the flask. To this flask, 1 M $CrCl_3 \bullet 6H_2O$ in 0.5 N HCl was added until the flask was full (approximately 80 ml) and

bubbled with N_2 gas. The Cr^{3+} was reduced to $Cr^{2+}$when the color changed from dark green to bright blue, approximately 20 min. A three-neck reaction flask was placed on top of a hot plate and had a gas-bubbling tube and condenser attached. Two 25 x 200-mm test tube H_2S-traps were attached to the condenser sequentially. The first test tube contained 20 ml of 0.5 N NaOH, while the second contained 10 ml of 0.5 N NaOH. Inoculated subcores were mixed with 5.0 ml of DIW and 5.0 ml of ethanol to form a slurry in the three-neck reaction flask for 20 min under constant N_2 gas sparging. After 20 min, 16.0 ml of 1 M Cr^{2+} and 8.0 ml of 12 N HCl were added, and the slurry was boiled gently for 40 min. At the end of the extraction, the contents of the two H_2S-traps were combined and duplicate 1-ml aliquots were taken for analysis. Each aliquot of sample was placed in a 20-ml scintillation vial and mixed with 10 ml of Beckman Coulter Ready Safe Liquid Scintillation Cocktail and read on a Beckman LS 6500 Multipurpose Scintillation Counter with quench correction. The fraction of injected $^{35}SO_4^{2-}$ converted to $^{35}S^{2-}$ (f ^{35}S) was calculated for both methods according to the equation:

(1) $f\ ^{35}S = \frac{^{35}\text{Sulfide produced} * \text{isotope correction factor}}{^{35}\text{Sulfate injected}}$

where:
^{35}Sulfide produced = µCi,
^{35}Sulfate injected = µCi $^{35}SO_4^{2-}$ injected into the subcore, and
isotope correction factor = 1.06 (Sorokin 1962) which corrects for the relative cellular metabolism discrimination against ^{35}S (Jorgensen, 1978).

The sulfate reduction rates (SRR) were calculated for both methods according to the following equation:
(2) $SRR = f\ ^{35}S * SO_4^{2-} * t_{inc}^{-1}$
where:
SO_4^{2-} = pore-water sulfate concentration in nmol l^{-1}, and
t_{inc} = length of time in days $^{35}SO_4^{2-}$ was incubated in subcores.

Sediment Characteristics

Percent Water and Percent Organic Matter

Sediment cores were taken with a 5.2-cm diameter PVC core tubing from the plots set aside for taking cores. Each core was examined to ensure that minimal compaction occurred. Burrow holes were avoided when sampling from crab plots. Subcores were taken from the cores with de-tipped 10-ml syringes through holes drilled into the core tubing at 2, 4, 6, 8, 10, 15, 20, and 25-cm depths. The subcores were capped with serum stoppers and transported back to the lab. The volume of the core was noted and the contents were removed from the syringe and weighed. The subcores were dried at 105ºC in a Thelco drying oven for 24-48 h. The subcores were reweighed and the mass loss was assumed to equal the sediment's water content. Moisture content is expressed on a dry mass basis. The dried subcores were put in a Thermolyne 10500 Muffle Furnace at 450ºC for 24 h and reweighed. The mass loss was assumed to be organic matter. Organic matter content is expressed on a dry mass basis.

Soil Composition

Cores from each site were collected for textural analysis using a 5.2-cm diameter PVC core tubing. A hydrometer method was used to measure sediment texture (Liu and Evett 1984). Sediment from each site was cut into 10-cm segments and dried in a Thelco drying oven at 105°C for 24 h. To reduce organic matter interference during textural analysis, 40.0 g of sediment were placed in an Erlenmeyer flask with 50 ml of Clorox® bleach and allowed to sit for 24 h. The sediment solution and 100 ml of dispersing agent (40 g of sodium hexametaphosphate ($(NaPO_3)_6$) l^{-1}) were added to a blender and allowed to stand for 10 min with occasional stirring, followed by blending at high speed for 5-10

min. Amyl alcohol was added as needed to reduce foam. The suspension was transferred to a hydrometer jar and the volume was brought to 1.0 l with DIW. The cylinder was inverted until the suspension was well mixed. Hydrometer readings were taken with a Fisher 151H hydrometer at 30 s when silt and clay remain in suspension and 2 h when only clay remains in suspension. The hydrometer was calibrated with a reading in DIW and a solution of 50 ml bleach and 100 ml dispersing agent diluted to 1.0 l with DIW. The % sand, silt, and clay was determined by the following equation:

$$(3)\ P = \frac{[(100000/W)\ G](R_C - G_L)}{G - G_L}$$

where:
P = % sediment remaining in suspension
W = oven dried weight of sample
G = specific gravity of soil (2.65)
G_L = specific gravity of water (1)
R_C = hydrometer reading corrected by composite correction factor
$R_C = R - R_L$ where R = hydrometer reading of sample and R_L is the difference between the hydrometer reading for DIW and DIW + bleach+ dispersing agent.

Infiltration Rate

The water's ability to infiltrate the marsh surface was measured on April 18, 2003 at LPC and UPC using a falling head infiltration method. This was done using PVC pipe 5.08 cm in diameter and 50 cm in length. It was inserted into the marsh to 10-cm depth. Sediments were checked for compaction by comparing the marsh surface inside and outside the pipe. The PVC pipe was filled to within 10 cm of the top of the pipe with water collected from the adjacent tidal creek making a column of water 30 cm tall. The change in water level in the PVC pipe was monitored over the course of an ebbing tide, low tide, and the start of high tide to determine how infiltration varied with the tidal cycle. At UPC, the PVC pipe was inserted an additional 5 cm into the sediment to ensure

that it was in the clay layer that underlies this area of the marsh and infiltration was measured again.

Tidal Flooding Duration

Tidal inundation was measured on May 15, 2001. One marker was inserted into the sediment at each site. The height of the surface water against the marker was noted approximately every 15 min over the course of a high tide.

Vegetation

End-of-the-Year Biomass

Aboveground biomass was collected in August of 2001 and 2002. A 0.0625 m^2 quadrat was randomly placed in the vegetation plots and the vegetation clipped at the marsh surface. One sample was taken per plot. The clipped plants were placed in black plastic garbage bags and returned to the lab, where live and dead plants were separated from one another and each plant identified to species level. The length of live stems was measured and the number of stems of each plant type and condition (i.e., live vs. dead) noted. The plants were dried in a Thelco drying oven at 80ºC to a constant mass and weighed.

Stable Sulfur Isotope Analysis

The dried live stems from the 2002 biomass collection were ground with a Willey Mill so that it passed a 40-mesh screen. A sample of the ground material from each plot was sent to Actlabs (Tucson, AZ) for stable sulfur isotope analysis where thermal ionization mass spectrometry was used to determine the sulfur isotope composition of the plant materials. The Canyon Diablo meteorite was used as the standard.

CHN Analysis

The remaining ground plant material was used for Carbon-Hydrogen-Nitrogen (CHN) analysis. Between 10 and 15 mg of plant material was used for the analysis. An EA 1108 CHNS-O Fisons elemental analyzer was used to determine % carbon and % nitrogen. The moles of carbon and nitrogen were calculated from the weight of the sample and the % carbon or nitrogen. The molar concentration was use to calculate the carbon:nitrogen (CN) ratio. Acetanalide and atropine were used as standards.

Root Growth

Root growth was measured using root growth litterbags (Blum 1993). Root growth bags were 2-mm Nylon mesh (Nylon Net Company, Memphis, TN, USA). The bags were approximately 20-cm long and sewn at 10-cm intervals. Each section of the litterbag contained 1-2 g dried root material collected in January 2001 from the low marsh area of UPC as explained above. Bags were buried to 20-cm depth with the top of the bag just below the marsh surface. Samples were collected approximately monthly from July 2001-September 2001 and March 2002-November 2002. Live roots were separated from the root material originally placed in the bag by visual inspection. Live roots were determined by color (white, black, and orange as opposed to brown) and turgor pressure. Once separated, the live roots were dried at 80ºC in a Thelco drying oven for 24 h and weighed to obtain dry weight. The roots were then put in a Thermolyne 10500 Muffle Furnace at 450ºC for 24 h and reweighed to obtain ash-free dry weight (AFDW).

Summary

A wide variety of variables were measured over the course of this experiment (Table 4). Not all variables were collected at the same frequency or over the same time frame. Most variable were collected on a monthly basis over the growing season, however, decomposition litter bags were sampled quarterly. To accommodate for the "missing" data, decomposition was assumed to occur at a constant rate over the sampling interval, and "missing" data points were interpolated accordingly. The iron treatment was not begun until 2002. To accommodate for missing data for 2001, 2002 data points were used for the corresponding months of 2001 that were missing. Variables sampled once were assumed not to change over the course of the experiment.

Statistical Analysis

The data were analyzed from two perspectives. The first analysis compared LPC results to UPC results regardless of treatment. This provided information as to why the sites exhibited different sediment and vegetation characteristics. The second analysis compared the three treatments; No Crabs, Crabs, and Iron addition. These experiments were employed to examine the effects crabs and iron have on the biogeochemistry of marsh sediment. The No Crabs treatment was a control with no crabs present in the plots and no added iron. The results are presented from both perspectives.

SPSS 11.1 statistical package was used for all analyses. Data were initially analyzed using principal components analyses (PCA). A PCA was done in order to explore which variables contributed to site differences and determine the possible variables that responded to the experimental manipulations. Principal components

analysis is a data reduction technique that combines all variables into only a few factors that account for the variation in the data. By analyzing the data in this manner,

Table 4. Frequency and time frame of measurements

Variable	**Frequency of Measurement**	**Sampling Time Frame**
Pore-water sulfate	Monthly	June 2001-September 2001 March 2002-November 2002
Pore-water chloride	Monthly	June 2001-September 2001 March 2002-November 2002
Pore-water sulfide	Monthly	June 2001-September 2001 March 2002-November 2002
Pore-water iron	Monthly	September 2001 March 2002-November 2002
Pore-water ammonium	Monthly	June 2001-September 2001 March 2002-November 2002
Pore-water phosphate	Monthly	June 2001-September 2001 March 2002-November 2002
pH	Monthly	June 2001-September 2001 March 2002-November 2002
PtEP	Monthly	June 2001-September 2001 March 2002-November 2002
Litter bag decomposition	Quarterly	June 2001-September 2001 March 2002-November 2002
Sulfate Reduction	Monthly	June 2001-September 2001 March 2002-November 2002
% sediment water	Monthly	June 2001-September 2001 March 2002-November 2002
% sediment OM	Monthly	June 2001-September 2001 March 2002-November 2002
Sediment Texture	Once	August 2002
Infiltration Rate	Once	April 2003
Tidal Inundation	Once	May 2001
End-of-the-Year Biomass	Twice	August 2001 August 2002
Leaf tissue $\delta^{34}S$	Once	August 2002
Leaf tissue CHN	Once	August 2002
Root growth	Monthly	June 2001-September 2001 March 2002-November 2002
Surface Elevation	Once	November 2002

the relationships among the variables become clearer. One analysis was done using all the variables measured at both sites. Because the two sites separated so clearly, the data from were also analyzed separately for each site to determine treatment effect.

A multiple analysis of variance (MANOVA) was also performed to determine which variables responded significantly to treatment as well as were different between sites. A MANOVA is designed to test differences among groups when there are multiple dependent variables and protect against inflated Type 1 error due to multiple tests. Data were log transformed to fit the assumptions of normality for analysis using MANOVA. The Levene's test of equality of error variances was still significant for most variables after log transformation, however (See Appendix E). The MANOVA was performed on the data set for both sites together testing for site and treatment effect using a 2-tailed test, with month and depth as covariates. A post-hoc test was done using the Tukey's honestly significant difference test. A Pearson's correlation matrix was also created using a 2-tailed model. Data are presented as ($r = \#$, $p = \#$) for Pearson's correlation results. An α-level of 0.05 was considered significant for all analyses.

Results

The results are presented from two perspectives, site and treatment. The effect of site is presented first in most cases followed by treatment. When depth or time covaries with the variable, the results are presented. A summary of the depth-averaged, annual-average data can be found in Table 5.

Table 5. Depth-Averaged, annual-averaged results of variables measured at LPC and UPC from June 2001 to November 2002 except in iron plots where measurements were taken from March 2002 to November 2002.

	LPC			UPC		
Variable	No Crabs	Crabs	Iron	No Crabs	Crabs	Iron
Bulk Density (g cm^{-3})	1.56	2.48	0.91	0.56	0.66	0.6
% OM	5.4	5.8	6.0	33.0	28.6	34.8
% H_2O	32	36	36	58	54	59
SO_4^{2-} (mmol l^{-1})	17.8	16.9	11.5	27.5	26.4	31.7
Cl^- (mmol l^{-1})	644	601	713	704	714	946
S^{2-} (µmol l^{-1})	70	69	119	32	44	109
$Fe2^+$ (µmol l^{-1})	63	53	46	77	379	346
Total Iron (µmol l^{-1})	71	57	42	76	93	598
NH_4^+ (µmol l^{-1})	32.7	19.2	27.3	6.8	8.9	27.8
PO_4^{3-} (µmol l^{-1})	7	7	9	5	4	4
pH	7.1	7.1	6.8	6.9	6.9	6.9
PtEP (mV)	19.5	54.7	40.1	-5.2	46.8	88.3
Decomposition (% AFDW lost)	12.4	17.4	-16.8	12.3	25.1	-3.8
SRR (nmol ml^{-1} d^{-1})	534.9	238.5	84.9	204.4	193.2	595.6
Root growth (g AFDW m^{-2} mon^{-1})	27.2	28.8	10.1	63.6	38.0	12.2

Principal Components Analysis

The sites LPC and UPC separated very clearly on PC1 and PC2 (Fig. 4), which accounted for 34% of the data's variability. The two sites separated primarily on PC 1. The loading factors contributing positively to PC 1 (i.e., were greater than 0.6) were % clay, % water, % OM, End-of-the-Year Biomass (EOYB), stem density, and $\delta^{34}S$; whereas bulk density contributed negatively (i.e., was less than –0.6). In other words, the sites were differently defined by a mix of sediment and vegetation characteristics. Examination of the same PCA, but identifying points by experiment showed no clear separation of the treatments (Fig. 5).

Because the sites separated so clearly, each site was analyzed individually for experimental treatment effects. When LPC data were considered, the treatment effects became apparent (Fig. 6). PC 1, 2, and 3 accounted for almost 41% of the data's variability. Sulfate reduction rates and % water contributed positively to PC 1, and bulk density contributed negatively. Positive loading factors to PC 2 included pore-water sulfate concentration, the SO_4:Cl ratio, and f ^{35}S. Stem density negatively contributed to PC 3. The treatments separated primarily on PC 3. The treatment effect was even more obvious at UPC (Fig. 7). PC 1, 2, and 3 accounted for over 48% of the data's variability. PC 1 positively included SRR, f ^{35}S, % water, and % OM; and negatively included bulk density. Stem density and $\delta^{34}S$ contributed positively to PC2, whereas CN contributed negatively. PC 3's positive loading factors were stem height and EOYB. At UPC, treatments separated on PC 2 and 3, both of which included aboveground vegetation characteristics.

Fig. 4. PCA of total data set by site

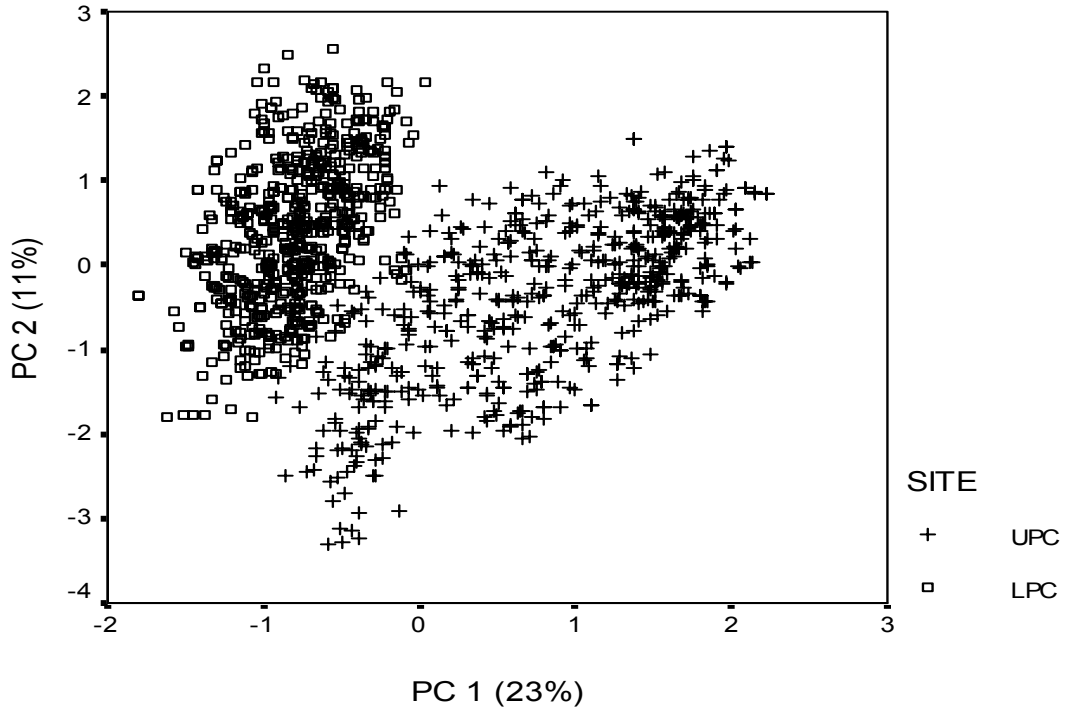


Fig. 5. PCA of total data set by treatment

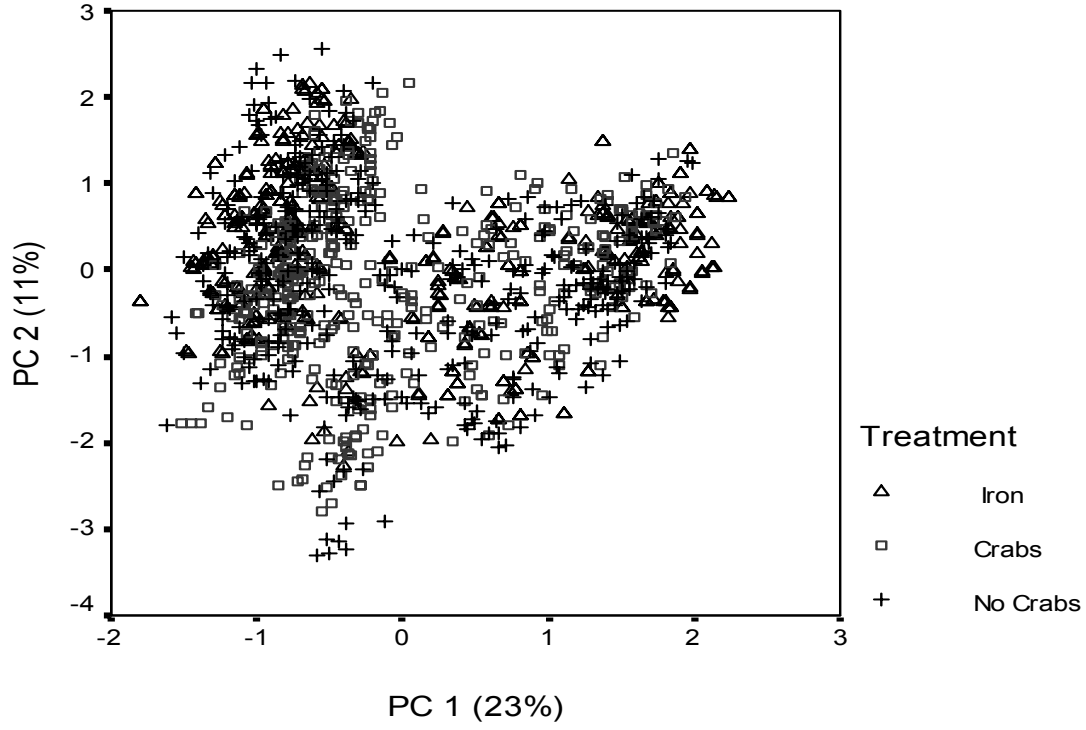


Fig. 6. PCA of LPC

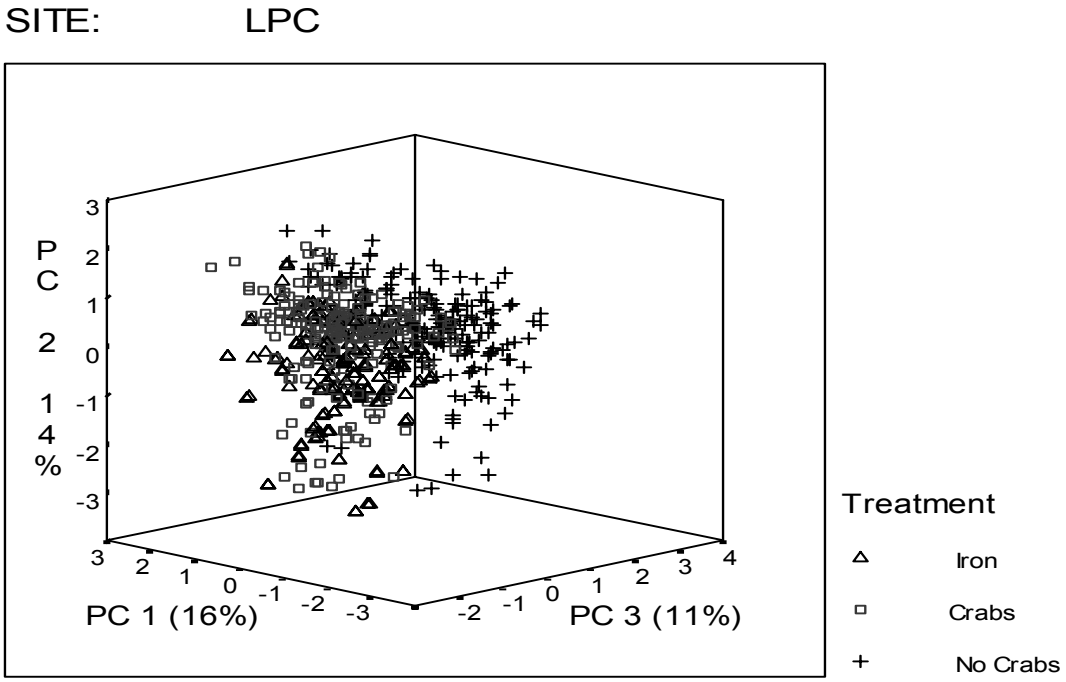
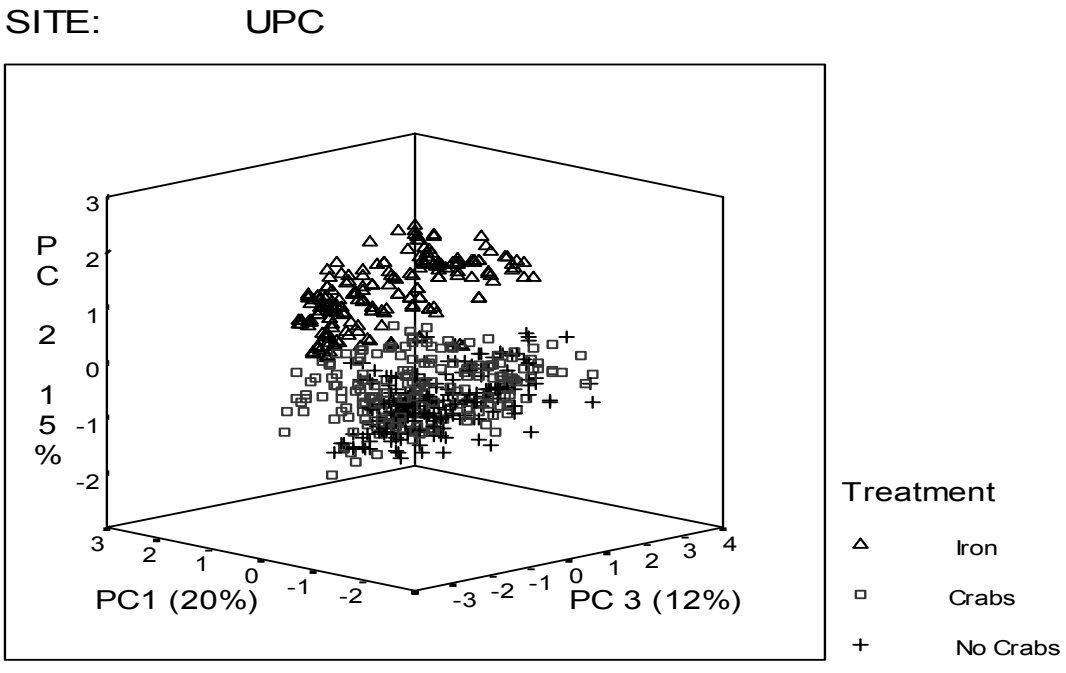


Fig. 7. PCA of UPC



Sediment Characteristics

The PCA results suggest that sediment characteristics are very important (Fig. 4) in establishing site differences. Some of the variables also appeared to respond to experimental manipulation, such as % water and %OM. To get a better understanding of how the variables responded to site and treatment, the results were examined using MANOVA. The following analyses were done using MANOVA.

Sediment Composition

Sand content was significantly different and higher and clay content was significantly different and lower at LPC than UPC ($p < 0.001$ for both) (Table 6). Silt content was not detectably different between the two sites. Experimental effects of the crab, no crab, and iron treatments were not tested for as it was assumed that the treatments would not alter sediment composition over the course of the experiments. The mineral content of the sediment by volume was much higher at LPC than UPC (Fig. 8). The mineral content at UPC only comprised 7% of the sediment volume within the top 10 cm, whereas LPC mineral content comprised 28% of the sediment volume in the top 10 cm. The sediments became more similar in both mineral content and volume characteristics with depth. Bulk density was significantly different and higher ($p < 0.001$) at LPC than UPC (Fig. 9), but it was not significantly affected by treatment. It was, however, affected by time ($p < 0.001$).

Percent Organic Matter

The UPC site had significantly different and higher organic matter content than

Table 6. Mineral sediment particle-size analysis.

Site	Depth	% Sand	% Silt	% Clay	Classification
LPC	0-10	53.7	39.3	7	Sandy loam
	10-20	50.7	35.3	14	Loam
	20-30	45.4	35.7	18.9	Loam
UPC	0-10	46.9	24.4	28.7	Sandy clay loam
	10-20	45.8	41.2	13	Loam
	20-30	37.1	40.1	22.8	Loam

Fig. 8. Sediment characteristics of Phillips Creek marsh by volume. (n=3). %mineral material = ((g sediment in core/2.65 (specific gravity of soil particles))/sediment core volume) * 100; % water = ((g water in core/1 (specific gravity of water))/sediment core volume) * 100; % OM = 100- % mineral - % water.

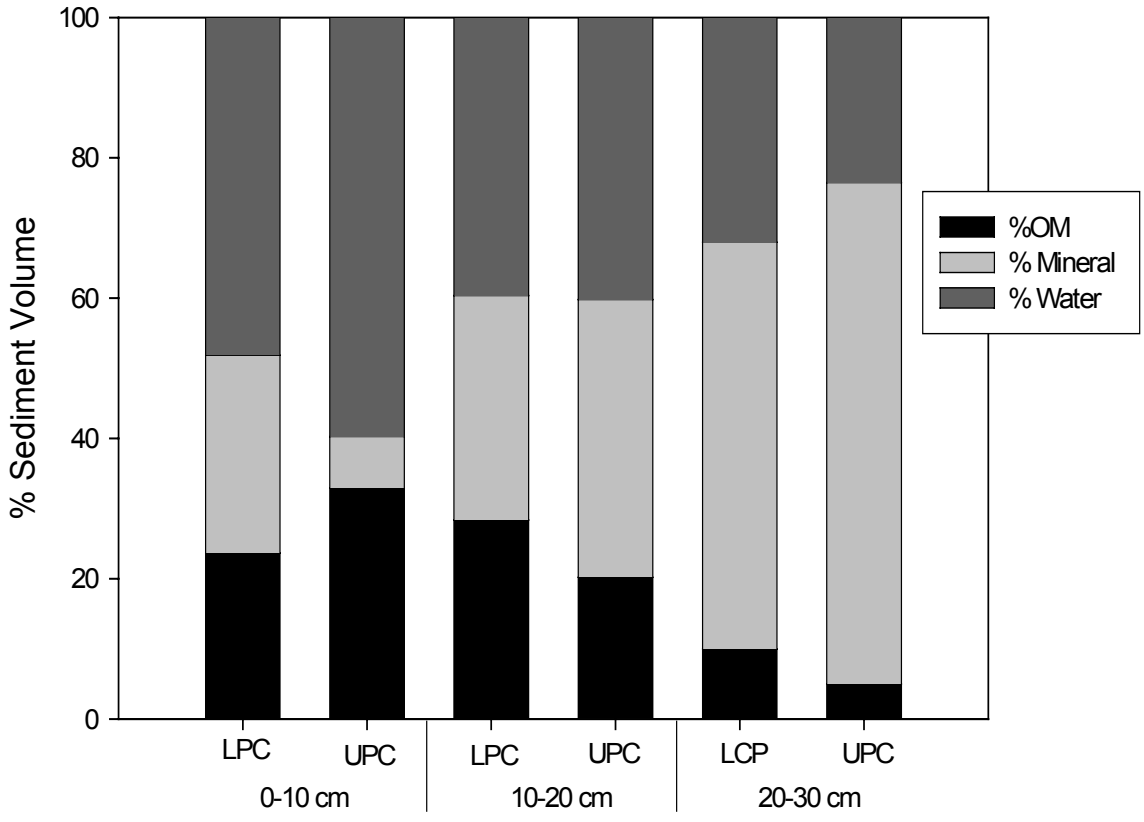
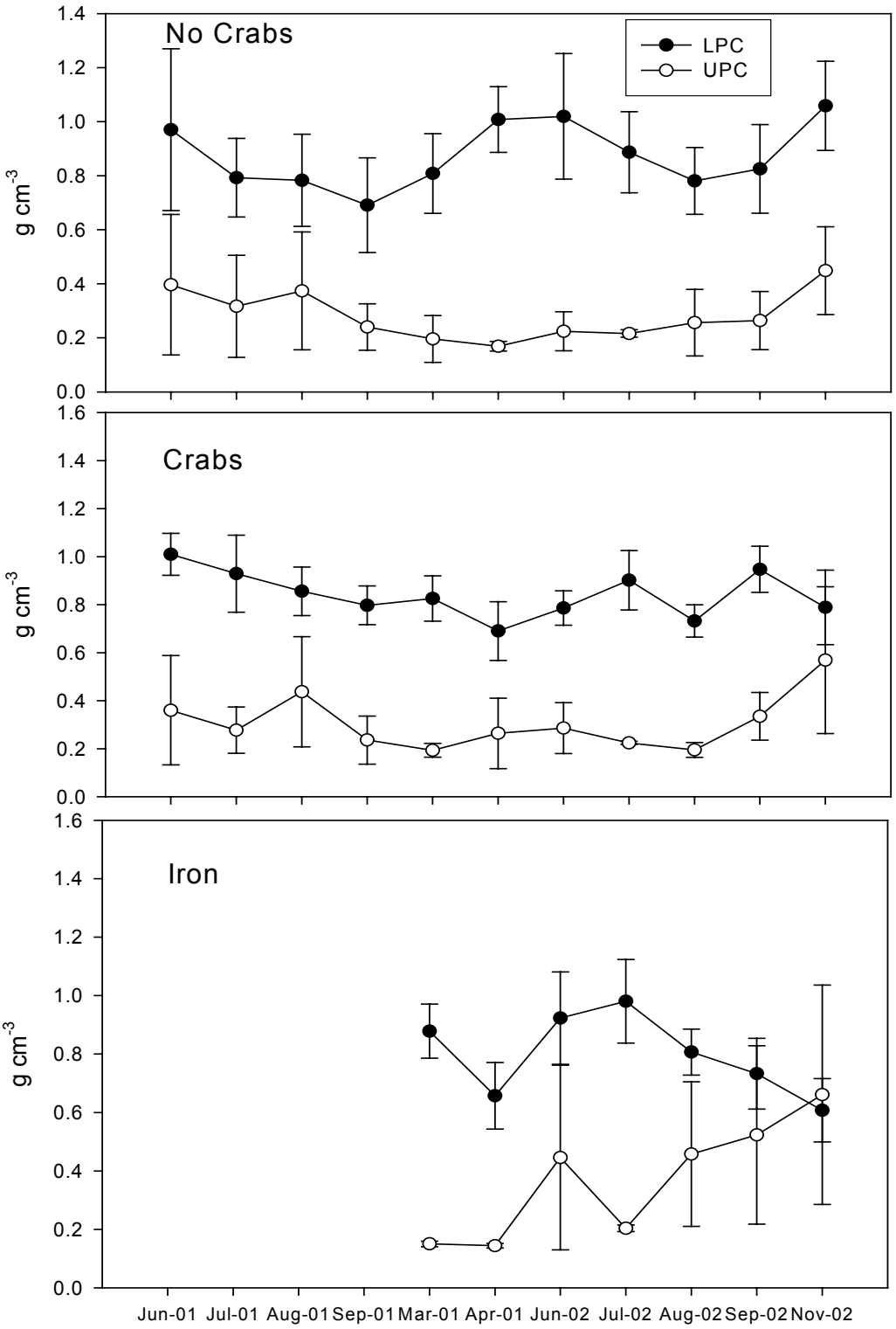


Fig. 9. Bulk density measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except in iron plots where measurements were made between March 2002 and November 2002. Error bars are one standard error. (n=2)



LPC ($p < 0.001$) (Fig.10). Analysis of experimental treatment showed %OM was different and highest in Iron plots and lowest in Crab plots ($p = 0.006$). Sediment OM content changed over time most dramatically at UPC ($p < 0.001$). These differences were not reflected in the bulk density results.

Sediment Temperature

Sediment temperature was measured at each site during sample collection. LPC temperatures were slightly higher than UPC (Fig. 11). The difference in temperature between the two sites in June 2002 was due to a rain fall event between the sampling of LPC and UPC.

Sediment Water and Tides

Tidal Flooding Duration

Tidal flooding was measured once over the course of a high tide at the start of the experiment to insure that each site had similar hydroperiods. The UPC site was at a slightly higher elevation the LPC so the flooding depth and duration were not as long at UPC as LPC, however, the UPC was constantly wet (Fig 12). The measurements for this graph were taken between a neap and spring tide cycle. It was observed that not all high tides flooded the two sites. Frequency of high tides flooding LPC is 22% (Harvey 1990). The flooding frequency at UPC is unknown, but because of the higher elevation, the frequency of flooding is likely to be less than at LPC.

Fig. 10. Sediment organic matter in the top 10 cm measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except in iron plots where the measurements were made between March 2002 and November 2002. Error bars are one standard error (n=2).

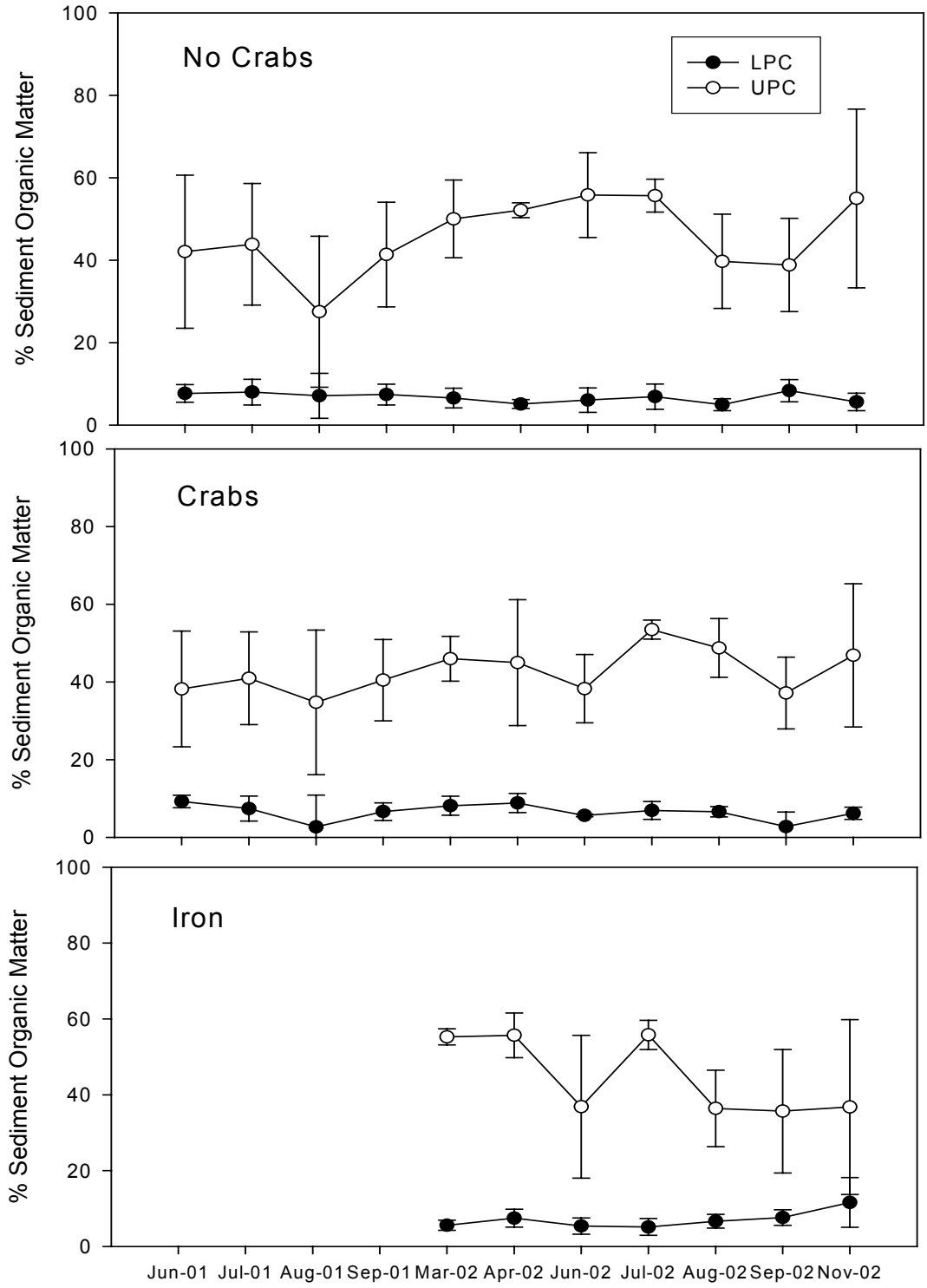


Fig. 11. Sediment temperature measured at LPC and UPC at monthly intervals from June 2001 to November 2002. (n=1)

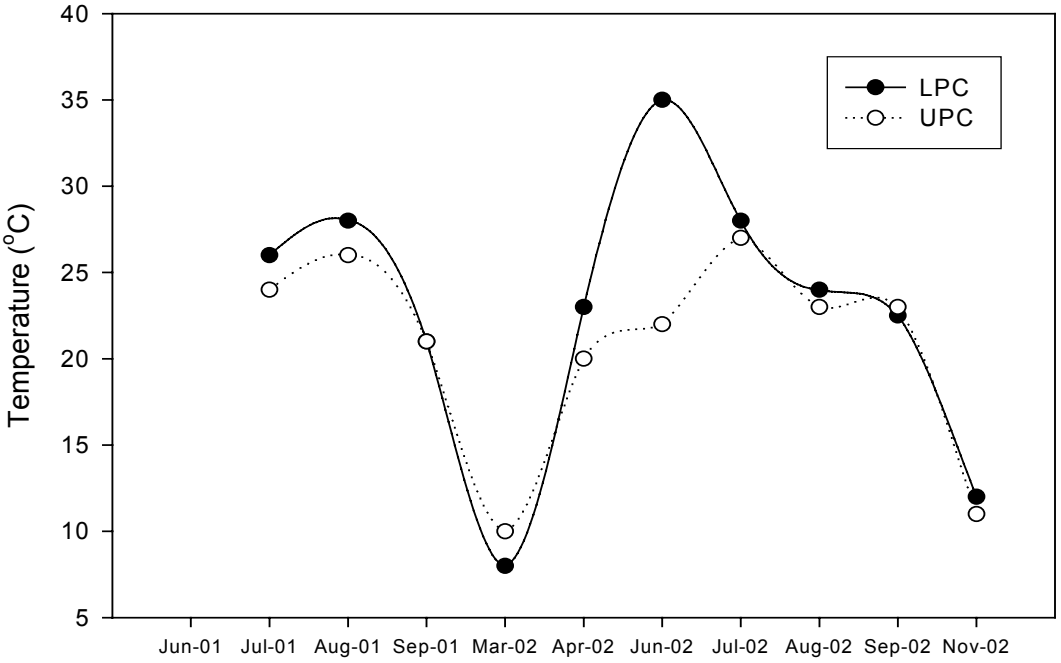
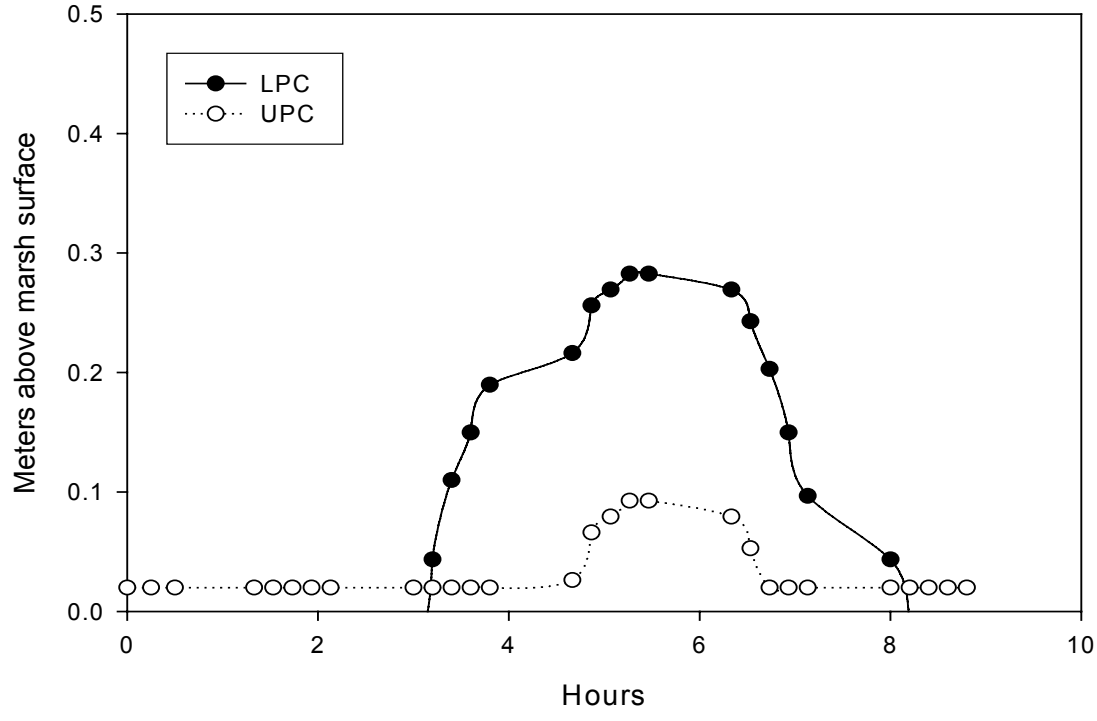


Fig. 12. Tidal flooding of LPC and UPC sites measured once on May 15, 2001.



Infiltration Rate

The infiltration rate was used as an indicator of potential exchange between tidal flood water and pore water. Measurements were taken in the "native" plots at each site, (LPC Crab plots avoiding burrows and UPC No Crab plots). The infiltration rates for the two sites were very different at 10 cm in depth. LPC had a very slow infiltration rate of 2 ml hr^{-1}, whereas UPC had an infiltration rate of 153 ml hr^{-1}. When infiltration was measured at UPC at 20-cm depth, where the sediments were primarily mineral, infiltration slowed to 2 ml hr^{-1}.

Percent Water

The UPC site had higher sediment water content than LPC (Fig. 13). The Iron treatment plots had the highest % H_2O and the Crab plots had the lowest ($p = 0.048$). The difference between the highest and lowest of each treatment at each site was small, however.

Pore-water Chemistry

Sulfate and Chloride

Pore-water sulfate concentrations were different and almost twice as high at UPC (28.2 mmol l^{-1}) as LPC (15.2 mmol l^{-1}) ($p < 0.001$) (Fig. 14) (See Appendix A for complete data set). Full strength sea water (34‰) is 28.4 mmol l^{-1} SO_4^{2-} (Stumm and Morgan 1996). Chloride was insignificantly higher at UPC (Fig. 15). Sulfate was different and highest in the No Crab plots (22.1 mmol l^{-1}) and lowest in the Crab plots (21.4 mmol l^{-1}) ($p = 0.013$). Chloride was highest in the Iron plots (829 mmol l^{-1})

Fig. 13. Percent sediment water in top 10 cm measured at LPC and UPC monthly from June 2001 to November 2002 except in iron plots where the measurements were made between March 2002 and November 2002. Error bars are one standard error (n=2).

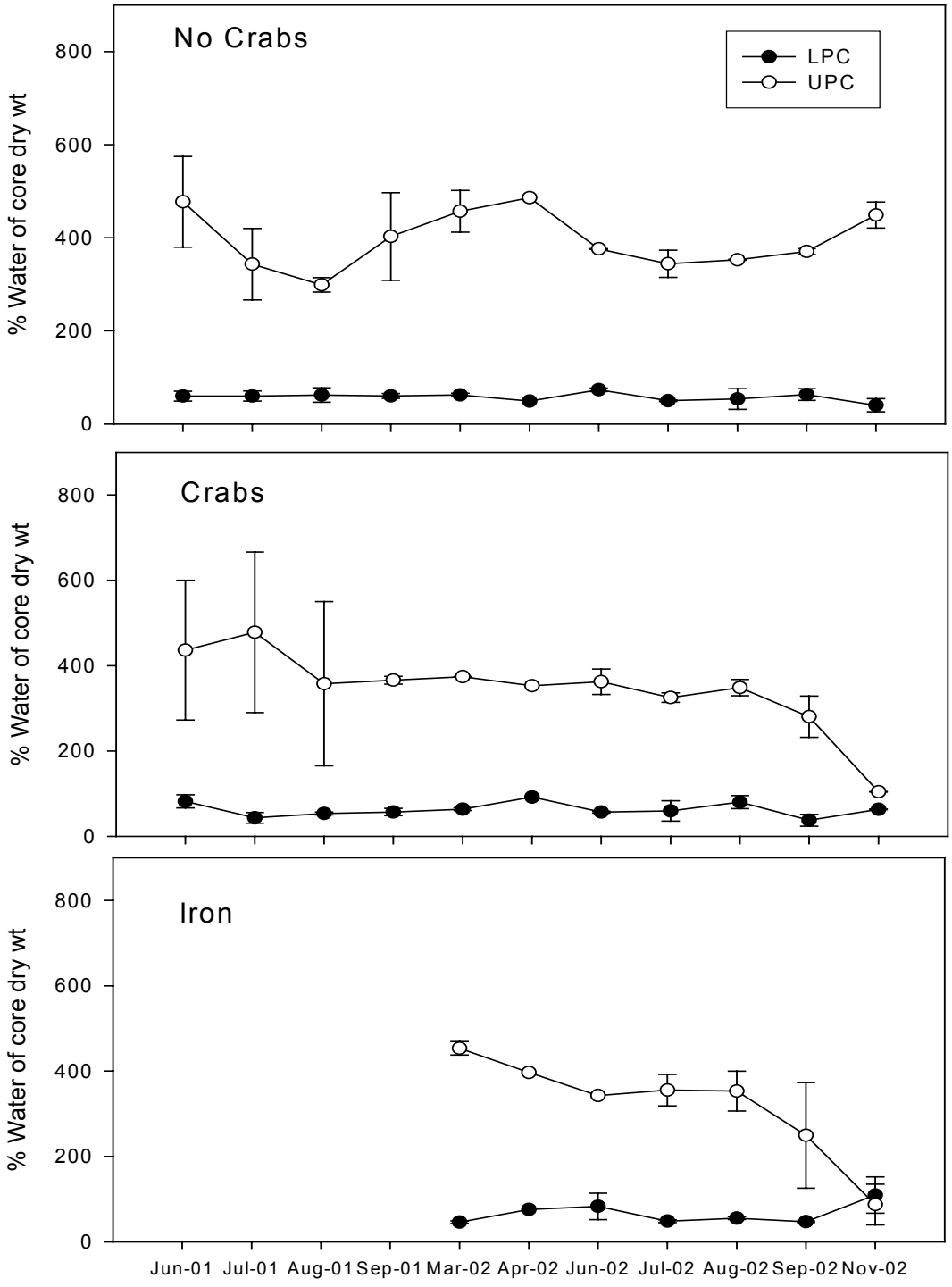


Fig. 14. Depth-average pore-water sulfate concentration measured at LPC and UPC measured at monthly intervals between June 2001 and November 2002, except in iron plots, where measurements were taken between March 2002 and November 2002. Error bars are 1 Standard Error (n=198).

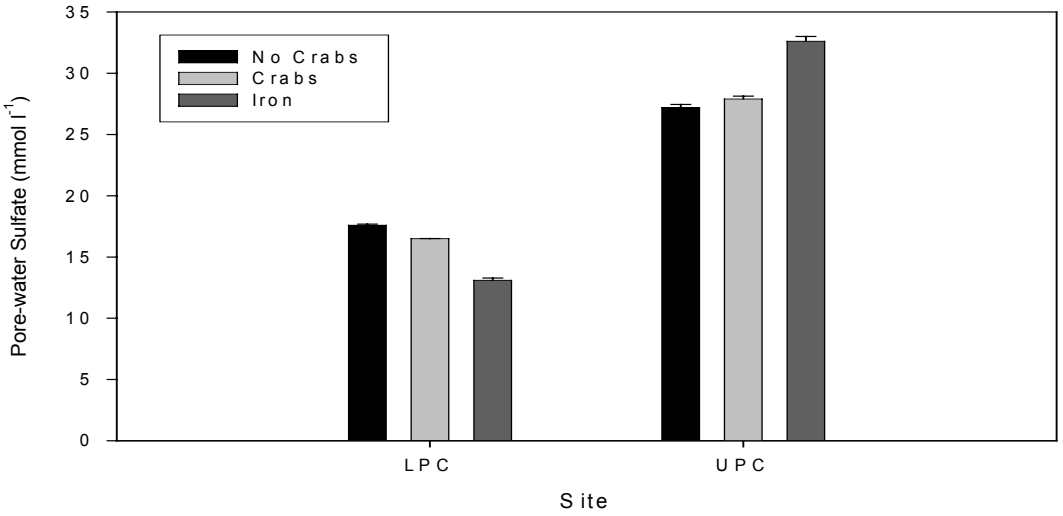
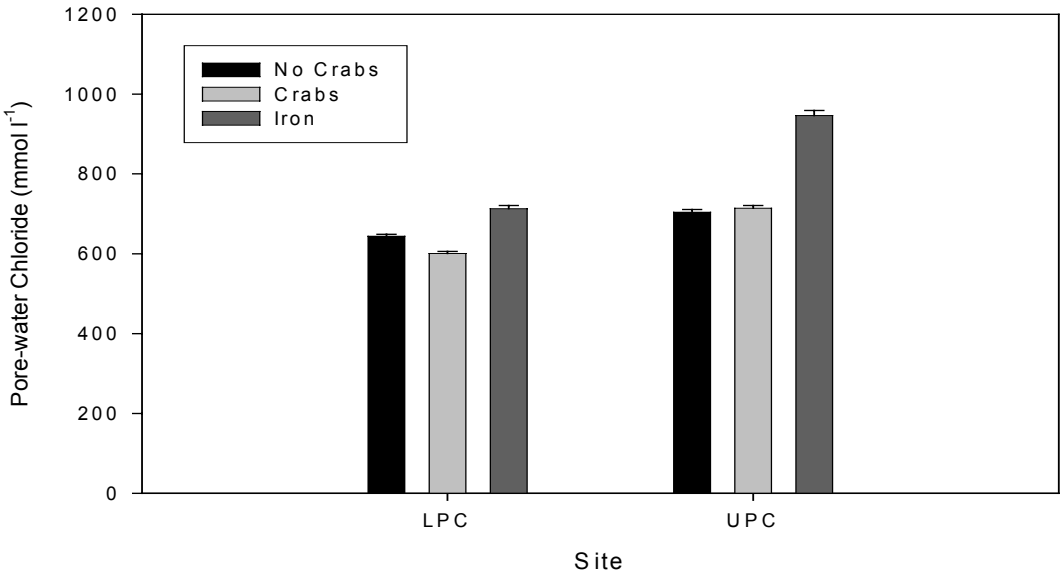


Fig. 15. Depth-average pore-water chloride concentration measured at LPC and UPC measured at monthly intervals between June 2001 and November 2002, except in iron plots, where measurements were taken between March 2002 and November 2002. Error bars are 1 Standard Error (n=198).



and lowest in the Crab plots (657 mmol l^{-1}) ($p < 0.001$). All chloride concentrations in all treatments at both sites were above sea water concentration, which is 420 mmol l^{-1} (Stumm and Morgan 1996).

The molar ratio between sulfate and chloride was calculated and compared to the SO_4:Cl of seawater (0.068). Sulfate concentration was depleted during most months and at all measured depths for all treatments at both sites (Fig. 16). In some months, however, pore water was enriched in sulfate relative to seawater. This occurred primarily during June, July, and August when temperature was at its peak. The annual averaged SO_4:Cl ratio was higher at LPC (0.044) than UPC (0.038) and was highest in the No Crabs plots (0.061) and lowest in the Iron plots (0.026) ($p < 0.001$ for both). There was also a substantial increase in salinity during the summer months of 2002 (Fig. 17). Extreme drought conditions existed in the Commonwealth of Virginia during this time (Stenger 2003).

Sulfide

Pore-water sulfide concentration was significantly different and higher at LPC (89 μmol l^{-1}) than UPC (65 μmol l^{-1}) ($p < 0.001$). Pore-water sulfide was highest in the Iron plots (114 μmol l^{-1}) and lowest in No Crabs plots (55 μmol l^{-1}) ($p = 0.058$). Pore-water sulfide increased in all plots during summer, peaking around July and August except UPC iron, which peaked in June (Fig. 18). These peaks approach or exceed the 250 μmol l^{-1} sulfide level that Bradley and Morris (1990) found to significantly reduce *S. alterniflora's* nitrogen uptake kinetics. The correlation between pore-water sulfide and ammonium concentrations was negative ($r = -0.238$, $p < 0.001$) (See Appendix G for

Fig. 16. The depth-averaged difference between the molar ratio of SO_4:Cl for seawater and pore water measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except in the iron plots where measurements were made between March 2002 to November 2002. Error bars are one standard error (n=18).

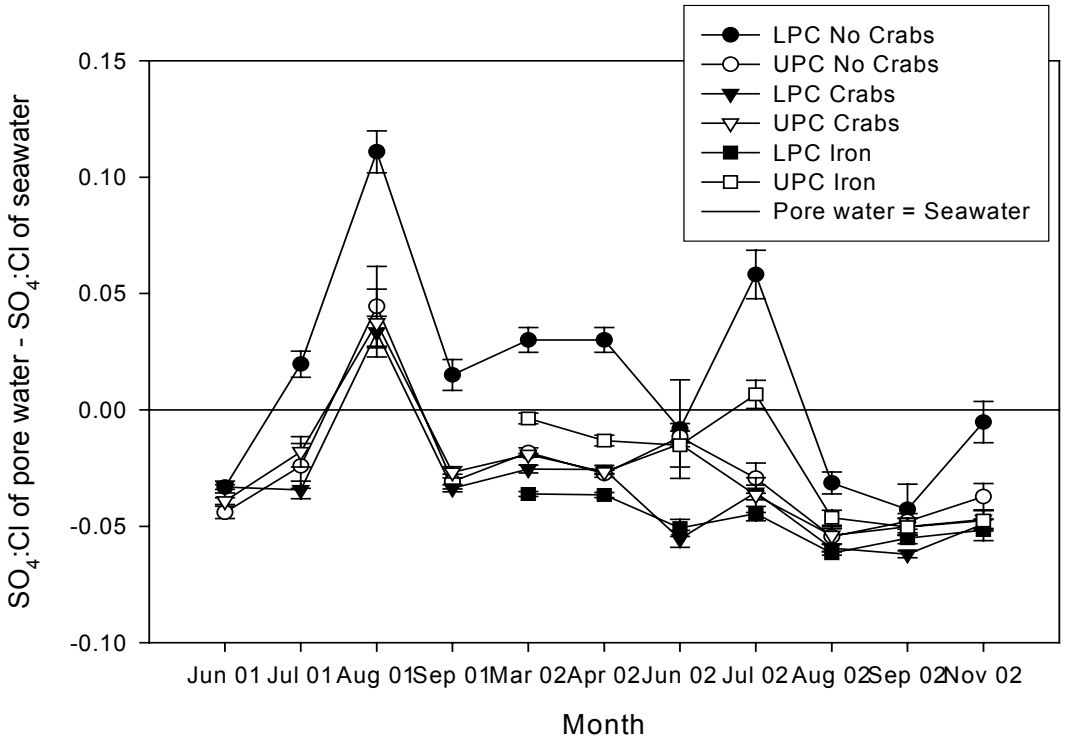


Fig. 17. Pore-water salinity at 5 cm depth measured at LPC and UPC at monthly intervals from June 2001 to November 2002. Error bars are one standard error (n=3).

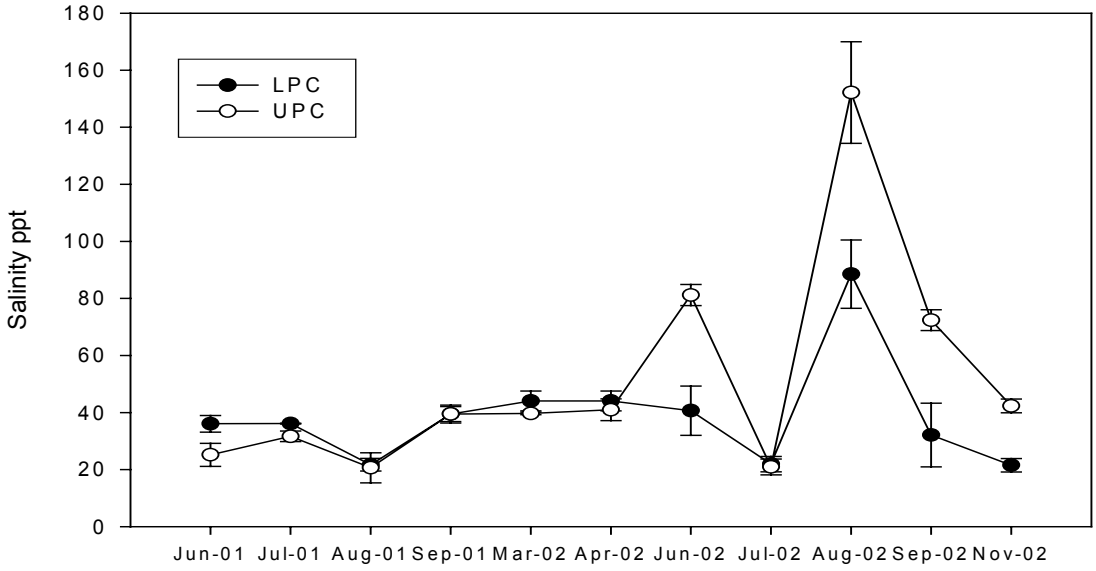
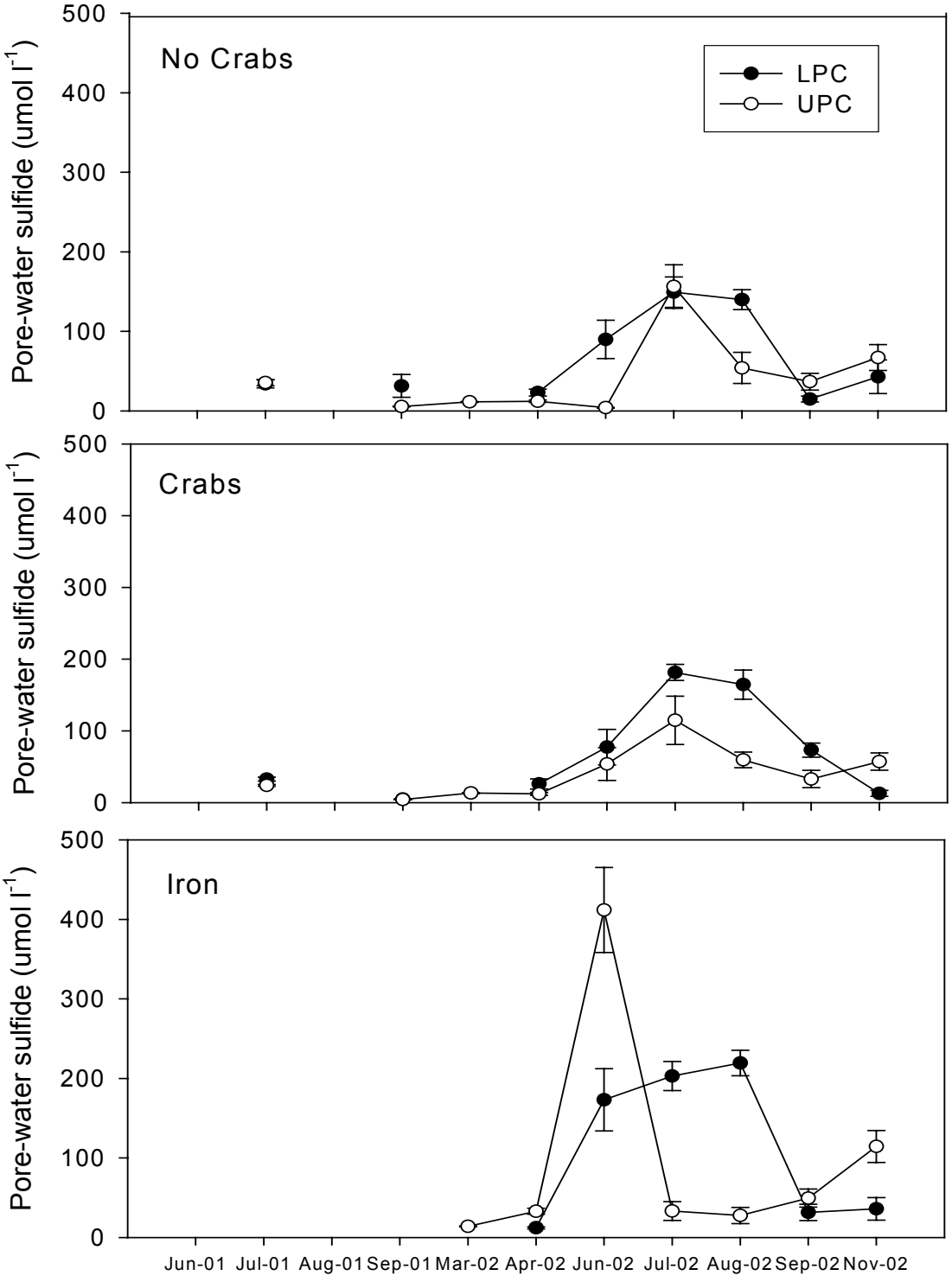


Fig. 18. Depth-averaged pore-water sulfide concentration measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except in iron plots where the measurements were made between March 2002 and November 2002. Error bars are one standard error. (n=18).



complete correlation table). There was a weak but significant negative correlation between pore-water sulfide and SRR ($r = -0.062$, $p = 0.032$) on a monthly basis, however, pore-water sulfide concentration was highest during the summer when SRR was high.

Iron

Ferrous iron pore-water concentrations were different and much higher at UPC (247 μmol l^{-1}) than LPC (55 μmol l^{-1}) ($p < 0.001$). Total dissolved iron concentrations were slightly higher than ferrous iron (UPC = 259 μmol l^{-1}; LPC = 56 μmol l^{-1}) suggesting that the dominant form of iron in the sediments was reduced iron. Neither total nor ferrous iron responded significantly to experimental manipulation (Fig. 19). Since the point of the iron addition experiment was to examine the hypothesis that reduced iron would remove sulfide from the pore water thereby reducing sulfide toxicity to plants, it should be noted that neither ferrous nor total dissolved pore-water iron concentration were correlated with pore-water sulfide concentrations either by treatment or when each site was examine for treatment effect individually.

Ammonium

Pore-water ammonium was higher in concentration at LPC (26 μmol l^{-1}) than UPC (14 μmol l^{-1}), but not significantly. Ammonium was different and highest in Iron plots (28 μmol l^{-1}) and lowest in Crab plots (14 μmol l^{-1}) ($p < 0.001$). There was a peak in ammonium concentration in April for LPC but not UPC except in the Iron plots (Fig. 20). Pore-water ammonium correlated significantly with SRR ($r = 0.186$, $p < 0.001$), decomposition ($r = 0.124$, $p < 0.001$), and root growth ($r = 0.142$, $p < 0.001$).

Fig. 19. Depth-averaged pore-water iron concentration measured at LPC and UPC at monthly intervals between September 2001 and November 2002, except for iron plots where measurements were taken between March 2002 and November 2002. Error bars are one standard error (n=162).

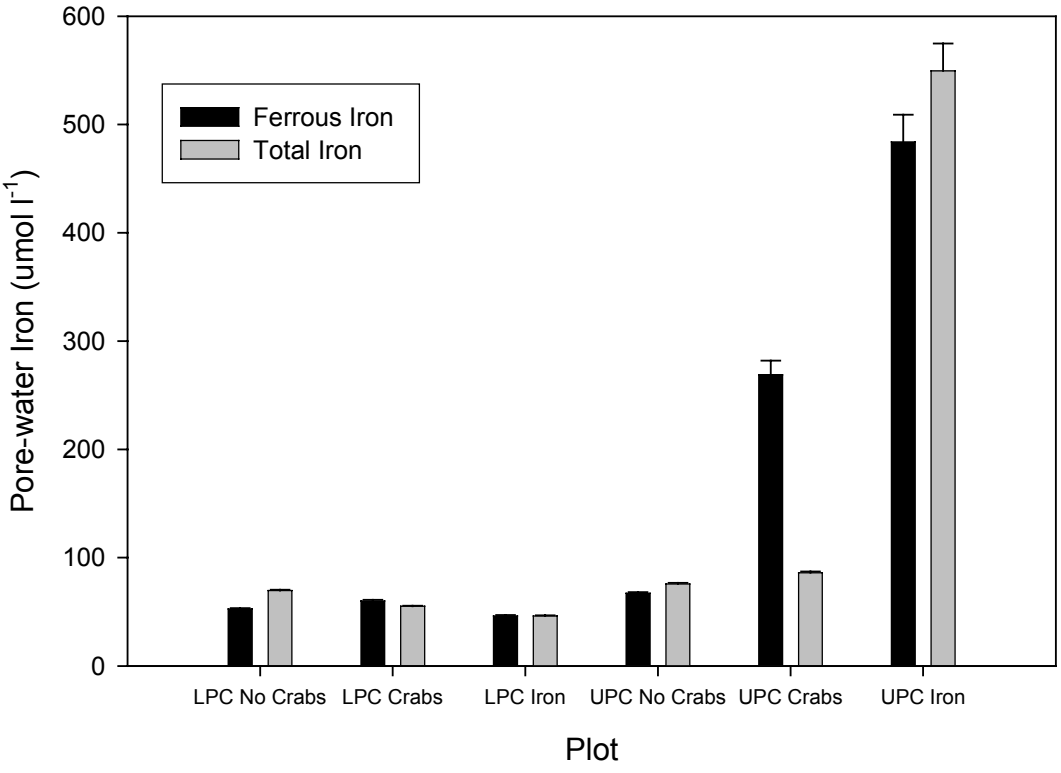
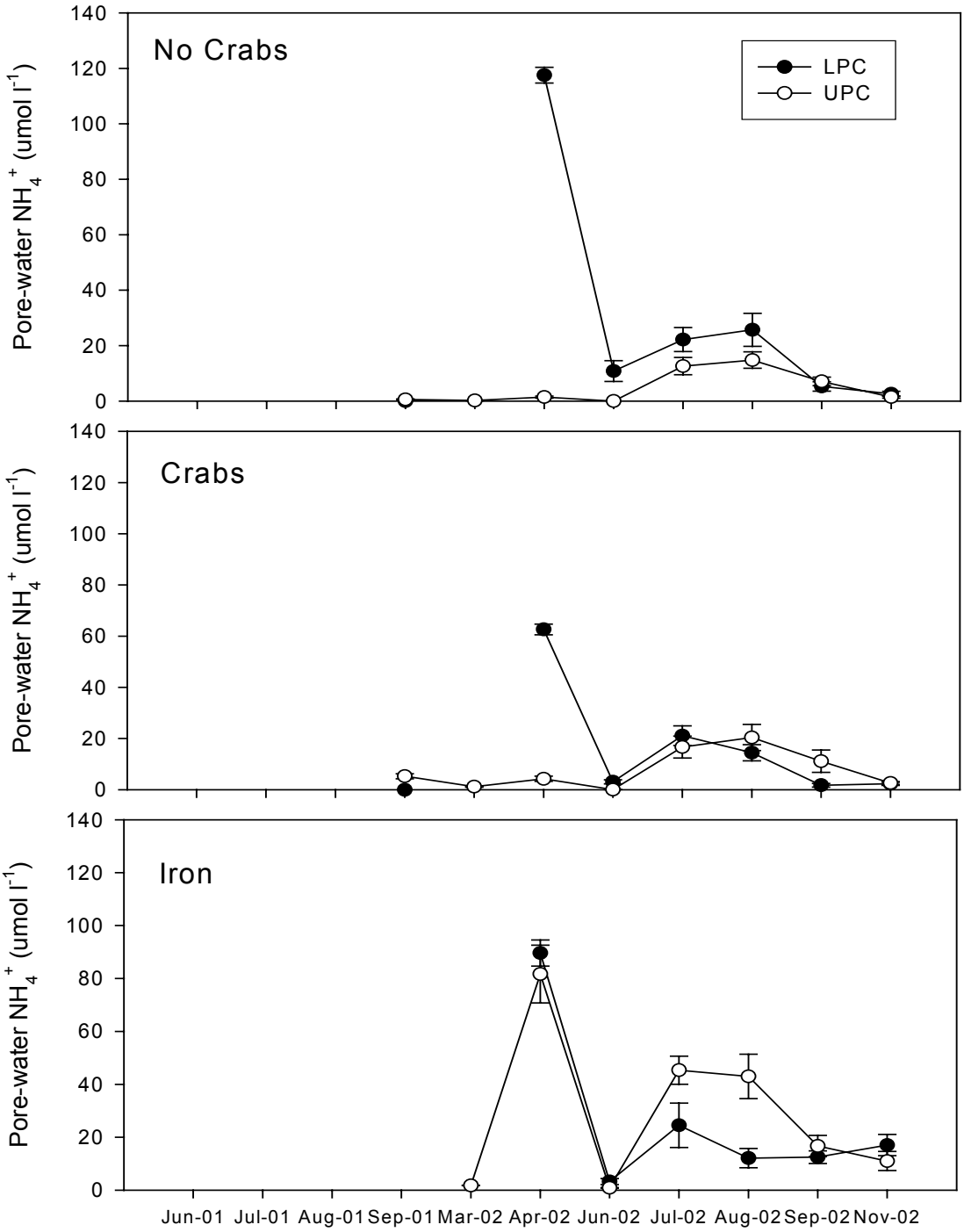


Fig. 20. Depth-averaged pore-water ammonium concentrations measured at LPC and UPC at monthly intervals from September 2001 to November 2002 except in iron plots where measurements were taken between March 2002 and November 2002. Error bars are one standard error (n=144).



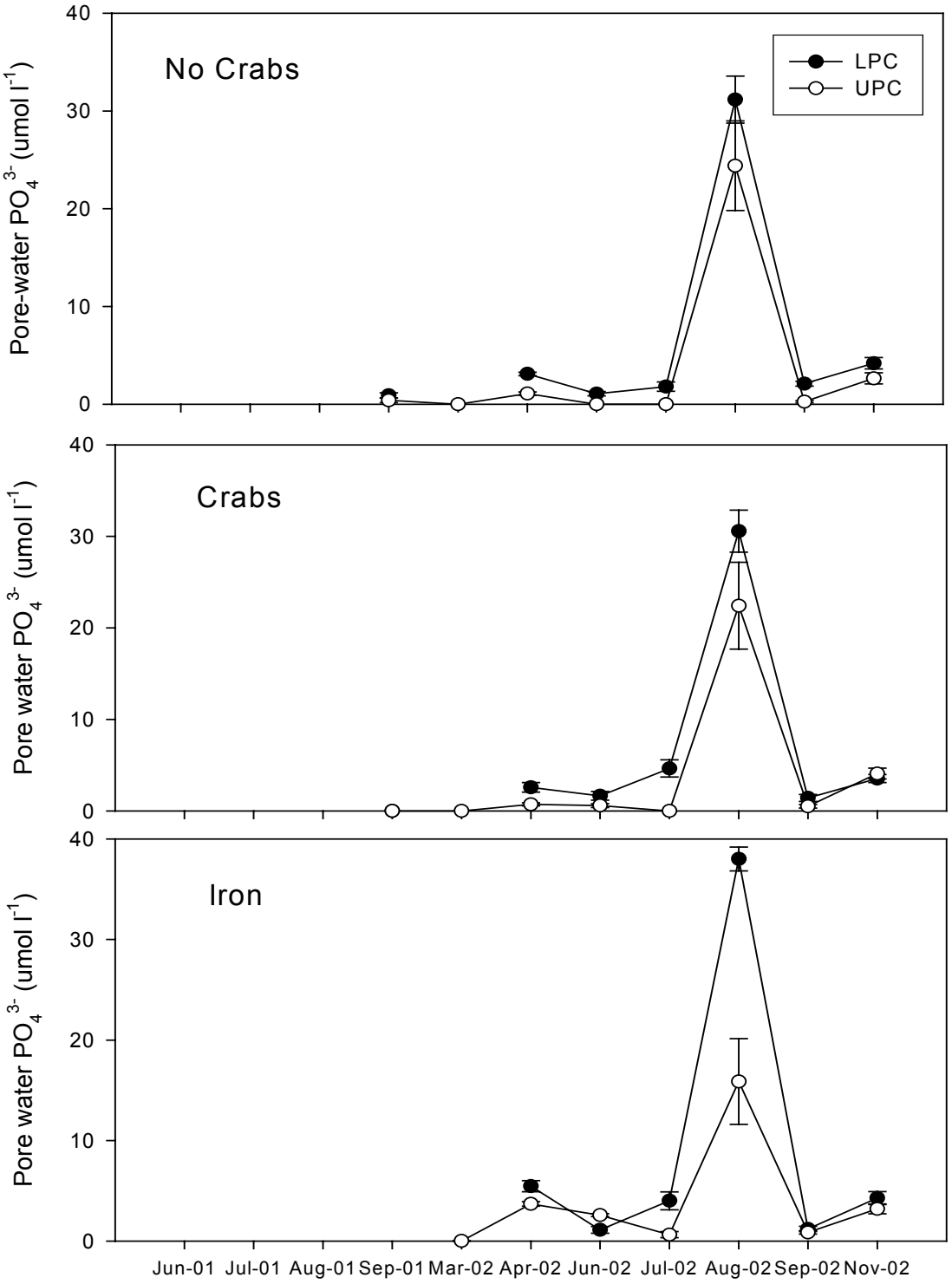
Phosphate

Phosphate bonds strongly with oxidized iron (Sherwood and Qualls, 2001; Smolders et al. 2001). Therefore, pore-water phosphate was measured to insure that the iron addition experiment was not interfering with phosphate availability for plant growth. Pore-water phosphate was significantly different and higher at LPC (8.1 μmol l^{-1}) than UPC (4.5 μmol l^{-1}) ($p < 0.001$). Pore-water phosphate concentration also responded significantly to treatment ($p < 0.001$) with Iron plots having the highest concentration (6.8 μmol l^{-1}) and No Crab plots having the lowest (6.1 μmol l^{-1}). There also appeared to be a temporal effect with phosphate peaking in August 2002 in all plots (Fig. 21). Pore-water phosphate was negatively correlated with both ferrous iron ($r = -0.172$, $p < 0.001$) and total dissolved iron ($r = -0.165$, $p < 0.001$).

pH

The pH of the sediment pore water was circum-neutral in all plots; however, there was a significant site ($p = 0.019$) and treatment effect ($p = 0.005$). The pH was higher at LPC (6.99) than UPC (6.87); pH was also highest in the Crab plots (7.02) and lowest in the Iron plots (6.82). There was a significant temporal effect on pH at both sites ($p < 0.001$) that corresponds with the variables that have the potential to affect pH (e.g., sulfate reduction and decomposition).

Fig. 21. Depth-averaged pore-water phosphate concentration measured at LPC and UPC at monthly intervals from September 2001 to November 2002 except for iron plots where measurements where made between March 2002 and November 2002. Error bars are one standard error (n=144).



Platinum Electrode Potential

Platinum electrode potential is a relative indictor of redox conditions, which is a measure of the reducing or oxidizing nature of an environment. There was no significant site effect for PtEP though it was generally higher at UPC (46 mV) than LPC (40 mV). The Iron plots had the highest PtEP (64 mV), and PtEP was lowest in the No Crabs plots (8 mV) ($p < 0.001$).

For all plots except Crab plots, PtEP was higher in the root zone (approximately 0-10 cm depth) and lower below 10 cm depth (Fig. 22). The plot with the highest average PtEP, UPC Iron, was also the plot with the greatest aboveground biomass. Crab plots had relatively high PtEP throughout the depths measured.

Decomposition

Litterbag Decomposition

Decomposition was measured as the percent ash-free dry weight (AFDW) lost from a litterbag over time. The UPC site had higher quarterly decomposition rates (11% AFDW loss quarterly) than LPC (4% AFDW loss quarterly) ($p < 0.001$). The Crab plots' decomposition was different and highest (21% AFDW loss quarterly), whereas the Iron plot's decomposition was the lowest (10% AFDW gain quarterly) ($p < 0.001$) (Fig. 23). Direct comparison of Iron plot measurements to the other treatments is difficult given that the Iron experiment was started at a different time of year with fresh organic material as opposed to the other experimental plots whose organic material had been collected and placed in the marsh a year earlier.

Fig. 22. Mean platinum electrode potential measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except in iron plots where measurements were taken between March 2002 and November 2002. Error bars are one standard error (n=198).

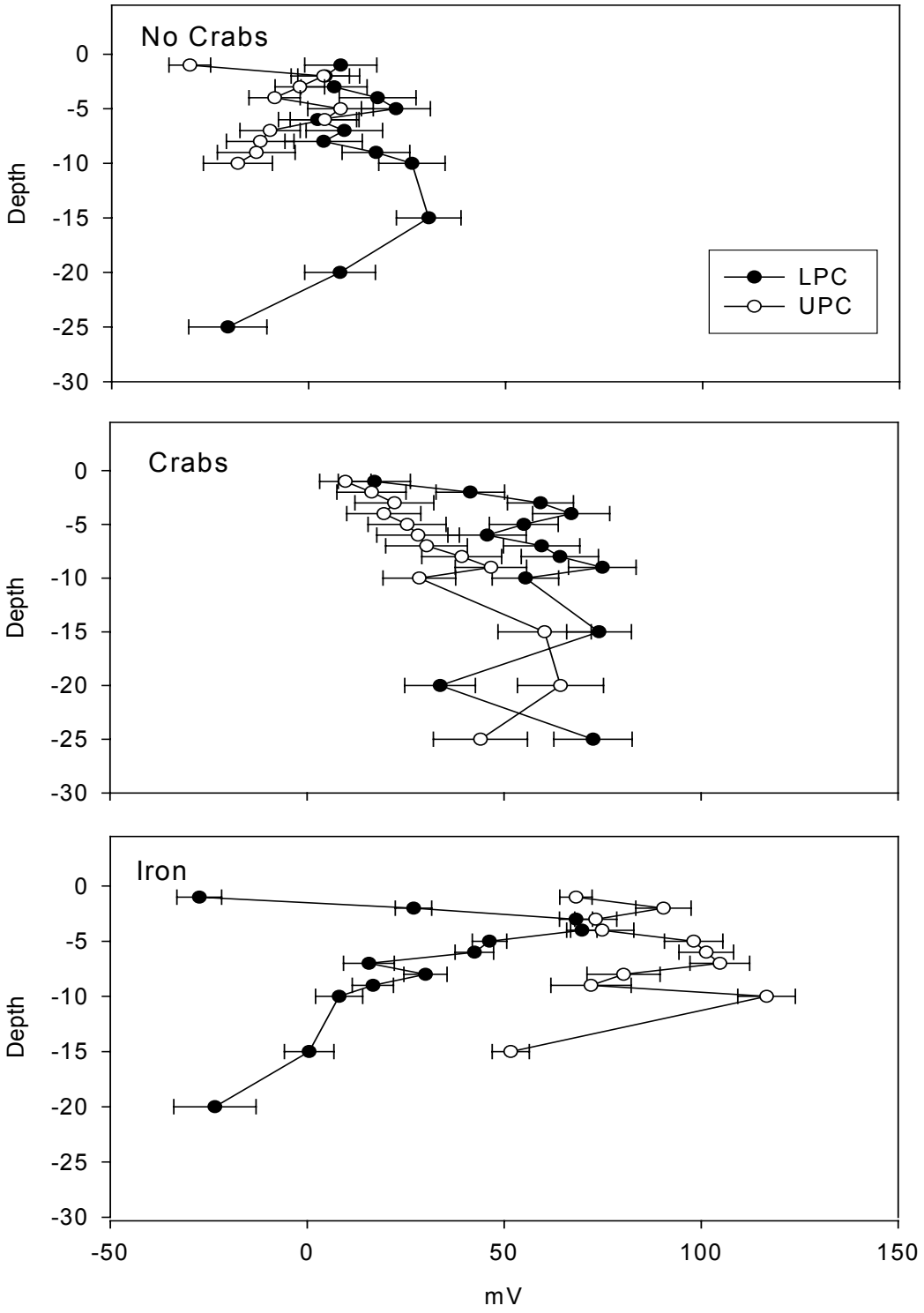
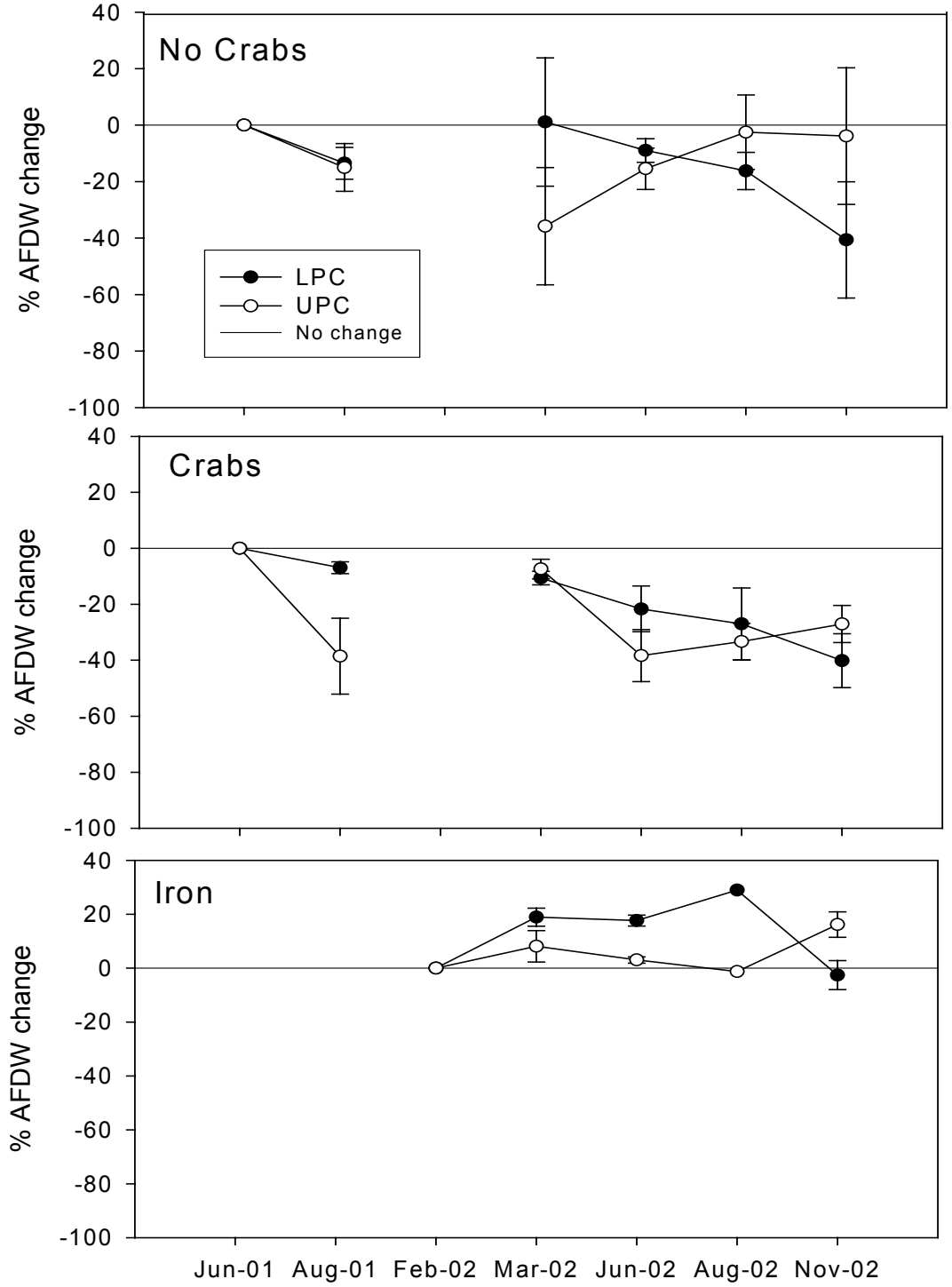


Fig. 23. Percent ash-free dry weight loss measured at LPC and UPC on a quarterly basis from June 2001 to November 2002 except in iron plots where measurements were taken between February 2002 and November 2002. Error bars are one standard error (n=3).



Sulfate Reduction Rates

Sulfate reduction rates (SRR) were significantly different and higher at UPC (328 nmol SO_4^{2-} ml^{-1} of sed d^{-1}) than LPC (199 nmol SO_4^{2-} ml^{-1} of sed d^{-1}) ($p < 0.001$), however, the f ^{35}S for UPC (0.016) was not significantly different from LPC (0.038). The SRR was different and highest in the Iron plots (340 nmol SO_4^{2-} ml^{-1} of sed d^{-1}) and lowest in the Crab plots (215 nmol SO_4^{2-} ml^{-1} of sed d^{-1}) ($p < 0.001$), whereas f ^{35}S was different and highest in the No Crabs plots (0.041) and lowest in the Crab plots (0.020) ($p < 0.001$). The highest SRRs occured during early spring and late summer except for Iron plots (Fig. 24). The difference in SRR values between 2001 and 2002 rates reflects a change in methodology. The 2001 results represent data collected using the AVS technique, whereas 2002 data were collected using the TRIS technique.

On a monthly basis, Iron plots had higher average SRR, however, this relationship reversed when sulfate reduction was calculated over an entire growing season (Fig. 25). This was done by scaling up from ml of sediment to a m^2 plot, scaling up from days to a month and then adding together the months for the growing season. For the 2002 growing season, the amount of sulfate reduced was highest in the Crab treatment and lowest in the No Crab treatment. Sulfate reduction continued to be higher at UPC. The total amount of sulfate reduced was approximately 65-80% of litterbag decomposition in the "native" plots.

Fig. 24. Depth-averaged sulfate reduction rates measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except iron plots where measurements were taken between March 2002 and November 2002. Error bars are one standard error (n=18).

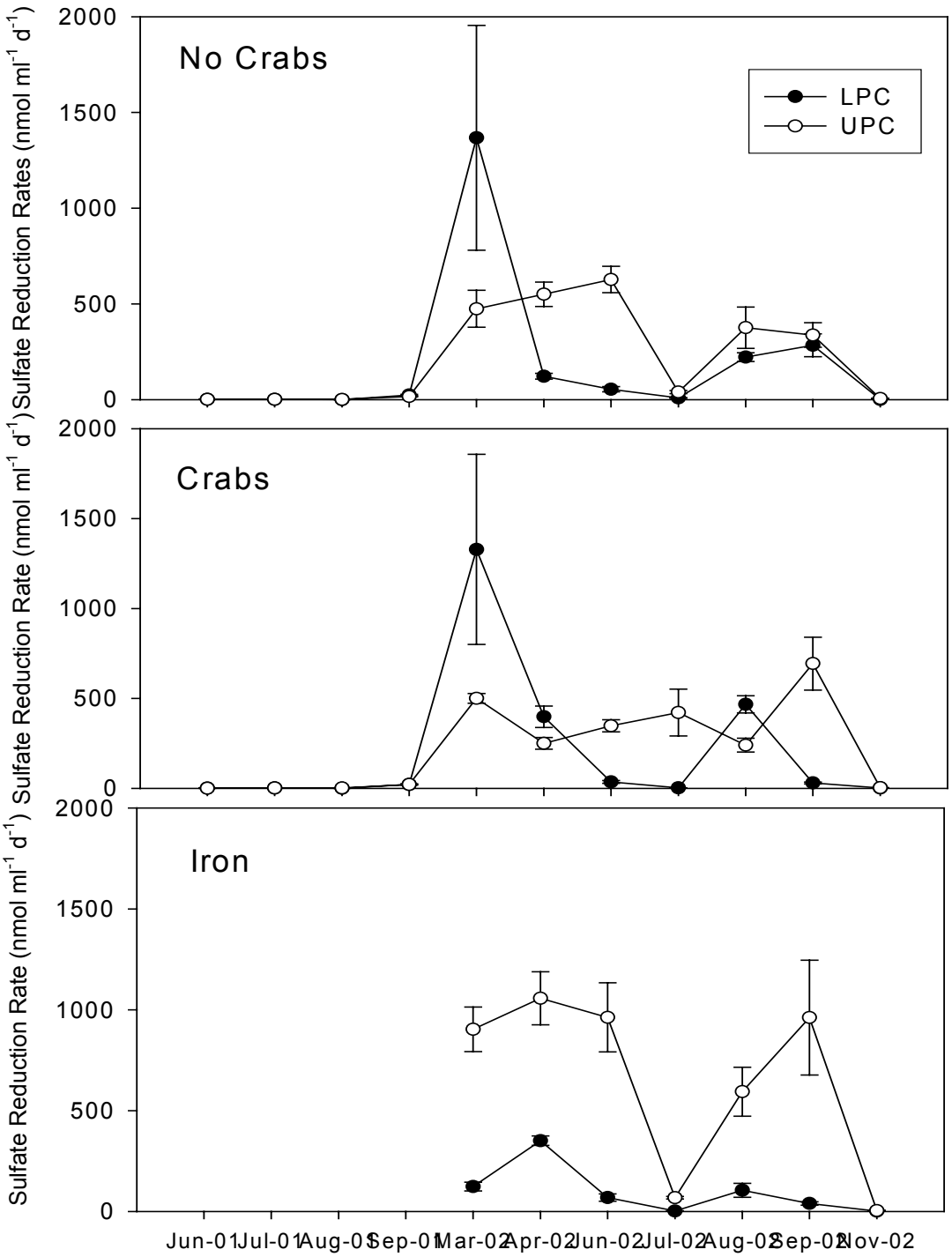
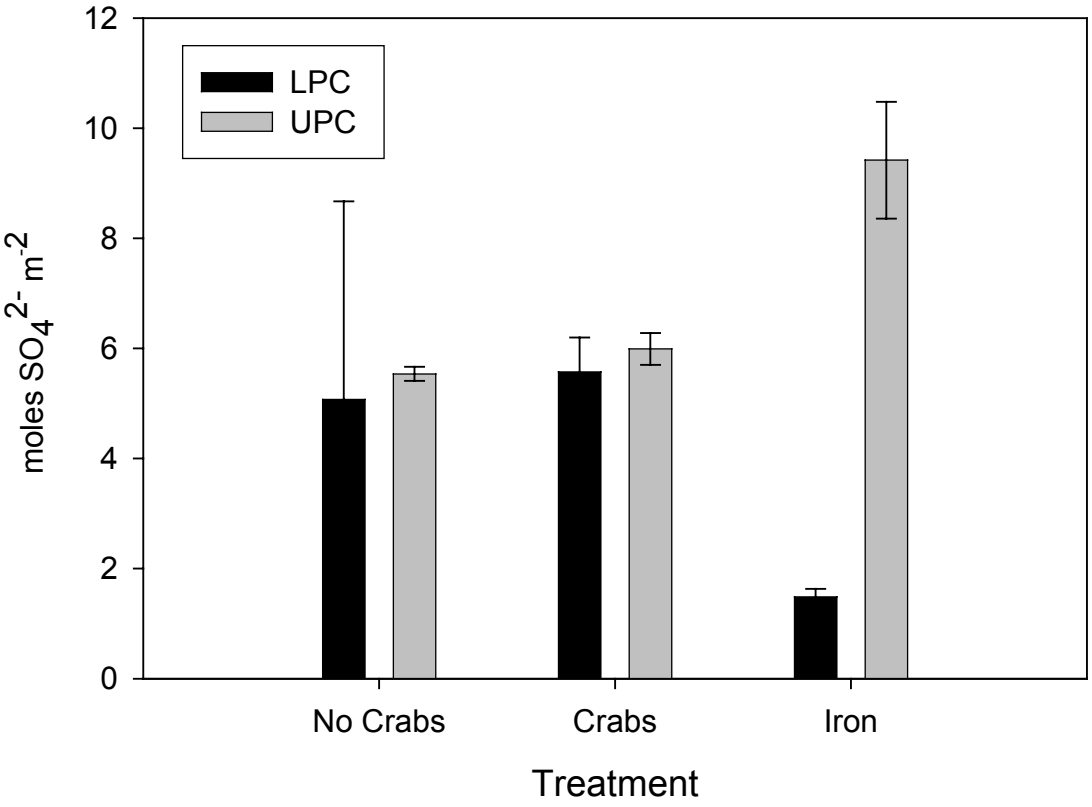


Fig. 25. Amount of sulfate reduced for the 2002 growing-season measured at LPC and UPC. Error bars are one standard error (n=21).



Vegetation

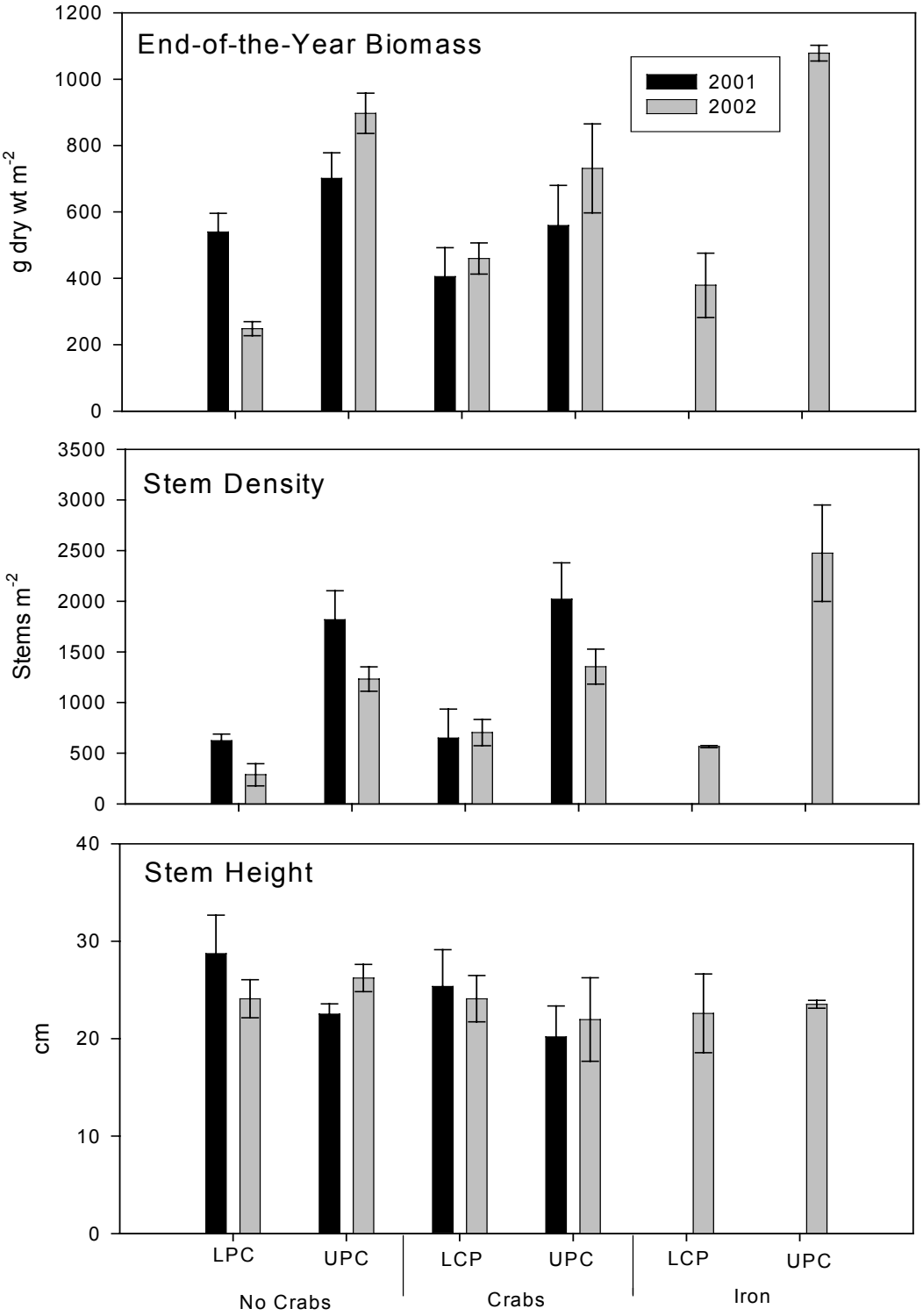
End-Of-The-Year Biomass

End-of-Year Biomass and stem density were significantly different and higher at UPC than LPC ($p < 0.001$ for both), whereas, stem height was different and taller at LPC than UPC ($p < 0.001$) (Fig. 26). The EOYB was different and greatest in Iron plots (729 g dry wt m^{-2}) and least in Crab plots (554 g dry wt m^{-2}) ($p < 0.001$). Stem density was highest in Iron plots (1520 stems m^{-2}) and lowest in No Crab plots (928 stems m^{-2}) ($p < 0.001$). The fact that stem density was lower in No Crab plots than Crab plots yet there was more EOYB in the No Crab plots than the Crab plots indicates that the difference in biomass was not due to a decrease in available marsh surface for plant colonization due to crab burrows. Stems were tallest in the No Crabs plots (25 cm) and shortest in the Crab plots (23 cm) ($p < 0.001$). Biomass increased from 2001 to 2002, whereas stem density decreased except for LPC No Crabs for both biomass and stem density. There was also a species shift to a monoculture of *S. alterniflora* from 2001 to 2002. In 2001, *S. patens* was found in LPC No Crab plots, and *S. patens* and *Disticlis spicata* were found in UPC plots. Lower biomass and the shift to *S. alterniflora* monoculture were coincident with the drought of 2002.

$\delta^{34}S$

Stable sulfur isotope ratios were measured in the leaves of *S. alterniflora* as a way to detect potential plant sulfide stress. The $\delta^{34}S$ ratio was determined by subtracting the ^{34}S:^{32}S ratio of sample material from that of the Canyon Diablo standard. The more negative the number, the greater the concentration of ^{32}S in the sample, the greater the

Fig 26. Vegetation characteristics measured at LPC and UPC in August 2001 and 2002 except iron plots that were only measured in 2002. Error bars are one standard error (n=3).



amount of sulfide taken up by the plant, and presumably the greater the sulfide stress (Chambers et al. 2001; Stribling et al. 1998). Plants in the Crab plots had the lightest $\delta^{34}S$ (3.7) whereas those in the No Crab plots were isotopically heaviest (6.7) ($p < 0.001$) (Table 7). On average, plants from LPC were isotopically lighter (-1.6) than those from UPC (11.8) ($p < 0.001$). Plants from the LPC Iron treatment where pore-water sulfide concentrations were the highest were the isotopically lightest $\delta^{34}S$ (-5.4).

Table 7. Stable S isotope ratios measured in *S. alterniflora* leaves at LPC and UPC in August 2002. (n=3)

Treatment	**Site**	**$\delta^{34}S$ ± Standard Error**	**Mean $\delta^{34}S$ for Treatment**
No Crabs	LPC	3.8 ± 1.6	6.7 ± 0.6
	UPC	9.5 ± 1.2	
Crabs	LPC	-3.1 ± 1.2	3.7 ± 1.3
	UPC	10.5 ± 0.5	
Iron	LPC	-5.4 ± 0.1	5.0 ± 1.9
	UPC	15.3 ±0.8	

Carbon-Nitrogen Analysis

The C:N ratio (CN) of plant foliage may be an indicator of sulfide stress because sulfide interferes with *S. alterniflora* N uptake and metabolism (Mendelssohn 1979; Bradley and Morris 1990; Koch et al. 1990) and, because the plants are the same species located in the same marsh, the CN can be compared between sites and between treatments to determine the effect of altering biogeochemistry of the marsh sediment on plant foliage CN (Morris, J.T., USC, Columbia, SC, USA). The CN of *S. alterniflora* plants was higher at UPC (25) than LPC (21) ($p < 0.001$) (Table 8). Plant CN values were highest in the No Crab plots (24) and lowest in the Iron plots (21), whereas there was very little difference between plants from No Crab and Crab plots ($p < 0.001$).

Table 8. Carbon-to-Nitrogen ratio for *S. alterniflora* leaves collected at LPC and UPC in August 2002. (n=3)

Treatment	Site	C:N ± Standard Error	Mean C:N for Treatment
No Crabs	LPC	18.4 ± 4.5	23.1 ± 1.3
	UPc	27.8 ± 1.5	
Crabs	LPC	23.1 ± 0.6	24.0 ± 0.3
	UPC	24.9 ± 4.2	
Iron	LPC	20.8 ± 2.8	21.3 ± 0.1
	UPC	21.8 ± 0.6	

Root Growth

The dry weight root growth per month was significantly higher at LPC ($p = 0.025$) than UPC, however UPC No Crabs plots had higher dry weight root growth than LPC Crab plots (the "native" plots). At LPC, the highest root growth occurred in the Crab plots and was lowest in the Iron plots. At UPC, the highest root growth was in the No Crab plots and the lowest in the Iron plots. There was no significant treatment effect. Ash-free dry weight root growth, however, was significantly higher at UPC (36.1 g AFDW m^{-2} mon^{-1}) than LPC (21.8 g AFDW m^{-2} mon^{-1}) ($p < 0.001$). Root growth was also significantly different and highest in the No Crab plots (43.4 g AFDW m^{-2} mon^{-1}) and lowest in the Iron plots (11.1 g AFDW m^{-2} mon^{-1}) ($p < 0.001$) (Fig. 27). The total root production for the 2002 growing season (March-November) was calculated for both dry weight root growth and AFDW root growth. Total dry weight root production for the 2002 growing season on average was greatest in the No Crab plots (Fig. 28). When AFDW root production was calculated, however, it was discovered that the root material from LPC and UPC had different ash contents. LPC's root material was approximately 58% ash, whereas UPC's root material

Fig. 27. Ash-free dry weight root production measured at LPC and UPC at monthly intervals from June 2001 to November 2002 except iron plots where measurements were taken from February 2002 to November 2002. Error bars are one standard error (n=3).

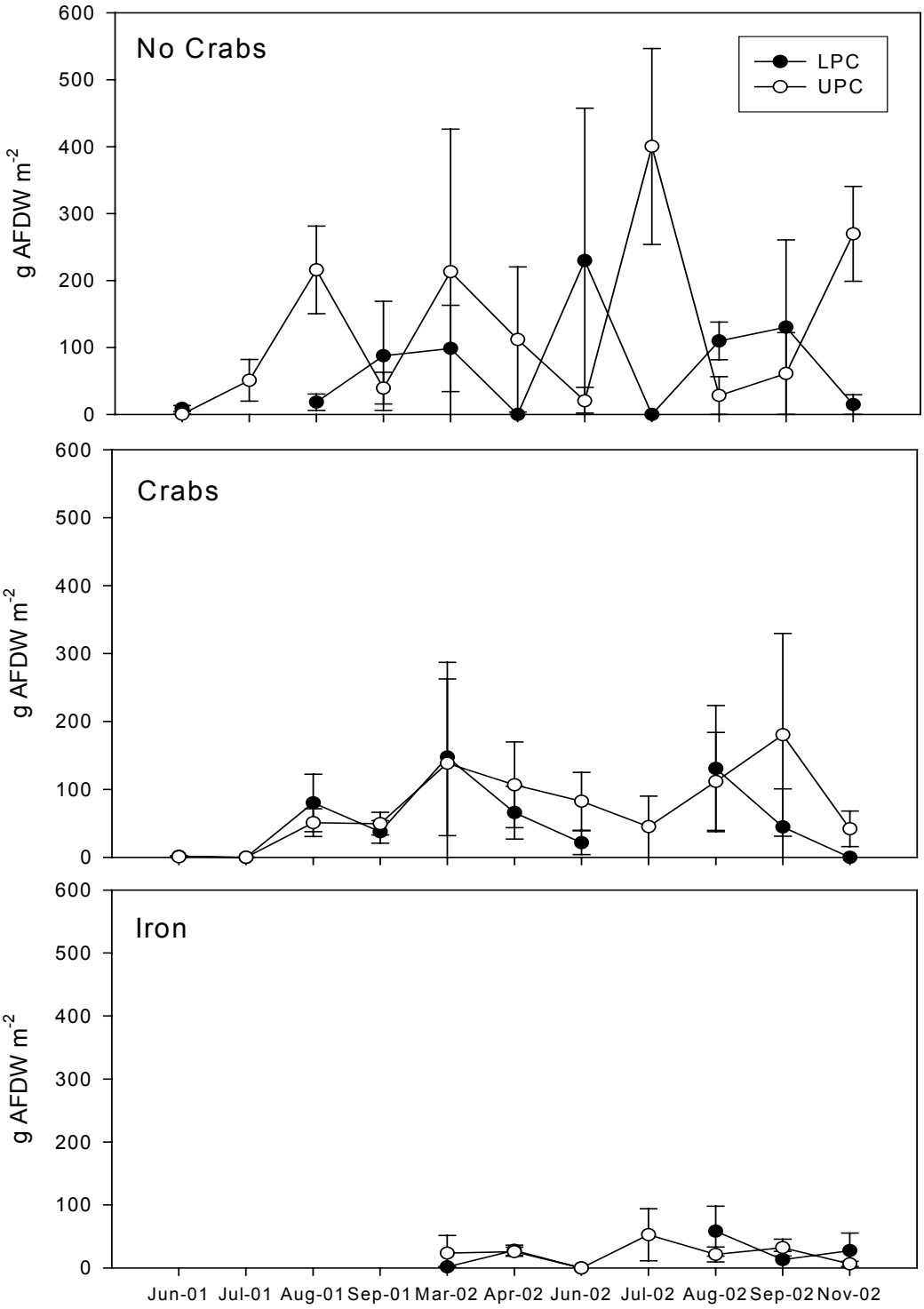


Fig. 28. Total dry weight root production at LPC and UPC from March to November 2002. Error bars are one standard error (n=3).

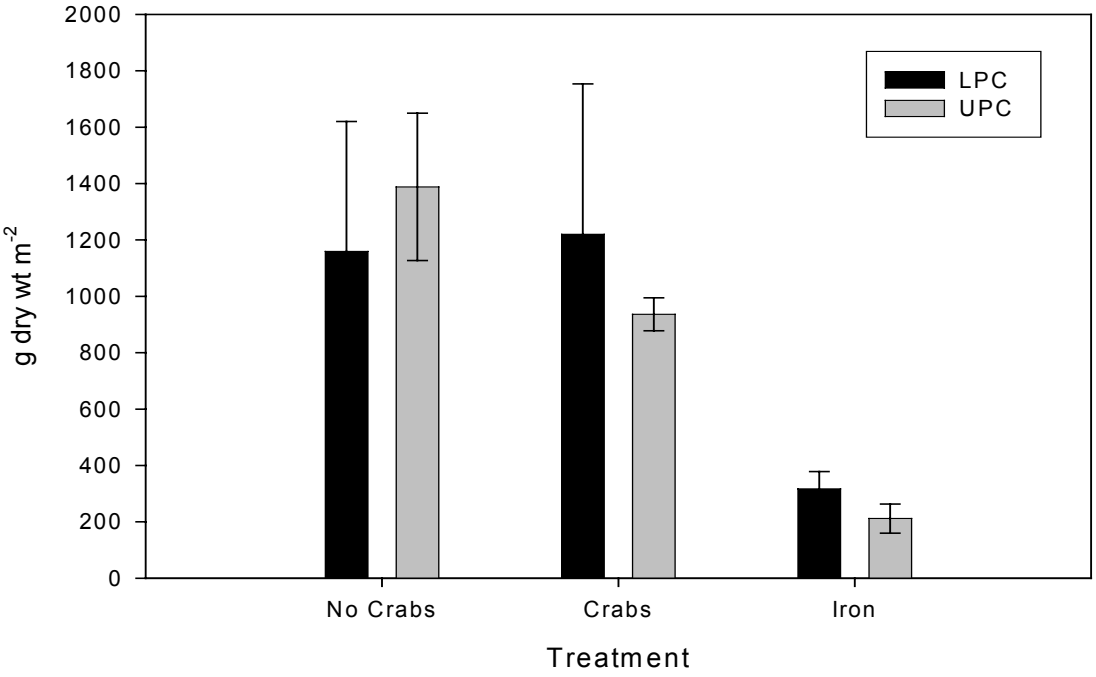
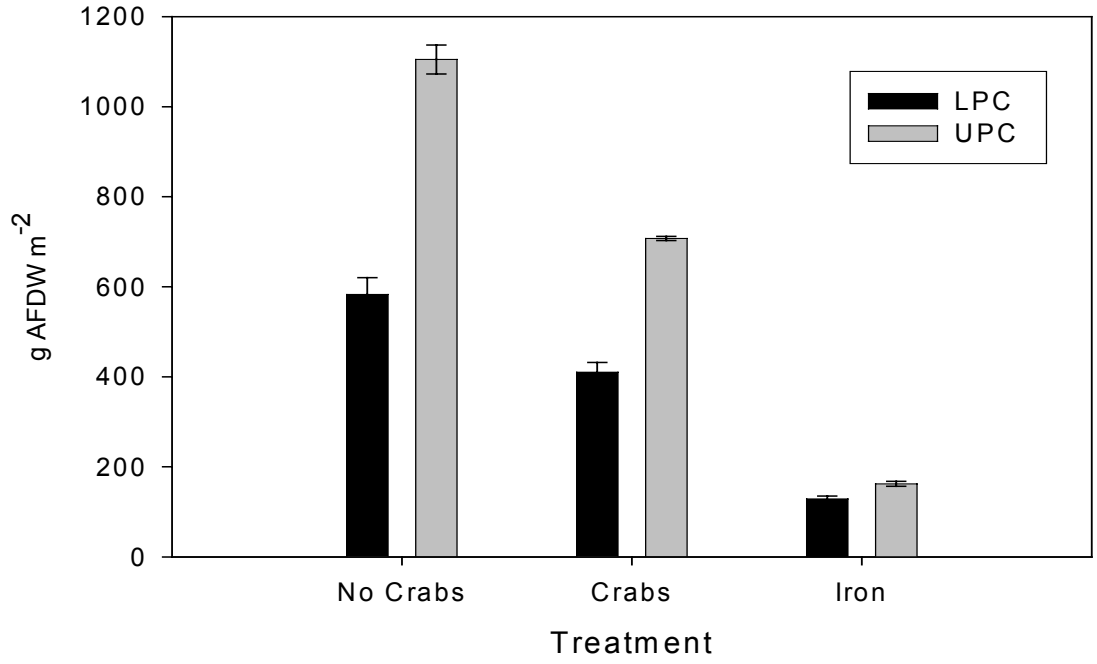


Fig. 29. Total ash-free dry weight root production at LPC and UPC from March to November 2002. Error bars are one standard error (n=3).



was approximately 23% ash. This dramatically changed the root production trends of the two sites (Fig. 29).

Annual total plant production (above- and belowground production) ranged widely among the plot types (Table 9). The UPC Iron plots had the highest total plant production (3113 g dry weight m^{-2} y^{-1}), whereas LPC Iron plots had the lowest (976 g dry weight m^{-2} y^{-1}). The root/shoot ratio is reported to be an indicator of plant stress. Stressed plants allocate more biomass to the roots than aboveground (Valiela et al. 1976; Schubauer and Hopkinson 1984). The No crab plots have the highest root/shoot ratios with an average root/shoot ratio of 1.8.

Table 9. Total primary production at LPC and UPC for 2002 ± one standard error (g dry weight m^{-2} y^{-1})

Plot	**Root Production**	**Aboveground Production***	**Total Production**	**Root/Shoot**
LPC No Crabs	1159 ± 266	432 ± 21	1591 ± 287	2.7
UPC No Crabs	1388 ± 151	1559 ± 61	2947 ± 212	0.9
LPC Crabs	1220 ± 308	799 ± 47	2019 ± 355	1.5
UPC Crabs	936 ± 34	1271 ± 135	2207 ± 169	0.7
LPC Iron	317 ± 35	659 ± 97	976 ± 132	0.5
UPC Iron†	1239 ± 162	1874 ± 24	3113 ± 186	0.7

*Aboveground production was converted from EOYB using a conversion factor of 1.74 (Morris and Haskin 1990). †UPC Iron root production = (litterbag decomposition (See Table 9) + weight gain in the decomposition litter bags)/0.77 (the %AFDW of UPC root material).

One of the hypotheses the crab and iron addition experiments were designed to test was that plants respond to high pore-water sulfide concentrations by creating more roots. There was a weak but significant negative correlation between pore-water sulfide concentration and dry weight root growth ($r = - 0.087$, $p = 0.003$). There was no correlation with pore-water sulfide concentration and AFDW root growth. There was,

however, a significant correlation between AFDW root growth and SRR although the explained variance is low (r = 0.063. p = 0.030).

Ash-free dry weight root production tended to be higher than decomposition except in UPC plots, where crab burrows were created (Table 10). The UPC No Crabs treatment had the greatest difference between root growth and decomposition (root growth 123% > litterbag decomposition) and therefore, the greatest potential for organic matter accumulation to occur.

Table 10. Root growth and decomposition at LPC and UPC for 2002. (g AFDW m^{-2} y^{-1})

Plot	**Root Production ± 1 S.E.**	**Litterbag decomposition ± 1 S.E.**	**%Difference**
LPC No Crab	583.2 ± 37.0	419.6 ± 108.3	+39
UPC No Crab	1104.8 ± 32.3	495.9 ± 126.8	+123
LPC Crab	410.2 ± 21.8	334.5 ± 26.9	+23
UPC Crab	707.3 ±4.7	1110.9 ± 195.0	-36
LPC Iron†	128.8 ±6.5	168.6 ± 15.1	-24
UPC Iron§	954.2 ± 5.5	882.5 ± 19.3	+8

†LPC Iron decomposition=Litterbag AFDW-root production. §Because sulfate reduction was greater than decomposition when computed by litterbag AFDW- root production, UPC Iron's decomposition was figured in the following manner: Sulfate reduction (g C m^{-2} y^{-1})/Average %SR was of decomposition (60.2%)/40% (g C to AFDW conversion) (Alexander 1967). Root growth = litterbag decomposition + weight gain in litterbags.

The UPC Crabs treatment resulted in more decomposition than root production (root growth 36% < litterbag decomposition). Root growth was 39% more and 23% more than litterbag decomposition in the LPC No Crabs treatment and LPC Crabs treatment, respectively.

Regional Perspective

Six marshes spanning the lower Delmarva Peninsula were sampled in August 2002 to determine if OM content measured in these marshes could be explained by the

experimental results from the Phillips Creek Marsh sites. The six marshes were chosen to represent a wide range of sediment OM content and differing vulnerabilities to sea-level rise (Ricker 1999) (See Methods Site Description section for selection criteria for these marshes).

The sediment characteristics of the six marshes were analyzed by PCA to determine if any variables contributed to site differences. The first three PCs accounted for 47% of the variability in the data. Two patterns were observed: the presence/absence of crabs and location along the Peninsula (northern, mid, and southern marshes), the data separated out on the second and third PCs (Figs. 30 and 31). End-of-the-Year Biomass contributed positively and % sand contributed negatively to PC2, whereas variables comprising PC 3, % clay, pore-water sulfide, and S^{2-}:Fe^{2+} ratio, were positive. The Crab/No Crab groupings overlapped on the northern peninsula sites. The two northern sites, Channel Point and Kegotank Farm, have very steep landward slopes, and Ricker (1999) hypothesized that marshes in this area are vulnerable to marsh loss as sea level rises.

Based on the results of the PCA, the sediment characteristics of the six marshes were also examined using MANOVA to compare sites with crabs to sites with no crabs and to compare southern, mid, and northern marshes along the Peninsula. The sediment characteristics were very different among sites (Table 11). Summer root growth was higher at sites with crabs than without crabs, and EOYB was higher at sites without crabs than at sites with crabs (Table 12). The root growth results did not agree with the results of the experimental manipulations in Phillips Creek marsh at UPC and LPC; however,

Fig. 30. PCA of six marshes located in the lower Delmarva Peninsula and sampled in August 2002. Separated by crab presence.

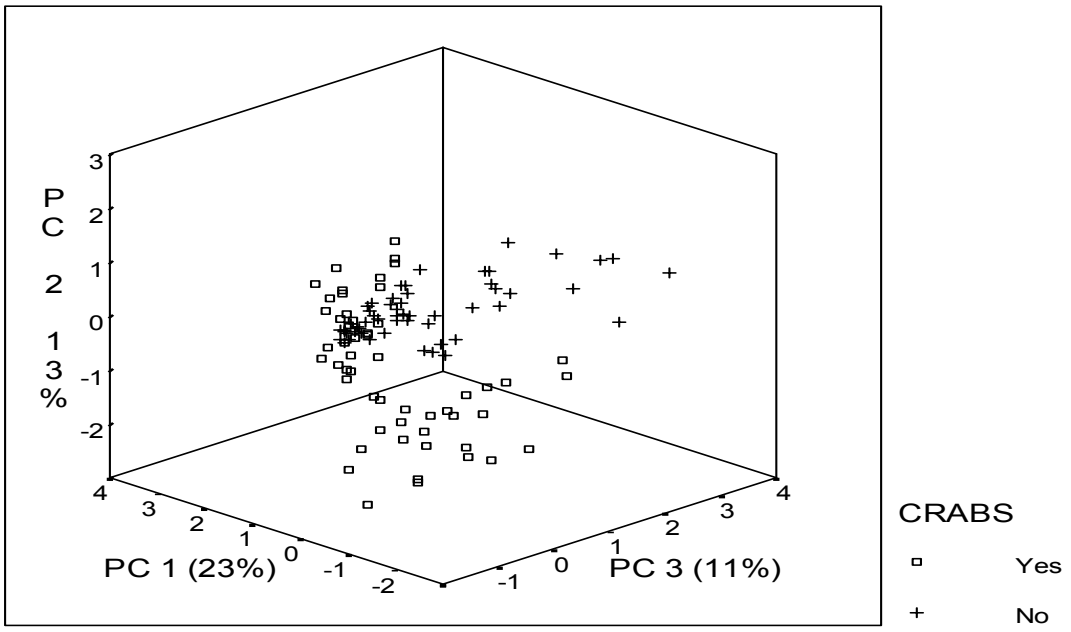


Fig. 31. PCA of six marshes located in the lower Delmarva Peninsula and sampled in August 2002. Separated by region.

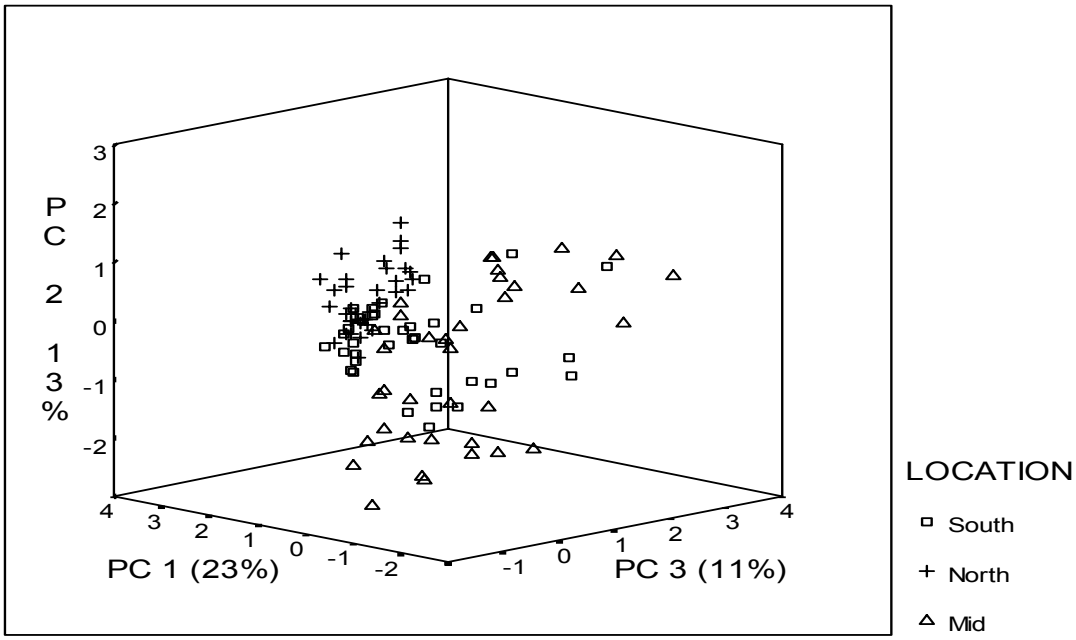


Table 11. Sediment characteristics of six marshes located in the lower Delmarva Peninsula and sampled in August 2002. (n=3)

Site	Depth (cm)	% Sand	% Clay	Bulk Density (g cm^3)	% OM	Textural Classification
Steelmans Landing*	0-10	10	22	0.39	40.1	Silt loam
	10-20	54	26	0.80	4.6	Sandy clay loam
Oyster	0-10	29	49	0.19	49.4	Clay loam
	10-20	26	30			Clay loam
Woodland Farm	0-10	30	26	1.11	3.7	Loam
	10-20	14	42	1.28	2.5	Silty clay
Belleview*	0-10	46	40	0.77	7.5	Loam
	10-20	62	24	1.03	2.6	Sandy loam
Channel Point	0-10	32	23	0.21	30.0	Loam
	10-20	32	25	0.21	25.3	Loam
Kegotank*	0-10	26	21	0.31	28.1	Silt loam
	10-20	13	29	0.21	35.1	Silty clay loam

*Indicates the presence of fiddler crabs.

Table 12. Results from six marshes in the lower Delmarva Peninsula and sampled in August 2002. (n=3)

Variable	No Crabs	Crabs	South	Mid	North
PTEP mV†	200	164	91	190	265
Reduced iron µmol l^{-1}	106.1	69.3	144.4	47.0	71.7
Sulfide µmol l^{-1} †	34.5	19.7	40.4	38.3	2.8
Sulfate mmol l^{-1}	43.4	50.3	53.4	44.0	43.2
Chloride ppt	71.5	81.1	71.1	82.4	75.4
Sulfate Reduction Rate nmol ml^{-1} d^{-1} †	1061.4	625.6	1621.1	228.3	681.1
End of the Year Biomass g dry wt m^{-2} *†	341.7	261.0	292.6	245.3	366.0
Root Growth AFDW m^{-2} *†	313.1	423.3	397.2	224.3	483.1
% Organic Matter *†	25.8	12.8	26.7	4.6	26.6
% Water *†	60.2	53.0	64.7	31.6	72.0
Bulk Density †	0.52	0.58	0.4	1.01	0.23

* Significant crab effect.
† Significant location effect.
See Appendix F for complete table with mean squares and F-values.

these results were driven by Kegotank Farm, which was unusual when analyzed with PCA. Kegotank Farm's grouping overlapped with the no crab clusters (Fig. 30). When Kegotank Farm root growth results were omitted from MANOVA analysis, the sites without crabs had significantly higher root growth than sites with crabs. The EOYB results were similar to results of Phillips Creek marsh. Neither SRR nor f ^{35}S in the six marshes were significantly affected by crabs. The SRRs were higher in the marshes without crabs but were highest in the Crab plots at Phillips Creek. Decomposition was not measured at the six marshes.

The pore-water chemistry of the six marshes was not generally affected by the presence of crabs. Only phosphate and chloride concentrations showed a significant effect; both were higher in the marshes with crabs than without crabs. The phosphate results agreed with the results from Phillips Creek marsh, but the chloride results did not. Though the differences were not statistically significant, pore-water sulfide was higher in the three marshes with no crabs than the three marshes with crabs.

Location (northern, mid, or southern Peninsula) also had a significant effect on many of the variables. The most striking difference was in pore-water sulfide concentrations. The average pore-water sulfide concentrations for the northern marshes were 2.8 μmol l^{-1}, whereas the mid and southern marshes ranged from 38.3-40.4 μmol l^{-1}. Platinum electrode potential was also much lower in the mid and southern marshes (91 and 190 mV, respectively) than the northern marshes (265 mV).

A PCA was done on the data of the regional marshes and the native plots at Phillips Creek marsh. The clustering of marshes with and without crabs becomes less clear but still overlapped at the northern sites (Fig. 32 and 33). The first three PCs

accounted for 49% of the variability in the data, which is slightly higher than the analysis with the regional marshes alone. The marshes primarily separate on PC 2, which is positively contributed to by %OM and EOYB and negatively by PtEP.

Fig. 32. PCA of six marshes located in the lower Delmarva Peninsula and Phillips Creek native marshes sampled in August 2002. Separated by crab presence.

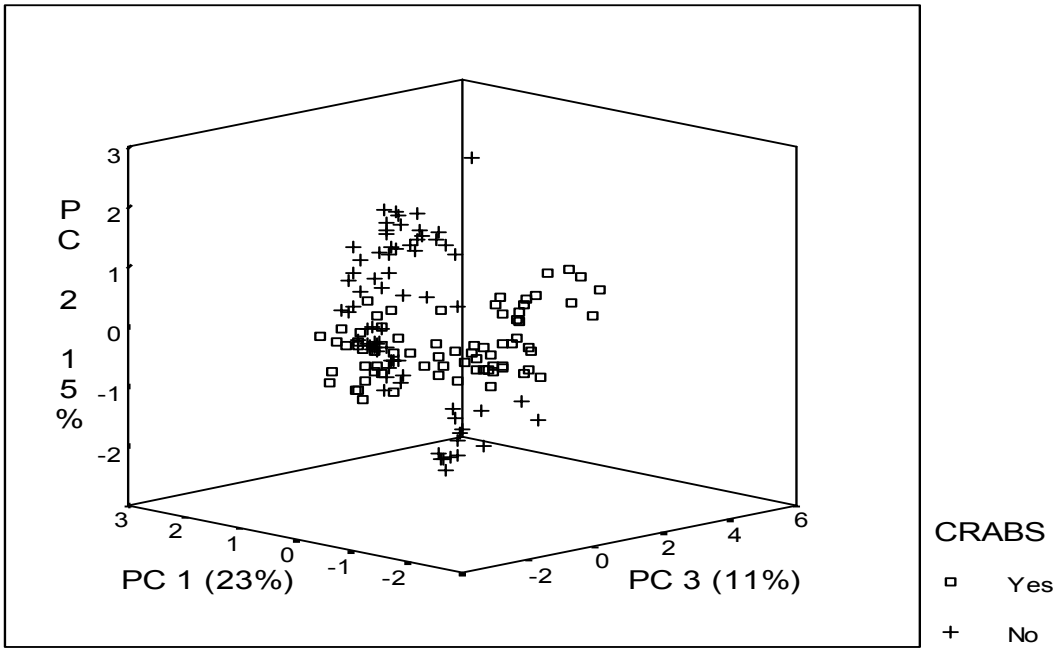
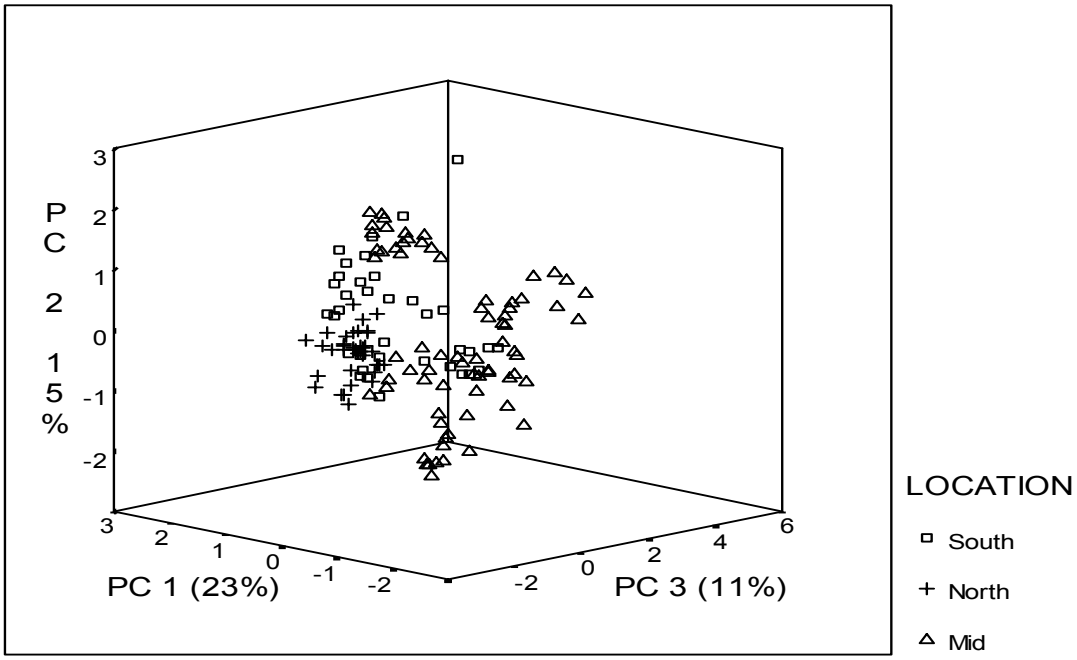


Fig. 33. PCA of six marshes located in the lower Delmarva Peninsular and Phillips Creek native marshes sampled in August 2002. Separated by region.



Discussion

Conceptual Model

The conceptual model presented in the Introduction hypothesizes that the availability of terminal electron acceptors and pore-water reduced iron concentration will have a dramatic impact on a marsh's ability to accumulate organic matter. Furthermore, I hypothesized that the availability of terminal electron acceptors would be influenced by sediment texture and the presence of macropores like those created by fiddler crabs. Sediment texture should impact the rate of infiltration of terminal electron acceptors and therefore the rate of decomposition. Fiddler crabs are expected to increase the marsh surface area by creating burrow holes in the marsh, therefore increasing the marsh surface/flood water interface. This increased interface should increase the availability of terminal electron acceptors including oxygen, in turn reducing pore-water sulfide concentration, and ultimately reduce sulfide stress on plants. It is further hypothesized that reduced sulfide stress will result in a reduction in root growth. Additionally, reduced iron should bind with sulfide, reducing pore-water sulfide concentration and concomitantly root growth. As a result of these alterations in geochemistry, the balance between root growth and decomposition may be affected, which in turn could impact the potential for OM accumulation.

The model also suggests that a positive feedback exists, where sulfate reduction leads to sulfide production, which increases root growth and provides more substrate to fuel sulfate reduction. The presumption that is the foundation of this feedback is that higher pore-water sulfide concentrations lead to greater root growth as a plant stress defense mechanism. Therefore, when crab burrows or reduced iron are present and pore-

water sulfide concentration is reduced, root growth is also reduced. Based on the results of the experiments described in this document, numbers have been added to the model (Fig. 34). Not all fluxes were measured, so the model could not be developed beyond the conceptual stage. Additional measurements need to convert this to a mechanistic model include; plant uptake of phosphate, ammonium, sulfate, and sulfide, root turnover, and pyrite formation. Note the addition of crab burrow excavation, which will be discussed below.

Root production and litterbag decomposition rates measured during the experiments in Phillips Creek marsh were used to calculate the potential for these sites to accumulate OM (Table 13). Root production exceeded decomposition rates regardless of site (i.e., LPC or UPC) or experimental treatment (Crabs, No Crabs, or Iron) with the exception of UPC plots where artificial crab burrows were constructed. In these plots, litterbag decomposition was greater than root production and greatly enhanced over the native condition (UPC without crabs). In LPC, the balance between root production and litterbag decomposition always favored OM accumulation, but at a much slower rate than the native condition (No Crabs) at UPC. Clearly, the balance between root production and decay rates provides a feasible explanation for the differences in the sediment OM concentrations at these two sites. Furthermore, it is the difference in root production rates between the two sites that is responsible for the ability of UPC to accumulate OM more rapidly than LPC as decay in the native plots (UPC No Crabs and LPC Crabs) is similar given the degree of uncertainty associated with the measurement of decomposition. These results are consistent with those of Blum (1993) who attributed differences in OM accumulation

Fig. 34. Conceptual model with some flux numbers. Fluxes are g C m^{-2} y^{-1} assuming 40% of AFDW is carbon (Alexander, 1967).

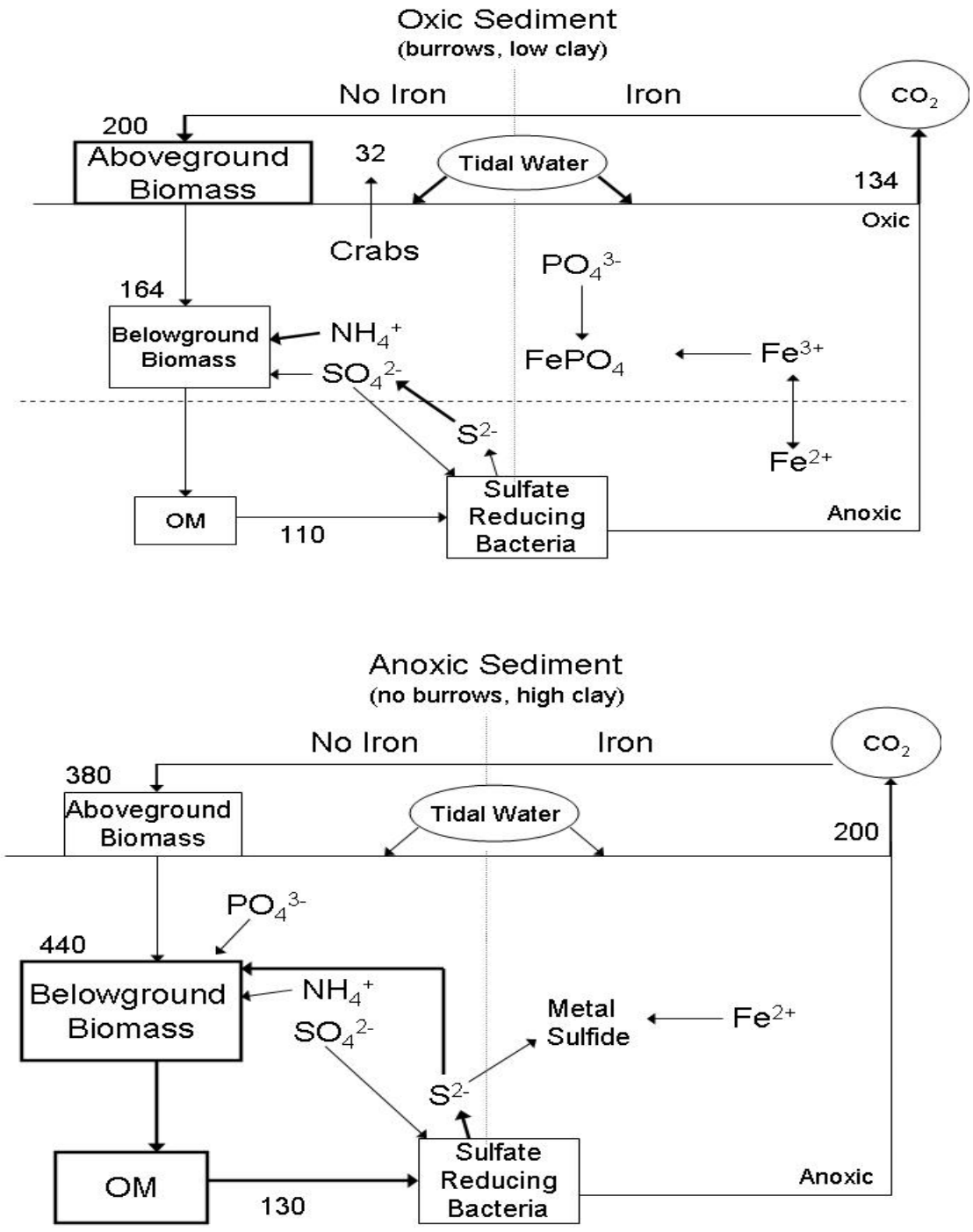


Table 13. Potential organic matter accumulation in g C m^{-2} y^{-1} at LPC and UPC. Conversion from AFDW to carbon was made assuming 40% of AFDW is carbon (Alexander, 1967).

Plot	**Root Production[§] ± 1 SD**	**Decomposition ± 1 SD**	**Root Production-Decomposition**	**Crab Excavation***	**Potential OM Accumulation†**
LPC No Crabs	233.3 ±207.6	167.8 ± 130.0	65.5		65.5
UPC No Crabs	441.9 ± 180.9	198.4 ± 152.2	243.5		243.5
LPC Crabs	164.1 ± 121.9	133.8 ±32.2	30.3	32.8	-2.5
UPC Crabs	282.9 ± 5.7	444.4 ± 234.0	-161.5	88.9	-250.4
LPC Iron	51.5 ± 36.2	67.4 ± 18.2	-15.9		-15.9
UPC Iron	381.7 ±31.0	353.0 ± 23.2	28.7		28.7

[§]Assumes a 1 yr turnover rate for roots (i.e. root production = root death)
*Crab Excavation estimated using 20% of annual root production. (Montague, 1982)
†Potential OM Accumulation = Root production – (Decomposition + Crab Excavation).

potential between the creek bank and low marsh zones to root production rather than decomposition rates at UPC.

When artificial crab burrows were constructed in the organic-rich sediments of UPC, decomposition was stimulated, shifting the balance between root production and decomposition to favor loss of OM. In addition to stimulating decomposition, an active fiddler crab population also will excavate belowground primary production, bringing OM to the marsh surface where it can be removed by tide or more efficiently decomposed under more oxidizing conditions. Montague (1982) reported that 20% of annual root production was excavated by crab burrowing activity. When this mechanism of OM loss was included in the calculation of OM accumulation potential, the differences in the ability of LPC and UPC to accumulate OM are exacerbated.

These results suggest that disturbances, such as the activity of burrowing animals, can alter the balance between decomposition and production to convert organic-rich marsh substrate to mineral substrate. Brinson et al. (1995) hypothesized that shifts like this occur during marsh state change at the VCR LTER. The results of the work presented here identifies fiddler crab disturbance as a potential mechanism of state change.

The experimental results from UPC and LPC lend support for most aspects of the conceptual model proposed in Fig. 1 and modified in Fig. 28. There were exceptions. The conceptual model predicts that increased sulfate reduction rates should increase pore-water sulfide concentrations. In fact, SRRs and pore-water sulfide concentrations were negatively correlated. Pore-water sulfide concentration was measured as a standing stock and is the difference between inputs and exports of sulfide. There are many possible export routes for sulfides including volatilization, metal sulfide formation, and efflux from the sediment into flooding tidal water. For example, pore-water sulfide was significantly lower at UPC. This may be the result of higher volatilization of sulfide because of higher permeability in the organic matter leading to more rapid upward movement of H_2S. This is supported by personal observation of a rotten egg smell characteristic of H_2S at UPC but not at LPC. The UPC site also had a higher reduced iron pore-water content than LPC, so there may have been sulfide removal from pore water through metal sulfide formation. And lastly, infiltration rates were much higher in the top 10 cm at UPC than LPC indicating there was greater pore water/floodwater interaction and, therefore, greater potential for dissolved sulfide (HS^-) efflux.

The negative correlation between pore-water sulfide concentration and dry weight root production and the lack of correlation between pore-water sulfide concentration and AFDW root production were in contrast to conceptual model predictions. One reason the correlation between pore-water sulfide concentration and root growth is not clear may be an experimental artifact. Plastic barriers were installed in the iron plots to prevent the migration of added iron. These barriers also prevented the natural movement of other solutes. This was most apparent with pore-water chloride and sulfide. There was a 9% increase in chloride concentration between LPC Crab plots and LPC Iron plots and a 45% increase between UPC No Crab plots and UPC Iron plots. Some of the increase in chloride concentration in the iron plots may be the result of the iron addition itself as the iron was added in the form of $FeCl_2$. The iron addition accounted for only 26% and 19% of the difference in chloride concentration between the iron plots and the native plots, respectively. Therefore, the addition of $FeCl_2$ does not account for the majority of the increase in chloride concentration in the iron plots. The difference in increase between LPC and UPC is probably due to the infiltration rate difference between the two sites. Infiltration was much more rapid at UPC than LPC in the top 10 cm of sediment, allowing for chloride infiltration of the UPC sediment. Pore-water sulfide was even more dramatically affected with a 69% increase in LPC Iron plots over the concentration in LPC Crab plots, and a 173% increase in UPC Iron plots over the concentration in UPC No Crab plots. The difference in SRRs among the plot types does not account for the difference in pore-water sulfide concentration. No barrier control plots were used to test the effect of the barriers alone.

Root growth (AFDW mon^{-1}) was correlated positively to SRR and SO_4^{2-} concentration. Pore-water sulfide concentration (standing stock) was not correlated with root growth, whereas sulfide production via SRR (flux) was correlated, although the explained variance was low. This lends support to the conceptual model's positive feedback loop between root growth and SRR. The conceptual model needs to be revised to reflect sulfide production via SRR as the driver for root growth instead of pore-water sulfide concentration, as the pore-water sulfide concentration is a balance between production and metal sulfide formation, volatilization, and efflux.

Root growth did respond to the treatments as hypothesized. Root growth was greatest in the No crab plots where SRR was highest, and there was a reduction in root growth found in the Crab and Iron plots where SRR was lower. Platinum electrode potential was also found to be lowest in the No crab plots. There was a weak but significant positive correlation between PtEP and root growth, however. This positive correlation may be the result of plants translocating oxygen through their roots into the rhizosphere. The more roots there are the more potential for an oxidized sediment. The low level of measured root growth in the Iron plots may be the result of high root death. New roots may have been produced and during the time between sampling events, died. This is supported by the high pore-water sulfide concentration and litterbag decomposition results in the Iron plots. The litterbags in the Iron plots experienced dramatic weight gain. This was most likely due to root in-growth followed by death. Although the mesh for the decomposition litterbags was very small, rhizomes were sometimes found to have grown straight through the bags. Small roots were also found growing on the exterior of the bags and may have entered the bags. Although every

effort was made to remove all new growth from the litterbags, roots growing into the bags may have died before the bag was sampled, leading to an apparent weight gain or lowering decomposition estimates. Based on the experiments conducted, the environmental factor(s) most likely responsible for increased root growth is not clear even though root growth responded to the experimental manipulations as hypothesized.

The conceptual model also predicted that decomposition should be affected by sediment texture and crab burrows. Sediment texture affects water infiltration rate and diffusion rates. The organic sediment at UPC had a much higher infiltration rate than LPC's mineral sediment. Along with higher water infiltration rates, the rate of sulfate movement into the sediment would have been greater at UPC. As a result, SRRs at UPC were less likely to be limited by sulfate availability than at LPC. Crab burrows increase marsh sediment surface area by increasing the tidewater—sediment interface. This should result in an increase in PtEP due to increases in the availability of O_2 and SO_4^{2-}, important terminal electron acceptors for microbial respiration of OM. Decay was highest in the Crab plots. Higher PtEP was also measured in these plots than the No Crab plots. The Iron plots had the highest PtEP of all the plots even though crab burrows were not present in these plots. This may be the result of changing the dominant redox couple from $SO4^{2-}/S^{2-}$ to Fe^{3+}/Fe^{2+} (Stumm and Morgan 1996). The UPC Iron plots had the highest PtEP and also had higher decomposition than UPC No crab plots. The UPC Crab plots, however, had the highest decomposition (265% more than UPC No Crab plots and 332% more than LPC Crab plots). What is clear from these data is that both high infiltration (and thus greater pore-water turnover) and crab burrows dramatically increased decomposition.

The conceptual model further predicts that pore-water ammonium uptake will be greater in more oxic sediments (including crab burrows). Ammonium uptake was not measured during these experiments; however, the C:N of plant foliage was determined. A high C:N may indicate less ammonium uptake or availability, whereas a low C:N may indicate high uptake or availability (Morris, J.T., USC, Columbia, SC, USA). It was found that C:N was higher at UPC than LPC and was highest in the No Crab plots and lowest in the Iron plots. These results, if the relationship between ammonium uptake and C:N is valid, support the conceptual model. The conceptual model hypothesizes that where SRRs are high, pore-water sulfide will inhibit ammonium uptake based on the findings of Bradley and Morris (1990).

The model also takes into account the binding of phosphate to iron in oxic sediments that may lead to decreased availability of phosphate for plant growth. In contrast to results reported by Morris (1988) in which iron addition resulted in P-limited plant growth, pore-water phosphate concentrations were greater in plots where iron was added than in the other two treatments. These results suggest that iron addition did not have a deleterious effect on phosphate availability to plants at either UPC or LPC.

Biogeochemistry of Regional Marshes

A survey of six marshes on the lower Delmarva Peninsula was conducted to determine if the results from UPC and LPC in Phillips Creek marsh were unique to this marsh or if the conceptual model was applicable to a wider range of marshes. The marshes used for the survey represented a wide variety of landscape settings, different levels of OM content, and the presence or absence of fiddler crabs. Ricker (1999) also

hypothesized that these marshes have different levels of vulnerability to sea-level rise based on their geomorphology.

Marshes without crabs had higher sediment OM and more clay, while marshes with crabs had lower sediment OM and more sand. Sediment pore-water sulfate concentrations were higher in marshes with crabs than marshes without crabs. This may be related to differences in infiltration caused by crab burrows. Sulfate reduction rates were higher in marshes without crabs where pore-water sulfide concentrations were also found to be higher. However, root growth was higher in marshes with crabs. This relationship was caused by one marsh, Kegotank Farm. Kegotank Farm is located downstream of an aquaculture farm and down slope of a soybean farm and, therefore, may be receiving a large quantity of nutrients. The crab population in this marsh is also smaller than in the other marshes with crabs, and the marsh may be at the very beginning of a state change from an organic marsh to a mineral marsh. Kegotank Farm was found to be incongruent when analyzed with PCA, and when it was removed from MANOVA analysis, root growth in the remaining five marshes was significantly higher in marshes without crabs. This directly supports the conceptual model.

One of the most notable discrepancies between the six marshes and the experimental results in Phillips Creek marsh is PtEP. It was found to be highest in the marshes without crabs. All PtEP measurements were high, however, probably the result of measurement timing (August 2002 when the drought was at its most extreme).

Location (north, middle, and south) along the Delmarva Peninsula was considered as a variable in this work because Ricker's (1999) model of marsh susceptibility to marsh loss due to sea-level rise predicted that marshes along the Peninsula experience different

levels of vulnerability. Her model predicted that the southern and northern regions have very little area available for marsh transgression, and that the southern marshes had low resistance to state change, while the northern marshes had intermediate to high resistance primarily due to higher elevations above mean sea level and steeper slopes. The mid-peninsula marshes had more area available for transgression but had low resistance to state change. This means that southern marshes are the most vulnerable to marsh loss due to sea-level rise; and southern and northern marshes are most likely to lose marsh area, while mid-peninsula marshes are more likely to lose forest area. Her analysis of susceptibility was based on geomorphology and did not consider the potential for these marshes to increase in elevation as a result of OM accumulation.

The mid-peninsula marshes are most distinct from the other marshes in sediment characteristics. They had highest bulk density, highest sand content, lowest clay content, and lowest OM content. Though the mid-peninsula marshes had the lowest root growth, they also had the lowest SRR and presumably the lowest decomposition. Therefore, there may be an opportunity for OM accumulation in these marshes. The southern marshes had the greatest SRR and low root growth; therefore OM accumulation potential is probably very small. The northern marshes had the highest root growth and moderate SRR, placing northern marsh vulnerability to sea-level rise between the southern and mid-peninsula marshes at least with respect to the ability to increase surface elevation by OM accumulation. These data support Ricker's (1999) assessment that southern marshes are the most vulnerable and the mid-peninsula marshes are the least vulnerable to marsh loss of the three regions of the lower Delmarva Peninsula.

There have been many salt marshes studies along the east coast of the United States over the past several decades. Though measurement techniques generally were different, it is instructive to compare results reported here to those of others to provide a broader context for this study. For example, at a site close to the UPC site, Aiosa (1996) found ammonium levels between 4.4-76.5 μM and phosphate concentrations between 1-50 μM. At Sapelo Island, ammonium has been measured between 30-70 μM (Whitney et al. 1981), while phosphate was found to be between 1-20 μM (Montague 1982). The ammonium concentrations found during this study were between 1-120 μmol l^{-1}, and the phosphate concentrations were <1-40 μmol l^{-1}.

Pore-water sulfide and reduced iron concentrations measured at LPC and UPC were <1-400 μmol l^{-1} and 1-200 μmol l^{-1}, respectively, which were similar to measurements for other marshes. Howarth and Giblin (1983) found pore-water sulfide concentrations between 50-500 μM increasing with depth at Sapelo Island, GA., and between 200-1000 μM in Great Sippewissett, MA (Giblin and Howarth 1984). Total reduced iron was between 1-20 μM at both Sapelo Island and Great Sippewissett (Giblin and Howarth 1984). At UPC, near the plots used in this study, Aiosa (1996) measured pore-water sulfide concentrations between 0-480 μM. Great Marsh, DE has pore-water sulfide concentrations ranging from 40-1530 μM and reduced iron concentrations ranging from 6-128 μM (Luther et al. 1991). In North Inlet, SC, Gardner et al. (1988) studied two marshes, one sandy and one muddy. The sandy marsh had pore-water sulfide concentrations in the range of 570-3260 μM, while the muddy marsh had pore-water sulfide concentrations in the range of 240-2900 μM. Though these measurements are

much higher than what was found in Phillips Creek, the pattern of having higher pore-water sulfide concentrations in the sandy marsh is consistent.

Root productivity at UPC and LPC (317-1105 g AFDW m^{-2} y^{-1}) was also comparable to productivity measured in other marshes even though the techniques employed to measure productivity were very different. Dai and Wiegert (1996) estimated belowground productivity at Sapelo Island to be 397 g C m^{-2} y^{-1} (993 g AFDW m^{-2} y^{-1}) using a simulation model based on plant physiology. Gallagher and Plumley (1979) using maximum-minimum macroorganic matter to calculate minimum belowground primary productivity estimated Sapelo Island root production at 770 g C m^{-2} y^{-1} (1925 g AFDW m^{-2} y^{-1}). Using a root growth litterbag method, Blum (1993) estimated root growth to be 2143 g dry wt m^{-2} y^{-1} (1650 g AFDW m^{-2} $y^{-}1$) in Phillips Creek very near to the UPC site. In Great Sippewissett, White and Howes (1994) estimated root production to be between 930-1020 g C m^{-2} y^{-1} (2325-2550 g AFDW m^{-2} y^{-1}) using an ^{15}N tracer.

The amount of carbon mineralized based on two types of measurements, mass loss in litterbags and sulfate reduction, measured in this study are substantially less than those estimated by Howarth and Hobbie (1982) for Great Sippewissett marsh. Their estimate of sulfate reduction alone (1800 g C m^{-2} y^{-1}) (Howarth and Hobbie 1982) far exceeds the maximum litterbag decomposition rate (444.4 g C m^{-2} y^{-1}) (Table 11) measured during this study. Though still high, their estimate of Sapelo Island's decomposition rate (870 g C m^{-2} y^{-1}) is more comparable to the results from this study (Howarth and Hobbie 1982). The percentage of decomposition that can be attributed to SRR (~60% on average) at UPC and LPC is very similar to the 70-90% measured by Howarth (1984). Howarth and Giblin (1983), working at Sapelo Island found SRR to be

40 mol S reduced m^{-2} y^{-1}; and Howarth and Teal (1979), working at Great Sippewissett, found SRR to be 75 mol S reduced m^{-2} y^{-1}. Both of these studies employed the Aqua regia technique to measure sulfate reduction. King (1988), however, reported SRR to be 13.3 mol S reduced m^{-2} y^{-1} at Belle Baruch, SC which is more comparable to rates at UPC and LPC when converted from μmol ml^{-1} d^{-1} to mol S reduced m^{-2} y^{-1} (1.5-9.4 mol S reduced m^{-2} y^{-1}). King (1988) used a chromium reducible sulfur (CRS) method that was similar to the one used in this study. In a previous study, King (1983) based his estimates of SRR on measures of ^{35}sulfide production from $^{35}SO_4^{2-}$ measured by the AVS technique. Using his October short form *S. alterniflora* results, an annual SRR of 4.1 mol S reduced m^{-2} y^{-1} was obtained. The differences between SRR based on the Aqua regia, CRS, and AVS methodologies may explain the wide range in results among the various studies.

Sulfate reduction rates measured as AVS production were very different from that measured as CRS production in this study. The TRIS (CRS) method measures AVS (S^{2-}, HS^-, H_2S, FeS) radioactivity in combination with the insoluble ^{35}S fractions (FeS_2, and crystalline mono- and polysulfides), and so cannot distinguish between the two. Therefore, in order to compare the two methods, SRR from August 2001 determined using AVS was compared to September 2001 SRR using TRIS (Table 14). Averaged over depth and including both sites, SRR determined using AVS was 5.4% ± 10.3 of total SRR determined by TRIS. These results are comparable to other sites where some form of CRS technique was used to determine %AVS of total SRR measured (Table 15). There is, however, considerable variability in results between methods and sites. A depth

Table 14. Acid volatile sulfide (AVS) percentage of total reduced inorganic sulfur (TRIS) measured at LPC and UPC. Results compare measurements taken in August 2001 as AVS only and September 2001 as TRIS.

Depth cm	**%AVS of TRIS ± 1 standard deviation**
2	8.0 ± 9.4
4	7.3 ± 11.2
6	11.1 ± 21.2
8	2.1 ± 1.2
10	2.9 ± 2.5
15	3.3 ± 2.7
20	1.7 ± 1.2
25	0.1 ± 0.0
Average	5.4 ± 10.3

Table 15. Acid volatile sulfide % of chromium-reducible sulfide

Location/ Type	**%AVS of CRS**	**Method**	**Source**
Phillips Creek, VA/salt marsh	5.4 ± 10.3	TRIS	this study
Sapelo Island, GA/salt marsh	8	Aqua Regia	Howarth and Giblin (1983)
Belle Baruch, SC/salt marsh	7-30	Chromium Reducible Sulfur	King (1988)
Great Sippewissett, MA/salt marsh	< 30	Aqua Regia	Howarth (1979)
Great Sippewissett, MA/salt marsh	44-82	Chromium Reducible Sulfur	Howes et al. (1984)

effect was also noted, with AVS representing a higher percentage of total SRR at the surface and decreasing with depth. King (1988) also noted a depth effect, however, he found the %AVS of CRS to be greater with depth. He also determined the fractions of insoluble ^{35}S and found that surface insoluble ^{35}S was S^o and was $Fe^{35}S_2$ at depth.

Much debate has occurred in the literature regarding the rapid formation of $Fe^{35}S_2$ during sulfate reduction measurements (Howarth and Teal 1979; Howarth and Giblin 1983; King 1983; Howarth and Merkel 1984; Howes et al. 1984; King 1988; Fossing and

Jorgensen 1989; Thode-Andersen and Jorgensen 1989). During the course of this debate, the Aqua regia method was determined to overestimate sulfate reduction because it reduced $^{35}SO_4^{2-}$ to $H_2{}^{35}S$ spontaneously (King 1983). The thermodynamics of pyrite formation over short incubation times was also debated (Howarth and Teal 1979; King 1983), but it was determined that radioactive label was being incorporated into insoluble ^{35}S fractions even though the mechanisms were not fully understood (Howes et al. 1984; King 1988). In 1992, Fossing et al. suggested that radiolabel might arise in the insoluble ^{35}S fractions through isotope exchange reactions and not necessarily through direct incorporation during SO_4^{2-} reduction. Although $^{35}SO_4^{2-}$ does not engage directly in isotope exchange, free $^{35}S^{2-}$ does (Fossing et al. 1992). The rate and direction of exchange depends on concentrations of each fraction; however, since all radiolabel exchange originates from free $^{35}S^{2-}$ that arises from SO_4^{2-} reduction, measurements of SRR that depend on the measurement of ^{35}S in reduced compounds are accurate (Fossing et al. 1992). Therefore, these investigators concluded that methods employing CRS are more accurate than AVS when determining sulfate reduction rates.

At LPC, Tirrell (1995) studied decomposition and found only a 20% loss in root mass after 561 d (approximately 19 months). This contrasts with this study, where mass loss was 40% of the starting mass after approximately 18 months. One explanation for this difference may be the starting material in the litterbags. Tirrell used roots and rhizomes collected from LPC, whereas this study used roots and rhizomes from UPC. Because the AFDW of UPC roots and rhizomes was much higher (77%) than LPC (42%) the mass loss Tirrell reported would have been much lower than measured in the experiments reported here. When the difference in AFDW between the two studies and

the uncertainties associated with litterbag studies are considered, the decay rates for the two studies are remarkably similar.

Montague (1982) found that the presence of crab burrows increased sediment respiration by 60%. This agrees very closely with the 55% increase in mass loss found at UPC between Crabs and No Crabs plots (Table 9). This is particularly remarkable given that sediment respiration includes mineralization by bacteria as well as plant root respiration and is therefore, an overestimation of OM mineralization; whereas mass loss is most likely an underestimation because of root growth into the litterbags and subsequent death. At LPC, decay in the No Crabs plots was 25% greater than in the Crabs plots. All crab burrows were not successfully removed from the LPC No Crab plots, however, although the density and size of the burrows were dramatically changed [No Crabs: 37 small burrows (≤1.0 cm diameter) m^{-2}; Crabs: 32 large and small burrows (1.0-3.5 cm diameter) m^{-2}; Iron: 21 small burrows (≤1.0 cm diameter) m^{-2}]. In plots that contained crab burrows, Montague found that root/rhizome density was significantly less (1982). He speculated that this was due to increased plant access to oxygen (though this was not measured) and nutrients as the burrow water contained significantly higher levels of ammonium than the sediment pore water (Montague 1982). Montague (1982) also found that fiddler crabs excavate approximately 20% of annual belowground production representing a substantial loss of belowground material to the marsh surface where it is more vulnerable to tidal removal or detritivory.

The results of stable S isotope analysis for Phillips Creek marsh were similar to those obtained by Stribling et al. (1998), whose work was conducted on the Chesapeake Bay side of the Delmarva Peninsula. Their $\delta^{34}S$ values ranged from -5.6‰ to +10.4‰,

like those from the Phillips Creek marsh that ranged from -5.4‰ to +15.3‰. Their work suggested that a low $\delta^{34}S$ is an indicator of sulfate limitation (Stribling et al. 1998); a conclusion that has ramifications for this study where the lowest $\delta^{34}S$ values where all found at LPC. The LPC site also had lower sulfate concentrations, a higher $f^{35}S$, and low infiltration rates (2 ml h^{-1}). The implications of these findings are that plants and bacteria at LPC may be sulfate limited because of slower infiltration rates.

The predominately mineral matrix found at LPC may result in slower tidal water infiltration than the organic matter matrix found at UPC. As Harvey (1990) points out based on work at LPC, a two directional flow system is at work in LPC sediments. The overriding tidal water enters the sediment through macropores (crab burrows and pores 0.075 mm - 5 mm (SSSA 1997). This water then slowly diffuses into the micropore matrix that dominates the sediment. The micropore water is then drawn upward by evapotranspiration causing an increase in solute concentration. The implications for sulfate using Harvey's (1990) two directional flow system are that sulfate enters the macropores, slowly diffuses into the micropores (<0.03 mm (SSSA 1997)) and is then consumed during sulfate reduction, producing sulfide, where the sulfide would be concentrated as water was removed by evapotranspiration. Thus, Harvey's model (1990) provides an explanation for the lower sulfate concentrations and higher pore-water sulfide and salinity concentrations at LPC. This model also suggests there would be less tidal—pore water interaction at LPC than UPC, leading to a build up of pore-water sulfide and salt in the sediments. The implications of this to plant growth and OM accumulation were discussed earlier.

Giblin and Howarth found similar patterns associated with infiltration as found in Phillips Creek marsh (1984). In Great Sippewissett marsh, infiltration was between 4 and 8 cm h^{-1}, however at Sapelo Island, infiltration was between 0.2 and 0.9 cm h^{-1} (Giblin and Howarth 1984). The higher infiltration rates at Great Sippewissett occurred in sediment that was 50-80% organic, while Sapelo Island's sediment was only 5-10% organic. Like the results at Phillips Creek marsh, the higher organic matter content sediment had higher infiltration rates.

The results from the work at LPC and UPC are not only similar to the results of others in different parts of LPC and UPC, they are also comparable to work conducted along the Atlantic coast of the United States of America. Measured productivity, both above- and belowground, was similar to work in other Atlantic coast marshes though measurement techniques varied. Sediment pore-water chemistry varied among marshes but patterns associated with plant response and fiddler crab populations were comparable.

Role of the Drought

This study was conducted during two years when drought conditions where at historic records in Virginia. The drought during the summer of 2002 was as intense as the 1930s drought (Stenger 2003). The 2002 drought may have altered the effect of the crab treatments on sediment biogeochemistry. During a drought, as the marsh surface dries down, greater infiltration of oxygen into the sediment will occur, potentially affecting decomposition. Aerobic decomposition in salt marshes may be slower than anaerobic decomposition as it is more energy efficient, and thus microbes need less substrate to obtain the same amount of carbon (Howarth and Hobbie 1982). No correlation was found between PtEP and decomposition, however. Although the lower

water content of the sediment may also have decreased decomposition as microbes need available water to function (Atlas and Bartha 1993) it is more likely that as water content decreased, solute concentration including metabolic toxins increased perhaps impairing microbial activity (Howarth and Hobbie 1982).

Plants roots also may respond to a decrease in water availability and are likely to be more sensitive to water availability than bacteria. As solute concentration increases, plants must use more energy to pull water into the roots (Larcher 1995). There was a significant positive correlation between sediment water content and root growth (AFDW) but not pore-water chloride concentration. The highest measured salinity for August 2002 was 157 ppt and the average for all of Phillips Creek marsh was 104 ppt. *S. alterniflora* has osmoregulating chemicals and salt glands (Mitsch and Gosselink 1993), however, so that the increasing solute concentrations may not have reached concentrations detrimental to plant growth over the time frame of the high salinity concentrations. Haines and Dunn (1976) found S. alterniflora dies during prolonged exposure (9 wks) to salinity in excess of 70 ppt. The salinity at Phillips Creek marsh changed substantially between months (Fig.17), and therefore, there was no noticeable die-off of vegetation in the marsh. When pore-water sulfide concentration increases, marsh plants respond by producing more roots (Koch et al. 1990; Howes and Teal 1994). Pore-water sulfide concentrations measured at LPC and UPC were generally lower than those necessary to effect *S. alterniflora* root growth (Bradley and Morris 1990), so this effect may be limited in Phillips Creek marsh.

Water availability is also a factor for fiddler crabs. As the water table falls away from the marsh surface, crabs must burrow deeper to get the water they need for

physiological processes (Montague 1982). This results in greater excavation of OM and increased surface area allowing for greater oxygen infiltration into the sediment. In the LPC Crab plots there was a large difference between average PtEP in the summer of 2001 (-14 mV) and 2002 (115 mV). Of the three groups of organisms likely to be affected by the drought, fiddler crabs and their activities may be the most sensitive to the drought.

The relative importance of each of these factors is unknown, and as a result the drought's effect on OM accumulation in these marshes may not be significant as the results of root growth and decomposition were like those of other marshes (Howarth and Hobbie 1982; Schubauer and Hopkinson 1984; White and Howes 1994; Dai and Wiegert 1996). However, Blum's (1993) measured root growth in an area near UPC was approximately 50% more than the highest measurement of this study, and decay was greater. Using the assumption that the ratio between g AFDW decomposed and the % AFDW remaining measured during this experiment can be applied to Blum's results (1993), decomposition during her study was approximately 700 g AFDW m^{-2} y^{-1}. Blum's root growth was also approximately 1650 AFDW C m^{-2} y^{-1}. The OM accumulation during this time was therefore approximately 950 g AFDW cm^{-2} y^{-1}, which is much higher than the estimated 610 g AFDW cm^{-2} y^{-1} for this study. Her study was conducted from 1988 to 1990, when the site received 30% more precipitation than during this study (Porter 2003).

Though the effects of drought are interesting to note, OM accumulation occurs over long time scales and therefore is unlikely to be substantially affected by a short-term deficit in precipitation. Short-term studied may provide insight into the mechanisms

controlling OM accumulation, but the rates of OM accumulation need to be measured over longer time scales to understand how geomorphology is affected.

Other Animal Impacts

Crabs are not the only animal in the salt marsh that alters biogeochemistry and OM accumulation. *Littoriaria irrorata* has been shown to reduce aboveground biomass by up to 85% (Silliman and Zieman 2001). This is primarily done through rasping behavior that creates wounds in the plant tissue to encourage microbial infection. The snails then feed on the senescing portions of the wounds, causing increased stem death and litter production. If this litter is not removed by tidal action, it may increase organic input into the sediment and concomitantly increase OM accumulation.

Larger animals such as deer, geese, and other herbivores can also have dramatic effects on OM accumulation. Muskrats, nutria, lesser snow geese, and wild boar reduce aboveground biomass as much as fourfold in Mississippi delta marshes and dramatically increase litter formation (Ford and Grace 1998). Sediment accretion was higher in grazed plots than ungrazed plots; however, belowground biomass was significantly reduced (Ford and Grace 1998). Overall, shallow subsidence was greater in grazed plots than ungrazed plots (Ford and Grace 1998).

In northern salt marshes, lesser snow geese forage for roots and rhizomes in early spring before snow melt creating peat barrens (Iacobelli and Jeffries 1991). The sediment temperature is raised in the peat barrens due to low albedo and increases the freeze-thaw cycle frequency. Through diffusive efflux, salt moves upward from the underlying marine sediments into the water of the peat barrens increasing salinity. This causes plant

death and a species shift to *Salicornia* spp. Organic matter input into the sediment is reduced, and erosion and peat oxidation is increased. These two effects dramatically decrease OM accumulation and recovery from these disturbances is on decadal time scales (Iacobelli and Jeffries 1991).

Deer can have an effect on OM accumulation through the creation of trails (Keusenkothen 2002). Vegetation and sediment characteristics are altered by deer trails. Sediment temperature is increased as well as bulk density. There is a shift in the dominant plant species and a decrease in % sediment OM (Keusenkothen 2002). Elevation is also lower along the trails than surrounding marsh. These types of effects are localized, however.

These examples illustrate that animals can have a profound effect on OM accumulation through herbivory, trampling, and burrowing activities. They can alter the amount of organic input into the sediments and change sediment characteristics such as bulk density and redox. Some of these changes are long lasting and may have a profound effect on a salt marsh's response to sea-level rise.

Implications

OM Accumulation Potential

A wide range of OM accumulation has been reported in the literature. In Great Sippewissett marsh, Howes et al. (1985) calculated OM accumulation to be approximately 90 g C m^{-2} y^{-1} using the C content of the sediment during the growing season, marsh accretion rate, and bulk density, whereas White and Howes (1994) using ^{15}N label estimated OM accumulation in Great Sippewissett marsh to be between 185-

200 g C m^{-2} y^{-1}. Andersen et al. (1997) estimated OM accumulation to be approximately 55 g C m^{-2} y^{-1} using sediment % C content and rate of sea-level rise. The results from these studies are comparable to higher LPC OM accumulation results that ranged from -2 and 65 g C m^{-2} y^{-1}. The OM accumulation potential at UPC was found to be much higher (245 g C m^{-2} y^{-1}), however. Anderson et al. (1997) worked very close to the LPC site. Their study site had very similar sediment characteristics to LPC including low OM content and a fiddler crab population. Both Howes and White worked in a New England short *S. alterniflora* salt marsh, and no information on sediment or fiddler crabs was given.

The results from Phillips Creek marsh can be applied to the landscape scale. Fiddler crabs were found to have an effect on above- and belowground production along the entire lower Delmarva Peninsula. The marshes studied represented a wide range of landscape settings and anthropogenic impact. Some were small with steep slopes while others were wide and flat. Some were down slope of active farms, while others were far removed from direct human activity. Regardless of the differences among the marshes, the marshes with fiddler crab populations produced less belowground biomass and proportionally more aboveground biomass that lead to lower OM accumulation potential and greater export of carbon to the estuary.

Of the variables measured at Phillips Creek marsh, fiddler crabs most influenced litterbag decomposition. The burrow holes may allow for greater infiltration of tidal water that contains terminal electron acceptors. Both aerobic and anaerobic decomposition were enhanced in plots with burrow holes supposedly because of greater tidal/pore water interaction. Root growth was also significantly lower in Crab plots than

No Crab plots. Both LPC and UPC crab plots experienced a 30-35% decrease in root growth compared to the No Crabs plots. Montague (1982) believed this decrease in root growth was a response to greater access to nutrients. Valiela et al. (1976) found that fertilized plots in Great Sippewissett marsh contained fewer roots than unfertilized plots. Pore water results from this study did not show an increase in nutrient levels in the Crab plots, however burrow water, which was where Montague (1982) found the higher nutrient levels, was not measured.

Impacts on Trophic Dynamics and Estuarine Food Webs

Root production was 20-130% greater than aboveground productivity in the No crab plots but 14-17% less than aboveground productivity in the Crab plots. Since aboveground production is assumed to be removed from the marsh surface (Chalmers et al. 1985; Morris and Whiting 1986; Morris 1988; Dame 1989), this greater allocation to aboveground production than belowground production in marshes with fiddler crabs in combination with crab burrow excavation of 20% of belowground production (Montague 1982) could have implications to the estuary's carbon cycle and food webs. Marshes with significant crab populations may export proportionally more fixed carbon to the estuary than marshes with no fiddler crabs as a result of proportionally greater aboveground production and excavation of belowground production.

The use of multiple stable isotopes has helped determine estuarine secondary production based on *S. alterniflora* as a food source (Currin et al. 1995; Deegan and Garritt 1997). Currin et al. (1995) found that standing dead *S. alterniflora* and microalgae were an important food source for *Uca* spp.(fiddler crabs), *Ilyanassa obseleta* (mud snails), and *Littoraria irrorata* (periwinkles). These species are preyed upon by

birds and *Fundulus heteroclitus* (mummichogs). Deegan and Garritt (1997) determined that species located in the mid and lower portions of an estuary are more dependent on *S. alterniflora* than the upper estuary. Primarily, benthic organisms feed on *S. alterniflora* detritus, while pelagic species feed on phytoplankton (Deegan and Garritt 1997). There is some mixing by resuspension and pelagic species engaged in benthic feeding, however. Estuaries where the marshes have active crab populations may be better able to support higher secondary production and more trophic levels or more complex food webs.

Sea-level Rise and Marsh Elevation

The purpose of this study was to determine what factors affect OM accumulation because that is the primary way salt marshes on the Delmarva Peninsula increase in elevation as these marshes do not receive significant sediment input (Brinson et al. 1995). The Delmarva Peninsula is subsiding due to post-glacial adjustment at a rate of 1.1 - 1.2 mm y^{-1} (Peltier and Jiang 1996) and has a relative sea-level rise of 2.75 - 3.5 mm y^{-1} (Davis 1987; Oertel et al. 1989). This means that Phillips Creek marsh must accrete > 3 mm y^{-1} in order to maintain its elevation relative to sea level. Based on ^{210}Pb data, Kastler and Wiberg (1996) found that LPC is only accreting 0.9-1.4 mm y^{-1} due to mineral sediment deposition along creek banks and that little mineral sediment deposition occurs away from the creek bank. This study showed that OM accumulation potential for LPC is very small. The estimated accretion rate at UPC was approximately 4 mm y^{-1}, however, well in excess of relative sea-level rise for this area. This is supported by Geographical Information Systems analysis of aerial photographs from 1938 compared to current aerial photographs. Analysis shows a gain in marsh area through upland

encroachment (Kastler and Wiberg 1996). Results from work done in a high marsh site near UPC also shows that that area of the marsh is keeping pace with sea level rise (Miller et al. 2001).

Rybczyk and Cahoon (2002) created the Integrated Wetland Elevation Model to predict wetland submergence potential. They found that the model was moderately sensitive to belowground productivity but insensitive to parameters controlling decomposition rates such as labile and refractory organic matter and depth (Rybczyk and Cahoon 2002). The model was most sensitive to deep subsidence (deep subsidence + eustatic sea-level rise = relative sea-level rise) and mineral input (Rybczyk and Cahoon 2002), however. They found that Mississippi delta marshes were in danger of submergence unless the deep subsidence value was set to between 0.35 and 0.7 cm y^{-1} (Rybczyk and Cahoon 2002). This is much less than the subsidence estimated by Peltier and Jiang (1996) for the Delmarva Peninsula. If Rybczyk and Cahoon's model can be applied to the VCR, then, regardless of the OM accumulation rate, Delmarva Peninsula marshes may be in danger of submerging.

Carbon Sequestration and Global Warming

Over the past several decades, global warming has become an important issue (Houghton et al. 1996). Accelerated global warming is believed to be caused by anthropogenic sources of greenhouse gases such as CO_2, CH_4, and N_20 (Houghton et al. 1996). One way to offset the increase in atmospheric CO_2 concentration is through sequestering of carbon in forests and peat-forming wetlands. Salt marshes may or may not be carbon sinks depending on their rate of OM accumulation. Based on the results from this study, fiddler crabs may play a significant role in whether a salt marsh is a sink

for carbon. The Crabs plots had negative OM accumulation potential, while the No Crabs plots accumulated 160 - 600 g AFDW m^{-2} y^{-1}. Over time and space, this could have a noteworthy impact on carbon sequestration. For example, the UPC site, which is 0.54 ha (Richardson et al. 1995), over a 10-year period, could potentially sequester 1300 kg C, whereas the LPC site will sequester little to no carbon over the same period. Though this is a small amount of carbon globally, it is only a small portion of one marsh. The VCR is approximately 14,000 ha (VCRLTER 1986). Approximately 37% (7 out of 19 marshes) of this area is marshes that do not have active fiddler crab populations. Assuming that marshes with no crabs will accumulate OM at the same rate as UPC, carbon sequestration for the VCR is approximately 1.26×10^7 kg C over 10 years. Globally, carbon sequestration by salt marshes is substantial. Salt marshes occupy 38×10^{10} m^2 of the earth (Woodwell et al. 1973). Making the above assumptions regarding carbon sequestration rate and percentage of marshes without fiddler crabs, salt marshes sequester 0.034 Gt C y^{-1} or 0.6% of the global emission of fossil fuels (Houghton et al. 1996). In comparison, northern hemisphere forests sequester 1.8% of global fossil fuel emissions (Houghton et al. 1996).

Conclusions

Organic matter accumulation is determined by two factors, root growth (and death) and decomposition. The rate of each of these factors is determined by environmental factors such as availability of terminal electron acceptors, stress caused by high concentrations of pore-water sulfide or salt, and the concentration of detoxifying agents such as reduced iron and oxygen. The balance of these environmental factors determines if OM will accumulate, and consequently determines if surface accretion by OM accumulation will keep pace with rising sea level. *S. alterniflora* has been shown to increase root production as a response to stress, such as high pore-water sulfide concentrations and low redox potential (Valiela et al. 1976; Schubauer and Hopkinson 1984). Decomposition rates are affected by the availability and type of terminal electron acceptor. These experiments were designed to determine how these factors interact to influence OM accumulation in salt marshes by focusing on plant stressors and terminal electron acceptor availability.

Fiddler crab burrows were manipulated to alter the availability of terminal electron acceptors and increase pore-water sulfide concentration by removing and excluding crabs from plots or creating artificial crab burrows. Reduced iron was added to plots to decrease pore-water sulfide concentration. These treatments were applied at two sites that had very different sediment characteristics. The LPC site was sandy with very little OM, and UPC was loamy with very high OM content. The two sites were also considered to be experimental treatments.

Production of belowground OM, root growth, responded significantly to manipulation of crab burrows or iron, and AFDW root growth was significantly higher at UPC than LPC. The UPC No Crab plots had the highest root production of all the plots. Root growth was significantly and positively correlated with SRR but not with pore-water sulfide concentration. The iron addition plots had the highest pore-water sulfide concentration but the lowest root growth compared to the crab manipulation plots. There is reason to believe that root growth was underestimated in these plots, as is evidenced by the weight gain that occurred in the decomposition litterbags. Root turnover in these plots may have been very high. Therefore, the lack of a positive correlation between root growth and pore-water sulfide concentration in all treatments may be an artifact of the method used to measure root production.

Pore-water sulfide concentration was related to sediment characteristics. Pore-water sulfide concentration was highest in plots where lateral and vertical movement of solutes was limited. In sediments composed primarily of mineral material such as LPC, tidal water enters the soil matrix through macropores traveling downward. It then diffuses into the micropores of the sediment and travels upward via the pull of evapotranspiration (Harvey 1990). Directional flow leads to an increase in solute concentrations. This may explain why pore-water sulfide concentration was higher at LPC where macropores are primarily burrow holes. The UPC site, on the other hand, is primarily organic and, as a result has a higher permeability. This allows for greater tidal/pore water interaction and less of an increase in solute concentration.

Decomposition and SRR were highest in Crab plots regardless of site. This may be due to increased access to terminal electron acceptors as is evidenced by higher PtEP

than in No Crab plots. Sulfate reduction accounted for between 30% in UPC Crab plots and 80% in LPC Crab plots of decomposition measured in the litterbags. Decomposition measured in the Iron plots was confounded by root growth into the decomposition litter bags. Although the apparent root production in the iron plots was low, rapid root turnover would not be detected at the sampling frequency used. Consequently, root production may have been underestimated in these plots as indicated by overall weight gain in the bags. The high rates of sulfate reduction in the Iron plots supports the conclusion that root turnover in the iron plots was more rapid than in plots where no iron was added. Over 200 g C m^{-2} y^{-1} were mineralized by sulfate reduction in the UPC Iron plots.

Many of the experimental results at Phillips Creek marsh can be extended to marshes along the entire lower Delmarva Peninsula to explain where OM accumulation is occurring. Fiddler crabs significantly impacted marshes regardless of the landscape setting. Marshes with fiddler crabs produced less belowground biomass. Organic matter content was lower in marshes with crabs. Although sulfate reduction rate measurements and pore-water sulfide concentration were higher in three regional marshes without crabs, and were hypothesized as central to understanding OM accumulation in the conceptual model, the relationship between SRR and pore-water sulfide concentration was not observed in the Phillips Creek marsh experiments. Pore-water characteristics were more affected by location along the Delmarva Peninsula (northern, mid, and southern regions) than the presence of fiddler crabs.

The results from both Phillips Creek marshes and the other six marshes on the Delmarva Peninsula generally support the conceptual model and the associated

hypotheses. Pore-water sulfide concentration was the most confounding variable, but this was most likely due to the many possible export routes such as tidal water exchange, gaseous emissions, and metal sulfide formation. Therefore the standing stock measurements of pore-water sulfide are underestimates of sulfide availability because all the possible fluxes of pore-water sulfide were not measured. However, the model hypothesized that root growth would be less in plots where terminal electron acceptors were not limiting (i.e., crabs were present) and/or iron was present and able to remove sulfide from the pore water. These hypotheses were supported by the experimental results. Higher root/shoot ratios were characteristic of plots without crabs and decay was greater in plots with crabs.

In conclusion, fiddler crabs decrease a marsh's OM accumulation potential and the ability to accrete vertically making the marsh more vulnerable to submergence by rising sea level. Crabs create large macropores that increase the availability terminal electron acceptors, like O_2 and SO_4^{2-}, thus increasing the rate of decomposition. Root production significantly decreased in the presence of crab burrows. With a high rate of decomposition and a low rate of root production, the potential for OM accumulation is small. Burrow excavation also removes OM. The combined effect of crabs on root production, decomposition, and OM removal may make it difficult for salt marshes to keep up with sea level rise, especially in marshes that receive little to no sediment input. This could have profound effects on the neighboring estuary, its trophic dynamics, and carbon sequestration.

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Appendix A. Definitions of Abbreviations.

LPC = Lower Phillips Creek marsh

UPC = Upper Phillips Creek marsh

PtEP = Platinum electrode potential (mV)

TD Fe = Total dissolved iron concentration (μmol l^{-1})

SRR = Sulfate reduction rates (nmol ml^{-1} d^{-1})

OM = Organic matter

AFDW RG = Root Growth (g ash-free dry weight m^{-2} mon^{-1})

EOYB = End-of-the-year biomass (g m^{-2})

f ^{35}S = fraction of injected $^{35}SO_4^{2-}$ converted to $^{35}S^{2-}$

Decomp = % ash-free dry weight loss from litterbag

Appendix B. Averaged Data for LPC and UPC

Codes

Site: 1 = LPC, 2 = UPC, Total = average of treatment regardless of site
Treatment: 1 = No Crabs, 2 = Crabs, 3 = Iron

Descriptive Statistics

	SITE	Treatment	Depth-average, Mean	Std. Deviation	N
PtEP (mV)	1	1	19.5	130.0	198
		2	54.7	111.6	179
		3	40.1	99.8	198
		Total	37.6	115.3	575
	2	1	-5.2	127.1	159
		2	46.8	152.8	198
		3	88.3	108.3	198
		Total	46.7	135.9	555
	Total	1	8.4	129.1	357
		2	50.6	134.7	377
		3	64.2	106.8	396
		Total	42.0	125.9	1130
pH	1	1	7.075	0.900	198
		2	7.129	0.906	179
		3	6.777	1.091	198
		Total	6.989	0.983	575
	2	1	6.906	0.995	159
		2	6.910	0.979	198
		3	6.857	0.767	198
		Total	6.890	0.913	555
	Total	1	7.000	0.946	357
		2	7.014	0.950	377
		3	6.817	0.943	396
		Total	6.940	0.950	1130
Fe2+ $\mu mol\ l^{-1}$	1	1	62.53	199.14	198
		2	53.21	109.20	179
		3	45.95	78.00	198
		Total	53.92	139.44	575
	2	1	77.30	144.62	159
		2	379.00	1376.94	198
		3	346.27	956.48	198
		Total	280.89	1011.11	555
	Total	1	69.11	176.87	357
		2	224.31	1012.69	377

		3	196.11	694.20	396
		Total	165.40	724.18	1130
TD Fe μmol l^{-1}	1	1	70.65	88.47	198
		2	56.78	64.51	179
		3	41.81	57.97	198
		Total	56.40	72.62	575
	2	1	76.18	87.36	159
		2	92.60	108.66	198
		3	598.48	1201.66	198
		Total	268.37	761.86	555
	Total	1	73.11	87.90	357
		2	75.59	92.07	377
		3	320.15	894.15	396
		Total	160.51	546.57	1130
% Sand	1	1	49.933	3.440	198
		2	50.326	3.329	179
		3	49.933	3.440	198
		Total	50.055	3.405	575
	2	1	44.444	3.802	159
		2	43.267	4.394	198
		3	43.267	4.394	198
		Total	43.604	4.259	555
	Total	1	47.489	4.519	357
		2	46.618	5.275	377
		3	46.600	5.164	396
		Total	46.887	5.020	1130
% Silt	1	1	36.767	1.803	198
		2	36.887	1.856	179
		3	36.767	1.803	198
		Total	36.804	1.817	575
	2	1	34.104	8.104	159
		2	35.233	7.692	198
		3	35.233	7.692	198
		Total	34.910	7.815	555
	Total	1	35.581	5.719	357
		2	36.018	5.772	377
		3	36.000	5.632	396
		Total	35.874	5.705	1130
%Clay	1	1	13.30	4.89	198
		2	12.79	4.84	179
		3	13.30	4.89	198
		Total	13.14	4.87	575
	2	1	21.45	7.04	159

		2	21.50	6.49	198
		3	21.50	6.49	198
		Total	21.49	6.64	555
	Total	1	16.93	7.19	357
		2	17.36	7.22	377
		3	17.40	7.05	396
		Total	17.24	7.15	1130
SRR nmol ml^{-1} d^{-1}	1	1	534.94	3933.96	198
		2	238.51	1132.25	179
		3	84.87	175.58	198
		Total	287.68	2399.09	575
	2	1	204.42	402.29	159
		2	193.15	365.08	198
		3	595.58	1178.31	198
		Total	339.95	789.68	555
	Total	1	387.73	2943.28	357
		2	214.68	822.95	377
		3	340.22	879.32	396
		Total	313.35	1798.03	1130
S2- µmol l^{-1}	1	1	70	125	198
		2	69	120	179
		3	119	159	198
		Total	87	138	575
	2	1	32	78	159
		2	44	91	198
		3	109	197	198
		Total	64	140	555
	Total	1	53	108	357
		2	56	107	377
		3	114	179	396
		Total	75	140	1130
NH4+ µmol l^{-1}	1	1	32.7	46.4	198
		2	19.2	27.6	179
		3	27.3	39.7	198
		Total	26.6	39.3	575
	2	1	6.8	13.2	159
		2	8.9	21.2	198
		3	27.8	39.4	198
		Total	15.0	29.2	555
	Total	1	21.2	37.9	357
		2	13.8	25.0	377
		3	27.5	39.5	396
		Total	20.9	35.2	1130

%H20	1	1	31.6	9.8	198
		2	36.0	8.4	179
		3	36.2	9.2	198
		Total	34.6	9.4	575
	2	1	58.2	24.1	159
		2	53.9	24.5	198
		3	59.3	25.5	198
		Total	57.0	24.8	555
	Total	1	43.5	22.0	357
		2	45.4	20.7	377
		3	47.7	22.3	396
		Total	45.6	21.7	1130
%OM	1	1	5.4	3.7	198
		2	5.8	4.0	179
		3	6.0	3.8	198
		Total	5.7	3.9	575
	2	1	33.0	23.2	159
		2	28.6	22.3	198
		3	34.8	23.3	198
		Total	32.1	23.0	555
	Total	1	17.7	20.9	357
		2	17.8	20.0	377
		3	20.4	22.0	396
		Total	18.7	21.0	1130
Root Growth g AFDW m^{-2} mon^{-1}	1	1	27.17	66.82	198
		2	28.84	60.99	179
		3	10.05	19.64	198
		Total	21.79	53.77	575
	2	1	63.57	109.35	159
		2	37.95	72.05	198
		3	12.23	18.24	198
		Total	36.12	76.13	555
	Total	1	43.38	90.03	357
		2	33.62	67.10	377
		3	11.14	18.96	396
		Total	28.83	66.07	1130
PO43- µmol l^{-1}	1	1	7	12	198
		2	7	12	179
		3	9	14	198
		Total	8	13	575
	2	1	5	14	159
		2	4	12	198
		3	4	9	198

		Total	4	12	555
	Total	1	6	13	357
		2	5	12	377
		3	6	12	396
		Total	6	12	1130
SO4 µmol l^{-1}	1	1	17757.290	11161.512	198
		2	16938.725	12782.916	179
		3	11472.072	11025.604	198
		Total	15338.166	11963.408	575
	2	1	27454.490	22751.801	159
		2	26397.944	21033.804	198
		3	31658.825	23855.001	198
		Total	28577.485	22644.275	555
	Total	1	22076.211	17943.613	357
		2	21906.697	18207.902	377
		3	21565.448	21132.261	396
		Total	21840.663	19189.154	1130
Cl- mg l^{-1}	1	1	22851.63	12297.78	198
		2	22132.25	11935.22	179
		3	25593.08	14407.41	198
		Total	23571.69	13021.29	575
	2	1	26308.24	19120.52	159
		2	25306.29	16966.15	198
		3	36101.64	20608.44	198
		Total	29444.65	19555.87	555
	Total	1	24391.13	15776.79	357
		2	23799.25	14858.34	377
		3	30847.36	18520.73	396
		Total	26456.20	16807.46	1130
EOYB g m^{-2}	1	1	354.4	150.3	198
		2	439.3	95.2	179
		3	379.2	137.2	198
		Total	389.4	135.1	575
	2	1	820.4	135.2	159
		2	668.7	201.1	198
		3	1078.4	33.6	198
		Total	858.3	224.9	555
	Total	1	561.9	272.8	357
		2	559.8	196.6	377
		3	728.8	363.9	396
		Total	619.7	298.5	1130
STEM DENSITY	1	1	410	210	198
		2	688	288	179

stems m^{-2}		3	565	15	198
		Total	550	232	575
	2	1	1465	406	159
		2	1597	484	198
		3	2474	676	198
		Total	1872	705	555
	Total	1	880	611	357
		2	1165	607	377
		3	1520	1068	396
		Total	1199	841	1130
STEM HEIGHT cm	1	1	25.7	4.6	198
		2	24.5	4.2	179
		3	22.5	5.7	198
		Total	24.2	5.0	575
	2	1	24.7	2.5	159
		2	21.3	5.6	198
		3	23.5	0.5	198
		Total	23.0	3.9	555
	Total	1	25.3	3.8	357
		2	22.8	5.2	377
		3	23.0	4.0	396
		Total	23.7	4.5	1130
$\delta^{34}S$	1	1	3.8	2.2	198
		2	-3.0	1.6	179
		3	-5.4	0.1	198
		Total	-1.5	4.2	575
	2	1	9.4	1.6	159
		2	10.4	0.6	198
		3	15.3	1.0	198
		Total	11.9	2.8	555
	Total	1	6.3	3.4	357
		2	4.0	6.8	377
		3	4.9	10.3	396
		Total	5.0	7.6	1130
SO4:Cl	1	1	0.0806	0.056	198
		2	0.0321	0.026	179
		3	0.0178	0.016	198
		Total	0.043	0.046	575
	2	1	0.044	0.036	159
		2	0.040	0.031	198
		3	0.032	0.019	198
		Total	0.038	0.029	555
	Total	1	0.064	0.051	357

		2	0.036	0.029	377
		3	0.025	0.019	396
		Total	0.041	0.039	1130
S:Fe	1	1	16	42	198
		2	20	60	179
		3	18	36	198
		Total	18	47	575
	2	1	2	10	159
		2	8	27	198
		3	13	43	198
		Total	8	31	555
	Total	1	10	33	357
		2	14	46	377
		3	16	39	396
		Total	13	40	1130
Bulk Density g cm^{-3}	1	1	1.56	5.19	198
		2	2.48	9.18	179
		3	0.91	0.23	198
		Total	1.62	5.98	575
	2	1	0.56	0.49	159
		2	0.66	0.52	198
		3	0.60	0.54	198
		Total	0.61	0.52	555
	Total	1	1.11	3.90	357
		2	1.52	6.39	377
		3	0.76	0.44	396
		Total	1.12	4.31	1130
f ^{35}S	1	1	0.071	0.410	198
		2	0.029	0.112	198
		3	0.015	0.028	198
		Total	0.038	0.247	594
	2	1	0.010	0.019	198
		2	0.012	0.020	198
		3	0.026	0.046	198
		Total	0.016	0.032	594
	Total	1	0.041	0.292	396
		2	0.020	0.081	396
		3	0.021	0.039	396
		Total	0.027	0.176	1188
Litterbag mass loss % AFDW loss	1	1	-12.39	20.32	198
		2	-17.42	15.32	179
		3	16.84	10.45	198

		Total	-3.89	21.96	575
	2	1	-12.25	22.36	159
		2	-25.06	15.66	198
		3	3.78	6.85	198
		Total	-11.10	19.89	555
	Total	1	-12.33	21.22	357
		2	-21.43	15.94	377
		3	10.31	10.98	396
		Total	-7.43	21.27	1130
C:N of plant tissue	1	1	18.3	0.0	198
		2	23.1	0.0	179
		3	20.8	0.0	198
		Total	20.6	1.9	575
	2	1	27.8	0.0	159
		2	24.9	0.0	198
		3	21.8	0.0	198
		Total	24.6	2.3	555
	Total	1	22.5	4.7	357
		2	24.0	0.9	377
		3	21.3	0.5	396
		Total	22.6	2.9	1130

Appendix C. Averaged Data for Six Regional Marshes

Codes

Crabs: 0 = Marshes without crabs, 1 = Marshes with crabs, Total = average of location regardless of presences of crabs

Descriptive Statistics

	CRABS	LOCATION	Depth-averaged Mean	Std. Deviation	N
PtEP mV	0	Mid	266.0	148.1	18
		North	282.8	45.1	18
		South	51.0	48.4	18
		Total	199.9	140.7	54
	1	Mid	114.8	80.3	18
		North	246.1	131.5	18
		South	131.7	100.6	18
		Total	164.2	119.7	54
	Total	Mid	190.4	140.2	36
		North	264.5	98.7	36
		South	91.3	87.9	36
		Total	182.1	131.2	108
pH	0	Mid	8.169	0.181	18
		North	8.062	0.392	18
		South	6.460	1.894	18
		Total	7.564	1.354	54
	1	Mid	7.405	0.983	18
		North	7.950	0.362	18
		South	7.963	0.840	18
		Total	7.773	0.805	54
	Total	Mid	7.787	0.797	36
		North	8.006	0.376	36
		South	7.211	1.633	36
		Total	7.668	1.113	108
FE2 umol l^{-1}	0	Mid	23	37	18
		North	60	54	18
		South	234	282	18
		Total	106	188	54
	1	Mid	70	91	18
		North	82	61	18
		South	54	90	18
		Total	69	81	54
	Total	Mid	47	72	36

		North	71	58	36
		South	144	225	36
		Total	87	145	108
TD Fe umol l^{-1}	0	Mid	31	37	18
		North	78	73	18
		South	117	51	18
		Total	75	65	54
	1	Mid	57	47	18
		North	104	52	18
		South	87	105	18
		Total	83	74	54
	Total	Mid	44	44	36
		North	91	64	36
		South	102	82	36
		Total	79	69	108
%SAND	0	Mid	21.704	8.263	18
		North	32.107	0.392	18
		South	32.275	10.065	18
		Total	28.695	8.907	54
	1	Mid	55.833	11.124	18
		North	19.359	6.467	18
		South	32.411	23.452	18
		Total	35.868	21.483	54
	Total	Mid	38.768	19.818	36
		North	25.733	7.885	36
		South	32.343	17.786	36
		Total	32.282	16.759	108
%SILT	0	Mid	44.166	0.000	18
		North	44.077	1.480	18
		South	29.589	10.642	18
		Total	39.277	9.211	54
	1	Mid	30.782	10.026	18
		North	55.742	2.271	18
		South	43.497	25.515	18
		Total	43.341	18.66	54
	Total	Mid	37.474	9.740	36
		North	49.910	6.210	36
		South	36.543	20.517	36
		Total	41.309	14.792	108
%CLAY	0	Mid	34.128	8.263	18
		North	23.815	1.087	18
		South	38.134	11.347	18
		Total	32.026	10.032	54

	1	Mid	13.383	1.539	18
		North	24.897	4.196	18
		South	24.090	2.065	18
		Total	20.790	5.986	54
	Total	Mid	23.756	12.040	36
		North	24.356	3.070	36
		South	31.112	10.739	36
		Total	26.408	9.973	108
SRR nmol ml^{-1} d^{-1}	0	Mid	203.30	334.82	18
		North	586.68	506.31	18
		South	2394.29	4139.49	18
		Total	1061.42	2558.20	54
	1	Mid	253.36	280.25	18
		North	775.45	989.79	18
		South	847.89	1914.73	18
		Total	625.57	1259.70	54
	Total	Mid	228.33	305.35	36
		North	681.07	780.72	36
		South	1621.09	3273.91	36
		Total	843.50	2018.80	108
S2 umol l^{-1}	0	Mid	61	102	18
		North	4	6	18
		South	37	71	18
		Total	34	74	54
	1	Mid	14	57	18
		North	1	2	18
		South	42	85	18
		Total	19	60	54
	Total	Mid	38	85	36
		North	2	4	36
		South	40	77	36
		Total	27	68	108
NH4 umol l^{-1}	0	Mid	24.5	36.3	18
		North	20.0	33.0	18
		South	6.4	4.0	18
		Total	17.0	28.9	54
	1	Mid	20.9	24.3	18
		North	30.1	32.1	18
		South	22.6	43.2	18
		Total	24.5	33.7	54
	Total	Mid	22.7	30.5	36
		North	25.1	32.5	36
		South	14.5	31.3	36

		Total	20.8	31.5	108
%H20	0	Mid	28.1	13.4	18
		North	74.1	1.5	18
		South	78.3	1.7	18
		Total	60.2	24.1	54
	1	Mid	35.0	14.1	18
		North	69.9	3.3	18
		South	51.1	10.5	18
		Total	52.0	17.6	54
	Total	Mid	31.6	14.0	36
		North	72.0	3.3	36
		South	64.7	15.7	36
		Total	56.1	21.4	108
%OM	0	Mid	3.7	3.5	18
		North	27.4	4.3	18
		South	46.2	6.1	18
		Total	25.7	18.1	54
	1	Mid	5.4	4.7	18
		North	25.6	7.3	18
		South	7.2	3.2	18
		Total	12.7	10.6	54
	Total	Mid	4.5	4.2	36
		North	26.5	6.0	36
		South	26.7	20.3	36
		Total	19.2	16.2	108
Root growth g dry wt/m2	0	Mid	172.28	47.57	18
		North	214.24	87.29	18
		South	842.01	638.56	18
		Total	409.51	479.12	54
	1	Mid	602.43	496.115	18
		North	1177.60	641.59	18
		South	105.21	48.71	18
		Total	628.41	638.25	54
	Total	Mid	387.35	410.15	36
		North	695.92	665.04	36
		South	473.61	582.07	36
		Total	518.96	572.34	108
PO43 umol l^{-1}	0	Mid	2	3	18
		North	0	0	18
		South	1	1	18
		Total	1	2	54
	1	Mid	1	1	18
		North	2	3	18

		South	6	4	18
		Total	3	4	54
	Total	Mid	1	2	36
		North	1	2	36
		South	3	4	36
		Total	2	3	108
SO4 umol l^{-1}	0	Mid	30986.566	25232.893	18
		North	32565.500	22185.979	18
		South	66611.250	35201.914	18
		Total	43387.772	32167.573	54
	1	Mid	56940.283	42458.760	18
		North	53782.416	32581.802	18
		South	40164.116	19583.314	18
		Total	50295.605	33101.977	54
	Total	Mid	43963.424	36852.186	36
		North	43173.958	29503.449	36
		South	53387.683	31112.989	36
		Total	46841.688	32670.052	108
CL mg l^{-1}	0	Mid	41994.055	6481.951	18
		North	35517.871	12315.766	18
		South	41152.436	6206.134	18
		Total	39554.787	9105.206	54
	1	Mid	49069.357	17703.366	18
		North	47885.385	10584.667	18
		South	37486.402	3953.555	18
		Total	44813.715	13002.544	54
	Total	Mid	45531.706	13620.113	36
		North	41701.628	12939.114	36
		South	39319.419	5454.885	36
		Total	42184.251	11479.840	108
EOYB g m^{-2}	0	Mid	338.8	55.2	18
		North	334.6	36.3	18
		South	351.5	16.2	18
		Total	341.6	39.2	54
	1	Mid	151.7	122.5	18
		North	397.4	116.4	18
		South	233.6	54.7	18
		Total	260.9	144.0	54
	Total	Mid	245.2	133.3	36
		North	366.0	90.7	36
		South	292.6	71.8	36
		Total	301.3	112.6	108
S:FE	0	Mid	13	25	18

		North	0.1	0.1	18
		South	4	17	18
		Total	6	18	54
	1	Mid	0.2	0.3	18
		North	0.1	0.5	18
		South	5	10	18
		Total	1	6	54
	Total	Mid	6	18	36
		North	0.1	0.3	36
		South	5	14	36
		Total	4	13	108
Bulk Density g cm^{-3}	0	Mid	1.13	0.34	18
		North	0.21	0.01	18
		South	0.21	0.02	18
		Total	0.51	0.48	54
	1	Mid	0.88	0.20	18
		North	0.25	0.04	18
		South	0.59	0.21	18
		Total	0.57	0.30	54
	Total	Mid	1.01	0.30	36
		North	0.23	0.04	36
		South	0.40	0.24	36
		Total	0.54	0.40	108
f ^{35}S	0	Mid	0.002	0.002	18
		North	0.004	0.004	18
		South	0.009	0.015	18
		Total	0.005	0.009	54
	1	Mid	0.004	0.006	18
		North	0.003	0.005	18
		South	0.007	0.012	18
		Total	0.005	0.008	54
	Total	Mid	0.003	0.004	36
		North	0.003	0.004	36
		South	0.008	0.013	36
		Total	0.005	0.008	108

Appendix D. Principal Components Analysis Output for LPC and UPC

PCA output of Total Data

Communalities

	Initial	Extraction
PtEP	1.000	.759
pH	1.000	.743
Stem Density	1.000	.842
Stem Height	1.000	.867
δ34S	1.000	.811
Bulk Density	1.000	.905
Decomp	1.000	.703
CN	1.000	.538
TD FE	1.000	.645
SRR	1.000	.929
S2	1.000	.609
NH4	1.000	.716
H20	1.000	.918
PO4	1.000	.522
SO4	1.000	.971
CL	1.000	.708
EOYB	1.000	.884
SO:CL	1.000	.961
f ^{35}S	1.000	.882
SAND	1.000	.826
SILT	1.000	.920
CLAY	1.000	.964
Root Growth	1.000	.686
OM	1.000	.909

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.519	22.997	22.997	5.519	22.997	22.997
2	2.693	11.222	34.219	2.693	11.222	34.219
3	2.167	9.027	43.246	2.167	9.027	43.246
4	1.790	7.459	50.704	1.790	7.459	50.704

5	1.379	5.744	56.448	1.379	5.744	56.448
6	1.266	5.276	61.724	1.266	5.276	61.724
7	1.193	4.969	66.693	1.193	4.969	66.693
8	1.119	4.664	71.358	1.119	4.664	71.358
9	1.071	4.462	75.820	1.071	4.462	75.820
10	1.023	4.264	80.084	1.023	4.264	80.084
11	.907	3.780	83.864			
12	.794	3.310	87.174			
13	.688	2.865	90.039			
14	.597	2.487	92.526			
15	.505	2.102	94.628			
16	.440	1.834	96.462			
17	.371	1.545	98.007			
18	.216	.900	98.907			
19	.109	.454	99.361			
20	.078	.323	99.684			
21	.047	.195	99.879			
22	.029	.121	100.000			
23	1.072E-11	4.468E-11	100.000			
24	4.413E-16	1.839E-15	100.000			

Extraction Method: Principal Component Analysis.

Component Matrix(a)

	Component									
	1	2	3	4	5	6	7	8	9	10
PtEP	.005	-.034	.172	.020	-.047	.253	.034	.174	.181	.773
pH	-.217	-.138	-.416	.221	.226	.603	-.064	-.020	.177	-.063
Stem Density	.670	-.344	.052	.354	-.282	.175	-.060	.022	.174	-.036
Stem Height	-.045	.022	-.032	.077	.688	-.218	.524	.191	-.025	-.157
δ34S	.739	-.347	.066	.351	-.073	.072	-.076	.026	.010	-.022
Bulk Density	-.751	-.308	.090	.379	-.091	-.029	.053	-.071	-.278	.019
Decomp	-.141	.173	.112	.109	-.289	.185	.551	-.001	.446	-.099
C:N	.443	-.344	-.021	-.028	.417	-.127	-.177	.031	-.003	.006
TD FE	.372	-.007	-.005	.063	-.409	-.541	.176	.087	.059	.028
SRR	.455	.661	.450	.206	.104	-.050	-.060	-.105	-.069	.089
S2	-.333	-.109	.221	.115	.064	-.148	.424	-.315	.156	.307
NH4	.135	.406	-.146	.147	-.388	-.025	.100	.509	-.097	-.245
H20	.782	.282	-.080	-.352	.076	.019	-.036	.061	.291	-.006
PO4	-.437	.081	.158	.110	-.091	.349	.295	.109	-.187	-.154
SO4	.360	.420	-.569	.511	.022	-.029	.025	-.238	-.113	.099

CL	.232	.458	.365	.334	.093	.310	-.130	-.178	.018	-.216
EOYB	.707	-.298	.121	.325	.291	-.018	.218	.126	.128	-.106
SO:CL	.273	.238	-.750	.386	-.018	-.165	.082	-.170	-.125	.197
f ^{35}S	.200	.581	.653	.154	.099	-.056	-.073	-.079	-.156	.074
SAND	-.386	.665	-.343	-.273	.092	.037	-.004	-.021	.178	.008
SILT	-.484	-.155	.172	.501	.084	-.263	-.317	.272	.362	-.016
CLAY	.669	-.363	.114	-.199	-.134	.182	.255	-.202	-.419	.007
Root Growth	.119	.152	-.061	.048	.128	.157	.056	.630	-.340	.295
OM	.881	.009	-.081	-.307	.011	.090	.086	.031	.123	.012

Extraction Method: Principal Component Analysis.
a 10 components extracted.

PCA of LPC

Communalities(a)

	Initial	Extraction
PtEP	1.000	.693
pH	1.000	.710
Stem Density	1.000	.834
Stem Height	1.000	.916
δ34S	1.000	.699
Bulk Density	1.000	.849
Decomp	1.000	.636
C:N	1.000	.507
TD FE	1.000	.652
SRR	1.000	.914
S2	1.000	.432
NH4	1.000	.642
H20	1.000	.885
PO4	1.000	.543
SO4	1.000	.912
CL	1.000	.626
EOYB	1.000	.928
SO:CL	1.000	.926
f ^{35}S	1.000	.897
OM	1.000	.756

Extraction Method: Principal Component Analysis.
a SITE = 1

Total Variance Explained(a)

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %

1	3.302	16.511	16.511	3.302	16.511	16.511
2	2.737	13.683	30.194	2.737	13.683	30.194
3	2.114	10.571	40.765	2.114	10.571	40.765
4	1.662	8.308	49.073	1.662	8.308	49.073
5	1.558	7.792	56.865	1.558	7.792	56.865
6	1.308	6.539	63.404	1.308	6.539	63.404
7	1.235	6.173	69.577	1.235	6.173	69.577
8	1.042	5.211	74.788	1.042	5.211	74.788
9	.949	4.745	79.533			
10	.836	4.178	83.711			
11	.779	3.895	87.606			
12	.629	3.146	90.752			
13	.525	2.625	93.377			
14	.419	2.094	95.471			
15	.391	1.957	97.427			
16	.296	1.478	98.906			
17	.133	.663	99.569			
18	.052	.259	99.827			
19	.035	.173	100.000			
20	1.304E-11	6.521E-11	100.000			

Extraction Method: Principal Component Analysis.
a SITE = 1

Component Matrix(a,b)

	Component							
	1	2	3	4	5	6	7	8
PtEP	-.070	-.116	-.130	-.371	.088	-.171	.016	.695
pH	-.078	.557	.029	-.101	.398	.043	-.466	-.075
Stem Density	.086	.123	-.603	-.031	.325	.512	.211	-.185
Stem Height	-.225	.357	.125	.736	-.315	-.046	-.178	.218
δ34S	-.227	.197	.544	-.298	-.388	.171	-.148	-.148
Bulk Density	-.803	-.157	.251	.025	.177	.201	.189	.096
Decomp	.155	-.120	-.005	.351	.330	-.507	.327	-.034
C:N	.169	-.078	-.528	-.214	.245	.249	.097	.129
TD FE	-.063	-.003	-.104	-.042	-.550	-.005	.530	-.229
SRR	.737	-.377	.335	.161	.035	.204	-.007	.219
S2	-.207	-.180	-.017	.271	.313	-.425	.070	.003
NH4	.443	.205	.288	.032	.008	.059	.561	-.032
H20	.813	.191	-.312	-.044	-.130	-.226	-.139	-.031
PO4	-.073	-.101	.304	.031	.517	-.140	.003	-.383
SO4	.335	.717	.427	-.031	.228	.116	.154	.115
CL	.522	-.249	.322	.159	.128	.221	-.210	-.231

EOYB	-.089	.353	-.397	.726	-.040	.321	-.019	.077
SO:CL	.110	.826	.289	-.100	.174	.021	.245	.215
f ^{35}S	.574	-.610	.272	.171	.003	.232	-.038	.190
OM	.546	.409	-.285	-.125	-.225	-.328	-.133	-.135

Extraction Method: Principal Component Analysis.
a 8 components extracted.
b SITE = 1

PCA of UPC

Communalities(a)

	Initial	Extraction
PtEP	1.000	.280
pH	1.000	.610
Stem Density	1.000	.727
Stem Height	1.000	.951
δ34S	1.000	.752
Bulk Density	1.000	.942
Decomp	1.000	.651
C:N	1.000	.859
TD FE	1.000	.702
SRR	1.000	.925
S2	1.000	.701
NH4	1.000	.730
H20	1.000	.937
PO4	1.000	.345
SO4	1.000	.963
CL	1.000	.686
EOYB	1.000	.888
SO:CL	1.000	.938
f ^{35}S	1.000	.855
OM	1.000	.897

Extraction Method: Principal Component Analysis.
a SITE = 2

Total Variance Explained(a)

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.050	20.252	20.252	4.050	20.252	20.252
2	3.081	15.406	35.658	3.081	15.406	35.658
3	2.495	12.474	48.132	2.495	12.474	48.132
4	1.955	9.775	57.907	1.955	9.775	57.907
5	1.383	6.916	64.823	1.383	6.916	64.823
6	1.259	6.296	71.119	1.259	6.296	71.119

7	1.115	5.573	76.692	1.115	5.573	76.692
8	.966	4.830	81.522			
9	.884	4.419	85.941			
10	.626	3.131	89.073			
11	.564	2.820	91.893			
12	.473	2.366	94.259			
13	.439	2.197	96.456			
14	.274	1.372	97.828			
15	.215	1.077	98.905			
16	.117	.584	99.489			
17	.050	.252	99.741			
18	.037	.183	99.924			
19	.015	.076	100.000			
20	8.144E-12	4.072E-11	100.000			

Extraction Method: Principal Component Analysis.
a SITE = 2

Component Matrix(a,b)

	Component						
	1	2	3	4	5	6	7
PtEP	.077	.286	.176	-.166	.003	-.083	.356
pH	-.430	.161	-.059	-.073	.286	-.508	.224
Stem Density	.122	.667	-.462	-.103	.174	.028	.111
Stem Height	.182	-.187	.810	-.008	.465	.058	-.087
δ34S	.338	.771	-.082	-.143	.115	.047	.019
Bulk Density	-.739	.449	.154	.383	.015	.053	-.143
Decomp	.153	.562	-.052	-.185	.436	.147	.251
C:N	-.200	-.669	.505	.080	.325	.027	-.063
TD FE	.395	.040	-.254	.144	.074	.593	-.320
SRR	.797	.163	.293	.261	-.327	-.047	.021
S2	-.241	.182	.237	.143	-.183	.582	.402
NH4	.333	.200	-.316	-.140	.220	-.116	-.630
H20	.762	-.421	-.146	-.371	-.019	-.035	.136
PO4	-.222	.369	.231	-.140	-.013	.000	-.293
SO4	.449	-.075	-.249	.771	.245	-.156	.118
CL	.396	.345	.295	.249	-.192	-.472	-.037
EOYB	.437	.346	.632	-.082	.405	.081	-.016
SO:CL	.302	-.231	-.392	.707	.344	.042	.141
f ^{35}S	.609	.275	.438	.218	-.408	-.015	-.048
OM	.697	-.383	-.167	-.455	.068	.010	.160

Extraction Method: Principal Component Analysis.
a 7 components extracted.
b SITE = 2

Appendix E. Principal Components Analysis of Six Regional Marshes

Communalities

	Initial	Extraction
TEMP	1.000	.819
PtEP	1.000	.511
pH	1.000	.638
FE2	1.000	.665
TD Fe	1.000	.541
SAND	1.000	.907
SILT	1.000	.871
CLAY	1.000	.768
SRR	1.000	.937
S2	1.000	.878
NH4	1.000	.797
H20	1.000	.953
OM	1.000	.908
Root growth	1.000	.764
PO43	1.000	.818
SO4	1.000	.933
CL	1.000	.814
EOYB	1.000	.734
SO4:CL	1.000	.831
S:FE	1.000	.778
Bulk Density	1.000	.956
f ^{35}S	1.000	.904

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.115	23.249	23.249	5.115	23.249	23.249
2	2.813	12.787	36.036	2.813	12.787	36.036
3	2.403	10.923	46.959	2.403	10.923	46.959
4	1.992	9.054	56.013	1.992	9.054	56.013
5	1.750	7.952	63.966	1.750	7.952	63.966
6	1.380	6.272	70.238	1.380	6.272	70.238
7	1.239	5.633	75.871	1.239	5.633	75.871
8	1.035	4.704	80.575	1.035	4.704	80.575

9	.797	3.623	84.198			
10	.743	3.379	87.576			
11	.585	2.660	90.236			
12	.552	2.509	92.745			
13	.442	2.008	94.753			
14	.369	1.677	96.430			
15	.269	1.222	97.652			
16	.193	.878	98.530			
17	.186	.843	99.373			
18	.061	.279	99.652			
19	.050	.228	99.880			
20	.015	.070	99.950			
21	.011	.050	100.000			
22	7.204E-16	3.274E-15	100.000			

Extraction Method: Principal Component Analysis.

Component Matrix(a)

	Component							
	1	2	3	4	5	6	7	8
TEMP	.328	.296	.597	.327	.079	.343	-.138	-.138
PtEP	-.130	.547	-.307	.229	-.179	.092	.044	.080
pH	-.547	.403	-.298	.075	.091	-.266	.042	.024
FE2	.396	-.152	.053	-.198	.293	.279	.302	-.434
TD Fe	.418	-.113	-.147	-.106	.348	-.034	.398	-.202
SAND	-.367	-.689	.066	-.300	.345	-.007	-.194	.216
SILT	.193	.529	-.488	.326	-.321	-.218	.191	-.150
CLAY	.331	.373	.613	.021	-.104	.335	.043	-.140
SRR	.512	-.228	.283	-.235	-.677	-.013	.099	.141
S2	-.397	.048	.642	.063	.165	-.421	.306	.049
NH4	-.220	.087	-.246	-.129	.005	.661	.284	.383
H20	.771	.305	-.150	-.382	.155	-.248	.013	.104
OM	.813	.190	.203	-.269	.277	-.114	-.074	.036
Root growth	.525	-.017	.115	.266	.277	.008	-.184	.541
PO43	-.392	.016	.028	-.236	.047	.091	.731	.250
SO4	.625	-.481	-.155	.508	.042	-.040	.158	.020
CL	.191	-.379	-.073	.749	.089	-.060	.158	.176
EOYB	.388	.644	.212	.167	.117	.088	.032	.271
SO4:CL	.722	-.410	-.122	.292	-.013	-.040	.173	-.101
SFE	-.377	.138	.623	.154	.063	-.394	.210	.043
Bulk Density	-.744	-.256	.273	.393	-.153	.251	-.016	-.145
f ^{35}S	.361	-.319	.196	-.220	-.739	-.122	.090	.128

Extraction Method: Principal Component Analysis.
a 8 components extracted.

Appendix F. MANOVA Output for LPC and UPC

Multivariate Tests(c)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.989	4257.522(a)	24.000	1099.000	.000
	Wilks' Lambda	.011	4257.522(a)	24.000	1099.000	.000
	Hotelling's Trace	92.976	4257.522(a)	24.000	1099.000	.000
	Roy's Largest Root	92.976	4257.522(a)	24.000	1099.000	.000
MONTH	Pillai's Trace	.384	28.561(a)	24.000	1099.000	.000
	Wilks' Lambda	.616	28.561(a)	24.000	1099.000	.000
	Hotelling's Trace	.624	28.561(a)	24.000	1099.000	.000
	Roy's Largest Root	.624	28.561(a)	24.000	1099.000	.000
DEPTH	Pillai's Trace	.854	268.188(a)	24.000	1099.000	.000
	Wilks' Lambda	.146	268.188(a)	24.000	1099.000	.000
	Hotelling's Trace	5.857	268.188(a)	24.000	1099.000	.000
	Roy's Largest Root	5.857	268.188(a)	24.000	1099.000	.000
SITE	Pillai's Trace	.979	2181.290(a)	24.000	1099.000	.000
	Wilks' Lambda	.021	2181.290(a)	24.000	1099.000	.000
	Hotelling's Trace	47.635	2181.290(a)	24.000	1099.000	.000
	Roy's Largest Root	47.635	2181.290(a)	24.000	1099.000	.000
TREATMEN	Pillai's Trace	1.311	87.212	48.000	2200.000	.000
	Wilks' Lambda	.112	90.872(a)	48.000	2198.000	.000
	Hotelling's Trace	4.137	94.631	48.000	2196.000	.000
	Roy's Largest Root	2.781	127.480(b)	24.000	1100.000	.000
SITE * TREATMEN	Pillai's Trace	1.343	93.704	48.000	2200.000	.000
	Wilks' Lambda	.067	131.396(a)	48.000	2198.000	.000
	Hotelling's Trace	7.836	179.246	48.000	2196.000	.000
	Roy's Largest Root	6.953	318.696(b)	24.000	1100.000	.000

a Exact statistic
b The statistic is an upper bound on F that yields a lower bound on the significance level.
c Design: Intercept+MONTH+DEPTH+SITE+TREATMEN+SITE * TREATMEN

Levene's Test of Equality of Error Variances(a)

	F	df1	df2	Sig.
TEMP	4.945	5	1182	.000
EH	16.795	5	1182	.000
PH	8.515	5	1182	.000
FE	7.651	5	1182	.000
TD FE	12.919	5	1182	.000
SAND	43.376	5	1182	.000
SILT	43.885	5	1182	.000
CLAY	42.214	5	1182	.000
SRR	19.537	5	1182	.000

S2	6.895	5	1182	.000
NH4	5.560	5	1182	.000
H20	62.134	5	1182	.000
OM	195.511	5	1182	.000
RG	11.306	5	1182	.000
PO4	6.979	5	1182	.000
SO4	1.514	5	1182	.183
CL	2.955	5	1182	.012
EOYB	130.472	5	1182	.000
DENSITY	157.082	5	1182	.000
HEIGHT	76.752	5	1182	.000
DELTA34S	148.838	5	1182	.000
SO:CL	2.140	5	1182	.058
S:FE	10.433	5	1182	.000
Bulk Density	35.573	5	1182	.000
f ^{35}S	27.250	5	1182	.000
Decomp	31.000	5	1182	.000
C:N	105.643	5	1182	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a Design: Intercept+MONTH+DEPTH+SITE+TREATMEN+SITE * TREATMEN

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	PtEP	988661.545(a)	7	141237.364	9.371	.000
	pH	97.942(b)	7	13.992	17.033	.000
	Fe2+	52385104.695(c)	7	7483586.385	15.558	.000
	TD Fe	71395973.857(d)	7	10199424.837	43.040	.000
	% Sand	25361.147(e)	7	3623.021	1311.466	.000
	% Silt	7061.686(f)	7	1008.812	38.125	.000
	%Clay	21229.376(g)	7	3032.768	93.166	.000
	SRR	82005571.797(h)	7	11715081.685	3.684	.001
	S2-	1354590.361(i)	7	193512.909	10.435	.000
	NH4+	309105.379(j)	7	44157.911	45.305	.000
	%H20	281415.473(k)	7	40202.210	176.922	.000
	%OM	270833.839(l)	7	38690.548	189.662	.000
	AFDW RG	427642.323(m)	7	61091.760	15.227	.000
	PO43-	12774.619(n)	7	1824.946	11.707	.000
	SO4	115183189609.46(o)	7	16454741372.780	61.430	.000
	Cl-	30075477269.670(p)	7	4296496752.810	16.689	.000
	EOYB	79752200.528(q)	7	11393171.504	612.640	.000
	Stem Density	614371265.273(r)	7	87767323.610	529.951	.000

	Stem Height	2532.638(s)	7	361.805	19.186	.000
	δ34S	63416.996(t)	7	9059.571	4499.752	.000
	SO4:Cl	.561(u)	7	.080	76.640	.000
	S:Fe	55979.382(v)	7	7997.055	4.993	.000
	Bulk Density	651.214(w)	7	93.031	5.127	.000
	f ^{35}S	.695(x)	7	.010	3.238	.002
	Decomp	239832.648(y)	7	34261.807	141.864	.000
	C:N	9742.966(z)	7	1391.852	.	.
Intercept	PtEP	12135.057	1	12135.057	.805	.370
	pH	3301.771	1	3301.771	4019.461	.000
	Fe2+	41156773.616	1	41156773.616	85.561	.000
	TD Fe	34440977.847	1	34440977.847	145.336	.000
	% Sand	227505.862	1	227505.862	82352.896	.000
	% Silt	87628.643	1	87628.643	3311.630	.000
	%Clay	20160.177	1	20160.177	619.316	.000
	SRR	68562066.242	1	68562066.242	21.560	.000
	S2-	174305.560	1	174305.560	9.400	.002
	NH4+	386162.939	1	386162.939	396.190	.000
	%H20	433624.910	1	433624.910	1908.297	.000
	%OM	107263.687	1	107263.687	525.808	.000
	AFDW RG	207046.894	1	207046.894	51.607	.000
	PO43-	552.230	1	552.230	3.542	.060
	SO4	166034020054.665	1	166034020054.665	619.849	.000
	Cl-	65180292671.285	1	65180292671.285	253.178	.000
	EOYB	32575460.736	1	32575460.736	1751.666	.000
	Stem Density	111006013.566	1	111006013.566	670.269	.000
	Bulk Density	46964.863	1	46964.863	2490.432	.000
	δ34S	2184.427	1	2184.427	1084.972	.000
	SO4:Cl	.447	1	.447	427.155	.000
	S:Fe	103.351	1	103.351	.065	.800
	Bulk Density	.292	1	.292	.016	.899
	f ^{35}S	.420	1	.420	13.69	.000
	Decomp	260.775	1	260.775	1.080	.299
	C:N	43574.102	1	43574.102	.	.
MONTH	PtEP	61919.523	1	61919.523	4.108	.043
	pH	70.864	1	70.864	86.267	.000
	Fe2+	27713634.580	1	27713634.580	57.614	.000
	TD Fe	25023251.927	1	25023251.927	105.595	.000
	% Sand	2.089	1	2.089	.756	.385
	% Silt	.675	1	.675	.026	.873
	%Clay	.389	1	.389	.012	.913

	SRR	15490004.787	1	15490004.787	4.871	.028
	S2-	5356.515	1	5356.515	.289	.591
	NH4+	171436.652	1	171436.652	175.888	.000
	%H20	12582.504	1	12582.504	55.373	.000
	%OM	3044.523	1	3044.523	14.924	.000
	AFDW RG	4634.709	1	4634.709	1.155	.283
	PO43-	3577.350	1	3577.350	22.948	.000
	SO4	22161536914.402	1	22161536914.402	82.735	.000
	Cl-	288757470.095	1	288757470.095	1.122	.290
	EOYB	65.860	1	65.860	.004	.953
	Stem Density	219152.226	1	219152.226	1.323	.250
	Stem Height	.918	1	.918	.049	.825
	δ34S	.014	1	.014	.007	.934
	SO4:Cl	.044	1	.044	41.722	.000
	S:Fe	15354.597	1	15354.597	9.586	.002
	Bulk Density	51.688	1	51.688	2.848	.092
	f ^{35}S	.111	1	.111	3.607	.058
	Decomp	10308.479	1	10308.479	42.683	.000
	C:N	.000	1	.000	.	.
DEPTH	PtEP	10445.100	1	10445.100	.693	.405
	pH	12.258	1	12.258	14.923	.000
	Fe2+	436114.834	1	436114.834	.907	.341
	TD Fe	90.135	1	90.135	.000	.984
	% Sand	13394.461	1	13394.461	4848.546	.000
	% Silt	5887.083	1	5887.083	222.483	.000
	%Clay	1521.555	1	1521.555	46.742	.000
	SRR	23378788.275	1	23378788.275	7.352	.007
	S2-	240076.796	1	240076.796	12.946	.000
	NH4+	26505.219	1	26505.219	27.193	.000
	%H20	117167.577	1	117167.577	515.631	.000
	%OM	66704.877	1	66704.877	326.988	.000
	AFDW RG	88046.806	1	88046.806	21.946	.000
	PO43-	5128.096	1	5128.096	32.896	.000
	SO4	33688717165.657	1	33688717165.657	125.769	.000
	Cl-	5121034581.894	1	5121034581.894	19.892	.000
	EOYB	655.261	1	655.261	.035	.851
	Stem Density	5520.844	1	5520.844	.033	.855
	Stem Height	.264	1	.264	.014	.906
	δ34S	.004	1	.004	.002	.962
	SO4:Cl	.066	1	.066	63.095	.000
	S:Fe	26.834	1	26.834	.017	.897

	Bulk Density	71.827	1	71.827	3.958	.047
	f ^{35}S	.067	1	.067	2.179	.140
	Decomp	60.723	1	60.723	.251	.616
	C:N	.000	1	.000	.	.
SITE	PtEP	6925.965	1	6925.965	.460	.498
	pH	3.958	1	3.958	4.818	.028
	Fe2+	13493317.736	1	13493317.736	28.051	.000
	TD Fe	11869088.183	1	11869088.183	50.086	.000
	% Sand	12118.526	1	12118.526	4386.681	.000
	% Silt	945.081	1	945.081	35.716	.000
	%Clay	19832.062	1	19832.062	609.236	.000
	SRR	513424.489	1	513424.489	.161	.688
	S2-	160134.351	1	160134.351	8.635	.003
	NH4+	37643.675	1	37643.675	38.621	.000
	%H20	137348.466	1	137348.466	604.443	.000
	%OM	190568.341	1	190568.341	934.169	.000
	AFDW RG	67710.082	1	67710.082	16.877	.000
	PO43-	2641.372	1	2641.372	16.944	.000
	SO4	47597835858.752	1	47597835858.752	177.695	.000
	Cl-	8739646600.237	1	8739646600.237	33.947	.000
	EOYB	60550409.094	1	60550409.094	3255.951	.000
	Stem Density	466634976.294	1	466634976.294	2817.603	.000
	Stem Height	341.582	1	341.582	18.113	.000
	δ34S	49561.487	1	49561.487	24616.444	.000
	SO4:Cl	.006	1	.006	5.260	.022
	S:Fe	31586.358	1	31586.358	19.720	.000
	Bulk Density	302.398	1	302.398	16.664	.000
	f ^{35}S	.151	1	.151	4.912	.027
	Decomp	12631.594	1	12631.594	52.302	.000
	C:N	4710.721	1	4710.721	.	.
TREATMEN	PtEP	656660.895	2	328330.447	21.784	.000
	pH	7.618	2	3.809	4.637	.010
	Fe2+	3945590.246	2	1972795.123	4.101	.017
	TD Fe	14606001.878	2	7303000.939	30.818	.000
	% Sand	4.812	2	2.406	.871	.419
	% Silt	37.867	2	18.933	.716	.489
	%Clay	18.820	2	9.410	.289	.749
	SRR	4970285.015	2	2485142.507	.781	.458
	S2-	887291.805	2	443645.903	23.924	.000
	NH4+	35590.183	2	17795.091	18.257	.000
	%H20	3361.649	2	1680.825	7.397	.001

	%OM	2511.408	2	1255.704	6.155	.002
	AFDW RG	214885.131	2	107442.565	26.780	.000
	PO43-	173.781	2	86.890	.557	.573
	SO4	139965723.030	2	69982861.515	.261	.770
	Cl-	12375769731.950	2	6187884865.975	24.035	.000
	EOYB	6649133.834	2	3324566.917	178.771	.000
	Stem Density	65823618.173	2	32911809.086	198.726	.000
	Stem Height	1244.762	2	622.381	33.003	.000
	δ34S	1585.614	2	792.807	393.775	.000
	SO4:Cl	.259	2	.130	123.868	.000
	S:Fe	9168.371	2	4584.185	2.862	.058
	Bulk Density	131.660	2	65.830	3.628	.027
	f ^{35}S	.107	2	.053	1.743	.175
	Decomp	202853.015	2	101426.508	419.966	.000
	C:N	1448.544	2	724.272	.	.
SITE * TREATMEN	PtEP	279661.370	2	139830.685	9.277	.000
	pH	5.774	2	2.887	3.515	.030
	Fe2+	4586876.543	2	2293438.271	4.768	.009
	TD Fe	17758166.686	2	8879083.343	37.468	.000
	% Sand	5.431	2	2.716	.983	.374
	% Silt	14.431	2	7.216	.273	.761
	%Clay	7.435	2	3.717	.114	.892
	SRR	35563628.862	2	17781814.431	5.592	.004
	S2-	30545.051	2	15272.526	.824	.439
	NH4+	30490.893	2	15245.446	15.641	.000
	%H20	1548.051	2	774.026	3.406	.034
	%OM	1317.189	2	658.594	3.228	.040
	AFDW RG	51616.501	2	25808.251	6.433	.002
	PO43-	715.196	2	357.598	2.294	.101
	SO4	7398012319.630	2	3699006159.815	13.809	.000
	Cl-	3504215349.948	2	1752107674.974	6.806	.001
	EOYB	10635417.763	2	5317708.881	285.947	.000
	Stem Density	56516699.549	2	28258349.774	170.628	.000
	Stem Height	831.458	2	415.729	22.045	.000
	δ34S	10483.050	2	5241.525	2603.387	.000
	SO4:Cl	.151	2	.075	71.968	.000
	S:Fe	4933.518	2	2466.759	1.540	.215
	Bulk Density	114.374	2	57.187	3.151	.043
	f ^{35}S	.260	2	.130	4.239	.015
	Decomp	8873.116	2	4436.558	18.370	.000

	C:N	3908.649	2	1954.324	.	.
Error	PtEP	16910969.399	1122	15072.165		
	pH	921.663	1122	.821		
	Fe2+	539706847.023	1122	481022.145		
	TD Fe	265885698.835	1122	236974.776		
	% Sand	3099.607	1122	2.763		
	% Silt	29689.108	1122	26.461		
	%Clay	36523.726	1122	32.552		
	SRR	3567982826.846	1122	3180020.345		
	S2-	20806170.640	1122	18543.824		
	NH4+	1093603.294	1122	974.691		
	%H20	254953.598	1122	227.231		
	%OM	228885.357	1122	203.998		
	AFDW RG	4501453.195	1122	4011.990		
	PO43-	174906.102	1122	155.888		
	SO4	300541293173.745	1122	267862115.128		
	Cl-	288856752040.949	1122	257448085.598		
	EOYB	20865656.025	1122	18596.841		
	Stem Density	185819089.078	1122	165614.161		
	Stem Height	21158.813	1122	18.858		
	δ34S	2258.977	1122	2.013		
	SO4:Cl	1.173	1122	.001		
	S:Fe	1797188.649	1122	1601.772		
	Bulk Density	20360.228	1122	18.146		
	f ^{35}S	36.182	1122	.031		
	Decomp	270975.443	1122	241.511		
	C:N	.000	1122	.000		
Total	PtEP	19900532.139	1130			
	pH	55450.738	1130			
	Fe2+	623005909.068	1130			
	TD Fe	366396086.611	1130			
	% Sand	2512622.630	1130			
	% Silt	1490967.240	1130			
	%Clay	393591.750	1130			
	SRR	3760944884.197	1130			
	S2-	28680269.407	1130			
	NH4+	1900596.780	1130			
	%H20	2891515.514	1130			
	%OM	896057.326	1130			
	AFDW RG	5868527.714	1130			
	PO43-	234341.312	1130			
	SO4	954750977184.043	1130			

	Cl-	1109853622498.211	1130			
	EOYB	534610995.200	1130			
	Stem Density	2426545664.000	1130			
	Stem Height	658808.320	1130			
	δ34S	94832.125	1130			
	SO4:Cl	3.675	1130			
	S:Fe	2063397.293	1130			
	Bulk Density	22452.978	1130			
	f ^{35}S	37.753	1130			
	Decomp	573199.817	1130			
	C:N	588766.591	1130			
Corrected Total	PtEP	17899630.944	1129			
	pH	1019.605	1129			
	Fe2+	592091951.717	1129			
	TD Fe	337281672.692	1129			
	% Sand	28460.754	1129			
	% Silt	36750.794	1129			
	%Clay	57753.102	1129			
	SRR	3649988398.643	1129			
	S2-	22160761.001	1129			
	NH4+	1402708.673	1129			
	%H20	536369.071	1129			
	%OM	499719.197	1129			
	AFDW RG	4929095.518	1129			
	PO43-	187680.721	1129			
	SO4	415724482783.207	1129			
	Cl-	318932229310.619	1129			
	EOYB	100617856.553	1129			
	Stem Density	800190354.350	1129			
	Stem Height	23691.451	1129			
	δ34S	65675.973	1129			
	SO4:Cl	1.734	1129			
	S:Fe	1853168.031	1129			
	Bulk Density	21011.442	1129			
	f ^{35}S	36.877	1129			
	Decomp	510808.091	1129			
	C:N	9742.966	1129			

a R Squared = .055 (Adjusted R Squared = .049)
b R Squared = .096 (Adjusted R Squared = .090)
c R Squared = .088 (Adjusted R Squared = .083)
d R Squared = .212 (Adjusted R Squared = .207)
e R Squared = .891 (Adjusted R Squared = .890)

f R Squared = .192 (Adjusted R Squared = .187)
g R Squared = .368 (Adjusted R Squared = .364)
h R Squared = .022 (Adjusted R Squared = .016)
i R Squared = .061 (Adjusted R Squared = .055)
j R Squared = .220 (Adjusted R Squared = .215)
k R Squared = .525 (Adjusted R Squared = .522)
l R Squared = .542 (Adjusted R Squared = .539)
m R Squared = .087 (Adjusted R Squared = .081)
n R Squared = .068 (Adjusted R Squared = .062)
o R Squared = .277 (Adjusted R Squared = .273)
p R Squared = .094 (Adjusted R Squared = .089)
q R Squared = .793 (Adjusted R Squared = .791)
r R Squared = .768 (Adjusted R Squared = .766)
s R Squared = .107 (Adjusted R Squared = .101)
t R Squared = .966 (Adjusted R Squared = .965)
u R Squared = .323 (Adjusted R Squared = .319)
v R Squared = .030 (Adjusted R Squared = .024)
w R Squared = .031 (Adjusted R Squared = .025)
x R Squared = .019 (Adjusted R Squared = .013)
y R Squared = .470 (Adjusted R Squared = .466)
z R Squared = 1.000 (Adjusted R Squared = 1.000)

Post-Hoc Test

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
FE	1	2	.0152	.06240	.968	-.1312	.1616
		3	-.0687	.06240	.513	-.2151	.0777
	2	1	-.0152	.06240	.968	-.1616	.1312
		3	-.0839	.06240	.370	-.2304	.0625
	3	1	.0687	.06240	.513	-.0777	.2151
		2	.0839	.06240	.370	-.0625	.2304
TD FE	1	2	.0599	.05364	.504	-.0660	.1858
		3	-.0032	.05364	.998	-.1291	.1227
	2	1	-.0599	.05364	.504	-.1858	.0660
		3	-.0631	.05364	.467	-.1890	.0628
	3	1	.0032	.05364	.998	-.1227	.1291
		2	.0631	.05364	.467	-.0628	.1890
SRR	1	2	-.0294	.08571	.937	-.2305	.1717
		3	-.5976(*)	.08571	.000	-.7987	-.3964
	2	1	.0294	.08571	.937	-.1717	.2305
		3	-.5682(*)	.08571	.000	-.7693	-.3670
	3	1	.5976(*)	.08571	.000	.3964	.7987
		2	.5682(*)	.08571	.000	.3670	.7693
S2	1	2	-.0834	.08761	.607	-.2890	.1222
		3	-.1989	.08761	.060	-.4045	.0067
	2	1	.0834	.08761	.607	-.1222	.2890
		3	-.1155	.08761	.385	-.3211	.0901

	3	1	.1989	.08761	.060	-.0067	.4045
		2	.1155	.08761	.385	-.0901	.3211
NH4	1	2	-.0378	.12039	.947	-.3203	.2448
		3	-.4734(*)	.12039	.000	-.7559	-.1909
	2	1	.0378	.12039	.947	-.2448	.3203
		3	-.4357(*)	.12039	.001	-.7182	-.1532
	3	1	.4734(*)	.12039	.000	.1909	.7559
		2	.4357(*)	.12039	.001	.1532	.7182
H20	1	2	.0010	.01490	.997	-.0339	.0360
		3	-.0229	.01490	.275	-.0578	.0121
	2	1	-.0010	.01490	.997	-.0360	.0339
		3	-.0239	.01490	.245	-.0588	.0111
	3	1	.0229	.01490	.275	-.0121	.0578
		2	.0239	.01490	.245	-.0111	.0588
Root Growth	1	2	-.1079	.12136	.647	-.3927	.1768
		3	.1298	.12136	.533	-.1550	.4145
	2	1	.1079	.12136	.647	-.1768	.3927
		3	.2377	.12136	.123	-.0471	.5225
	3	1	-.1298	.12136	.533	-.4145	.1550
		2	-.2377	.12136	.123	-.5225	.0471
PO4	1	2	.0880	.14114	.807	-.2432	.4192
		3	-.4663(*)	.14114	.003	-.7975	-.1351
	2	1	-.0880	.14114	.807	-.4192	.2432
		3	-.5542(*)	.14114	.000	-.8854	-.2231
	3	1	.4663(*)	.14114	.003	.1351	.7975
		2	.5542(*)	.14114	.000	.2231	.8854
SO4	1	2	.0686	.04892	.339	-.0461	.1834
		3	.1248(*)	.04892	.029	.0100	.2396
	2	1	-.0686	.04892	.339	-.1834	.0461
		3	.0562	.04892	.484	-.0586	.1710
	3	1	-.1248(*)	.04892	.029	-.2396	-.0100
		2	-.0562	.04892	.484	-.1710	.0586
CL	1	2	.0228	.02011	.492	-.0243	.0700
		3	-.1059(*)	.02011	.000	-.1531	-.0587
	2	1	-.0228	.02011	.492	-.0700	.0243
		3	-.1287(*)	.02011	.000	-.1759	-.0815
	3	1	.1059(*)	.02011	.000	.0587	.1531
		2	.1287(*)	.02011	.000	.0815	.1759
EOYB	1	2	-.0051	.01594	.944	-.0425	.0323
		3	-.0788(*)	.01594	.000	-.1162	-.0414
	2	1	.0051	.01594	.944	-.0323	.0425
		3	-.0736(*)	.01594	.000	-.1110	-.0362
	3	1	.0788(*)	.01594	.000	.0414	.1162
		2	.0736(*)	.01594	.000	.0362	.1110
SO:CL	1	2	.0458	.04664	.588	-.0637	.1553
		3	.2307(*)	.04664	.000	.1213	.3402
	2	1	-.0458	.04664	.588	-.1553	.0637

		3	.1849(*)	.04664	.000	.0755	.2944
	3	1	-.2307(*)	.04664	.000	-.3402	-.1213
		2	-.1849(*)	.04664	.000	-.2944	-.0755
S:FE	1	2	-.0986	.11033	.644	-.3575	.1603
		3	-.1302	.11033	.465	-.3891	.1287
	2	1	.0986	.11033	.644	-.1603	.3575
		3	-.0316	.11033	.956	-.2905	.2273
	3	1	.1302	.11033	.465	-.1287	.3891
		2	.0316	.11033	.956	-.2273	.2905
f ^{35}S	1	2	-.0772	.07101	.522	-.2438	.0895
		3	-.5908(*)	.07101	.000	-.7574	-.4242
	2	1	.0772	.07101	.522	-.0895	.2438
		3	-.5136(*)	.07101	.000	-.6803	-.3470
	3	1	.5908(*)	.07101	.000	.4242	.7574
		2	.5136(*)	.07101	.000	.3470	.6803
C:N	1	2	-.8038 (*)	.2271	.001	-1.3367	-.2709
		3	1.5082 (*)	.2271	.000	.9753	2.0412
	2	1	.8038 (*)	.22701	.001	.2709	1.3367
		3	2.3120 (*)	.22701	.000	1.7791	2.8449
	3	1	-1.5082 (*)	.2271	.000	-2.041	-.9753
		2	-2.3120 (*)	.22701	.000	-2.8449	-1.7791
Decomp	1	2	8.5779(*)	1.1719	.000	5.8276	11.328
		3	-23.0194 (*)	1.1720	.000	-25.769	-20.27
	2	1	-8.5779(*)	1.1720	.000	-11.328	-5.828
		3	-31.5973(*)	1.1720	.000	-34.347	-28.847
	3	1	23.0194(*)	1.1720	.000	20.269	25.770
		2	31.5973(*)	1.1720	.000	28.847	34.348
Bulk Density	1	2	-.0090	.0328	.959	-.0859	.0679
		3	.0310	.0328	.611	-.0459	.1078
	2	1	.0090	.0328	.959	-.0679	.0859
		3	.0400	.0328	.441	-.0369	.1169
	3	1	-.0310	.0328	.611	-.1078	.0459
		2	-.0400	.0328	.441	-.1169	.0369
DELTA34S	1	2	2.975(*)	.5313	.000	1.728	4.222
		3	1.700(*)	.5313	.004	.453	2.947
	2	1	-2.975(*)	.5313	.000	-4.222	-1.728
		3	-1.275(*)	.5313	.044	-2.522	-.028
	3	1	-1.700(*)	.5313	.004	-2.947	-.453
		2	1.275(*)	.5313	.044	.028	2.522
HEIGHT	1	2	2.3934 (*)	.3128	.000	1.659	3.1274
		3	2.2643 (*)	.3128	.000	1.5303	2.9983
	2	1	-2.3934 (*)	.3128	.000	-3.1274	-1.6594
		3	-.1291	.3128	.910	-.8631	.6049
	3	1	-2.2643 (*)	.3128	.000	-2.9983	-1.5303
		2	.1291	.3128	.910	-.6049	.8631
DENSITY	1	2	-213.09(*)	56.227	.000	-345.04	-81.14
		3	-592.24(*)	56.227	.000	-724.19	-460.30

	2	1	213.09(*)	56.227	.000	81.14	345.04
		3	-379.15(*)	56.227	.000	-511.10	-247.21
	3	1	592.24(*)	56.227	.000	460.30	724.19
		2	379.15(*)	56.227	.000	247.21	511.10
OM	1	2	2.5770	1.4931	.196	-.9268	6.0807
		3	-.4703	1.4931	.947	-3.9740	3.0334
	2	1	-2.5770	1.4931	.196	-6.0807	.9268
		3	-3.0472	1.4931	.103	-6.5510	.4565
	3	1	.4703	1.4931	.947	-3.0335	3.9740
		2	3.0472	1.4931	.103	-.4565	6.5510
SAND	1	2	.000	.3670	1.000	-.861	.861
		3	.000	.3670	1.000	-.861	.861
	2	1	.000	.3670	1.000	-.861	.861
		3	.000	.3670	1.000	-.861	.861
	3	1	.000	.3670	1.000	-.861	.861
		2	.000	.3670	1.000	-.861	.861
SILT	1	2	.000	.4003	1.000	-.939	.939
		3	.000	.4003	1.000	-.939	.939
	2	1	.000	.4003	1.000	-.939	.939
		3	.000	.4003	1.000	-.939	.939
	3	1	.000	.4003	1.000	-.939	.939
		2	.000	.4003	1.000	-.939	.939
CLAY	1	2	.00	.502	1.000	-1.18	1.18
		3	.00	.502	1.000	-1.18	1.18
	2	1	.00	.502	1.000	-1.18	1.18
		3	.00	.502	1.000	-1.18	1.18
	3	1	.00	.502	1.000	-1.18	1.18
		2	.00	.502	1.000	-1.18	1.18
PH	1	2	-.060	.0673	.643	-.218	.098
		3	.143	.0673	.086	-.015	.301
	2	1	.060	.0673	.643	-.098	.218
		3	.203(*)	.0673	.007	.045	.361
	3	1	-.143	.0673	.086	-.301	.015
		2	-.203(*)	.0673	.007	-.361	-.045
PtEP	1	2	-42.4440 (*)	8.9634	.000	-63.478	-21.410
		3	-53.5387(*)	8.9634	.000	-74.573	-32.505
	2	1	42.4440 (*)	8.9634	.000	21.410	63.478
		3	-11.0947	8.9634	.431	-32.128	9.9393
	3	1	53.5387(*)	8.9634	.000	32.504	74.572
		2	11.0947	8.9634	.431	-9.9393	32.128

Based on observed means.

* The mean difference is significant at the .05 level.

Appendix G. MANOVA Output for Six Regional Marshes

Multivariate Tests(c)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.999	4763.503(a)	20.000	83.000	.000
	Wilks' Lambda	.001	4763.503(a)	20.000	83.000	.000
	Hotelling's Trace	1147.832	4763.503(a)	20.000	83.000	.000
	Roy's Largest Root	1147.832	4763.503(a)	20.000	83.000	.000
CRABS	Pillai's Trace	.838	21.536(a)	20.000	83.000	.000
	Wilks' Lambda	.162	21.536(a)	20.000	83.000	.000
	Hotelling's Trace	5.189	21.536(a)	20.000	83.000	.000
	Roy's Largest Root	5.189	21.536(a)	20.000	83.000	.000
LOCATION	Pillai's Trace	1.573	15.484	40.000	168.000	.000
	Wilks' Lambda	.032	19.019(a)	40.000	166.000	.000
	Hotelling's Trace	11.301	23.167	40.000	164.000	.000
	Roy's Largest Root	9.264	38.910(b)	20.000	84.000	.000
CRABS * LOCATION	Pillai's Trace	1.537	13.935	40.000	168.000	.000
	Wilks' Lambda	.047	14.977(a)	40.000	166.000	.000
	Hotelling's Trace	7.839	16.069	40.000	164.000	.000
	Roy's Largest Root	5.639	23.685(b)	20.000	84.000	.000

a Exact statistic
b The statistic is an upper bound on F that yields a lower bound on the significance level.
c Design: Intercept+CRABS+LOCATION+CRABS * LOCATION

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	PtEP	819887.962(a)	5	163977.592	16.339	.000
	pH	37.851(b)	5	7.570	8.136	.000
	FE2	498659.984(c)	5	99731.997	5.742	.000
	TD Fe	87046.558(d)	5	17409.312	4.092	.002
	SAND	15004.462(e)	5	3000.892	20.337	.000
	SILT	8588.073(f)	5	1717.615	11.816	.000
	CLAY	6860.389(g)	5	1372.078	37.004	.000
	SRR	58205916.534(h)	5	11641183.307	3.142	.011
	S2	52149.560(i)	5	10429.912	2.376	.044
	NH4	5606.683(j)	5	1121.337	1.134	.347
	H20	40637.750(k)	5	8127.550	96.137	.000
	OM	25436.981(l)	5	5087.396	195.375	.000
	Root growth	16728656.267(m)	5	3345731.253	18.625	.000
	PO43	387.336(n)	5	77.467	9.391	.000
	SO4	18733955382.367(o)	5	3746791076.473	4.003	.002

	CL	2655339019.140(p)	5	531067803.828	4.733	.001
	EOYB	742010.180(q)	5	148402.036	24.582	.000
	SO4:CL	7.224(r)	5	1.445	4.606	.001
	S:FE	2474.565(s)	5	494.913	2.789	.021
	Bulk Density	13.921(t)	5	2.784	80.743	.000
	f ^{35}S	.001(u)	5	.000	1.679	.146
Intercept	PtEP	3582201.449	1	3582201.449	356.941	.000
	pH	6351.243	1	6351.243	6825.800	.000
	FE2	830718.467	1	830718.467	47.826	.000
	TD Fe	681777.190	1	681777.190	160.260	.000
	SAND	112550.401	1	112550.401	762.745	.000
	SILT	184298.435	1	184298.435	1267.888	.000
	CLAY	75320.183	1	75320.183	2031.325	.000
	SRR	76841240.816	1	76841240.816	20.741	.000
	S2	79524.521	1	79524.521	18.117	.000
	NH4	46764.261	1	46764.261	47.280	.000
	H20	340460.784	1	340460.784	4027.139	.000
	OM	40145.798	1	40145.798	1541.751	.000
	Root growth	29086576.667	1	29086576.667	161.923	.000
	PO43	385.031	1	385.031	46.676	.000
	SO4	236967532340.053	1	236967532340.0	253.174	.000
	CL	192187194202.340	1	192187194202.3	1712.682	.000
	EOYB	9805434.914	1	9805434.914	1624.236	.000
	SO4:CL	117.800	1	117.800	375.487	.000
	S:FE	1733.834	1	1733.834	9.771	.002
	Bulk Density	32.599	1	32.599	945.388	.000
	f ^{35}S	.003	1	.003	39.650	.000
CRABS	PtEP	34467.480	1	34467.480	3.434	.067
	pH	1.183	1	1.183	1.271	.262
	FE2	36738.459	1	36738.459	2.115	.149
	TD Fe	1438.686	1	1438.686	.338	.562
	SAND	1388.910	1	1388.910	9.413	.003
	SILT	445.800	1	445.800	3.067	.083
	CLAY	3408.467	1	3408.467	91.924	.000
	SRR	5129138.279	1	5129138.279	1.384	.242
	S2	5920.632	1	5920.632	1.349	.248
	NH4	1534.394	1	1534.394	1.551	.216
	H20	1801.121	1	1801.121	21.305	.000
	OM	4582.896	1	4582.896	176.001	.000
	Root growth	1293797.505	1	1293797.505	7.202	.008
	PO43	112.686	1	112.686	13.661	.000
	SO4	1288390356.750	1	1288390356.750	1.377	.243

	CL	746720624.452	1	746720624.452	6.654	.011
	EOYB	175885.653	1	175885.653	29.135	.000
	SO4:CL	.005	1	.005	.016	.899
	S:FE	491.142	1	491.142	2.768	.099
	Bulk Density	.095	1	.095	2.758	.100
	f ^{35}S	6.997E-06	1	6.997E-06	.090	.764
LOCATION	PtEP	543299.903	2	271649.951	27.068	.000
	pH	12.134	2	6.067	6.520	.002
	FE2	184647.969	2	92323.984	5.315	.006
	TD Fe	67559.559	2	33779.779	7.940	.001
	SAND	3058.796	2	1529.398	10.365	.000
	SILT	4010.162	2	2005.081	13.794	.000
	CLAY	1201.573	2	600.787	16.203	.000
	SRR	36340676.256	2	18170338.128	4.905	.009
	S2	32132.688	2	16066.344	3.660	.029
	NH4	2227.548	2	1113.774	1.126	.328
	H20	33363.292	2	16681.646	197.319	.000
	OM	11707.102	2	5853.551	224.799	.000
	Root growth	1824850.043	2	912425.021	5.079	.008
	PO43	104.981	2	52.491	6.363	.002
	SO4	2325120973.522	2	1162560486.761	1.242	.293
	CL	707243023.414	2	353621511.707	3.151	.047
	EOYB	266570.423	2	133285.212	22.078	.000
	SO4:CL	3.635	2	1.817	5.793	.004
	S:FE	874.501	2	437.251	2.464	.090
	Bulk Density	11.993	2	5.997	173.903	.000
	f ^{35}S	.001	2	.000	3.407	.037
CRABS * LOCATION	PtEP	242120.579	2	121060.289	12.063	.000
	pH	24.535	2	12.267	13.184	.000
	FE2	277273.556	2	138636.778	7.982	.001
	TD Fe	18048.314	2	9024.157	2.121	.125
	SAND	10556.756	2	5278.378	35.771	.000
	SILT	4132.111	2	2066.055	14.214	.000
	CLAY	2250.349	2	1125.175	30.345	.000
	SRR	16736101.999	2	8368051.000	2.259	.110
	S2	14096.240	2	7048.120	1.606	.206
	NH4	1844.740	2	922.370	.933	.397
	H20	5473.336	2	2736.668	32.371	.000
	OM	9146.983	2	4573.491	175.639	.000
	Root growth	13610008.719	2	6805004.359	37.883	.000
	PO43	169.669	2	84.834	10.284	.000
	SO4	15120444052.095	2	7560222026.047	8.077	.001

	CL	1201375371.275	2	600687685.637	5.353	.006
	EOYB	299554.103	2	149777.052	24.810	.000
	SO4:CL	3.584	2	1.792	5.713	.004
	S:FE	1108.922	2	554.461	3.125	.048
	Bulk Density	1.833	2	.916	26.574	.000
	f ^{35}S	.000	2	5.770E-05	.745	.477
Error	PtEP	1023654.785	102	10035.831		
	pH	94.909	102	.930		
	FE2	1771701.258	102	17369.620		
	TD Fe	433927.437	102	4254.191		
	SAND	15051.089	102	147.560		
	SILT	14826.583	102	145.359		
	CLAY	3782.092	102	37.079		
	SRR	377881057.091	102	3704716.246		
	S2	447732.045	102	4389.530		
	NH4	100887.188	102	989.090		
	H20	8623.244	102	84.542		
	OM	2655.988	102	26.039		
	Root growth	18322483.795	102	179632.194		
	PO43	841.401	102	8.249		
	SO4	95470601891.200	102	935986293.051		
	CL	11445842752.526	102	112214144.633		
	EOYB	615769.062	102	6036.952		
	SO4:CL	32.000	102	.314		
	S:FE	18099.032	102	177.441		
	Bulk Density	3.517	102	.034		
	f ^{35}S	.008	102	7.743E-05		
Total	PtEP	5425744.196	108			
	pH	6484.003	108			
	FE2	3101079.709	108			
	TD Fe	1202751.185	108			
	SAND	142605.952	108			
	SILT	207713.091	108			
	CLAY	85962.663	108			
	SRR	512928214.442	108			
	S2	579406.126	108			
	NH4	153258.131	108			
	H20	389721.778	108			
	OM	68238.767	108			
	Root growth	64137716.729	108			
	PO43	1613.768	108			
	SO4	351172089613.620	108			

	CL	206288375974.007	108			
	EOYB	11163214.157	108			
	SO4:CL	157.024	108			
	S:FE	22307.431	108			
	Bulk Density	50.037	108			
	f ^{35}S	.012	108			
Corrected Total	PtEP	1843542.747	107			
	pH	132.760	107			
	FE2	2270361.242	107			
	TD Fe	520973.995	107			
	SAND	30055.551	107			
	SILT	23414.656	107			
	CLAY	10642.481	107			
	SRR	436086973.625	107			
	S2	499881.605	107			
	NH4	106493.871	107			
	H20	49260.994	107			
	OM	28092.969	107			
	Root growth	35051140.062	107			
	PO43	1228.737	107			
	SO4	114204557273.567	107			
	CL	14101181771.666	107			
	EOYB	1357779.243	107			
	SO4:CL	39.224	107			
	S:FE	20573.597	107			
	Bulk Density	17.438	107			
	f ^{35}S	.009	107			

a R Squared = .445 (Adjusted R Squared = .418)
b R Squared = .285 (Adjusted R Squared = .250)
c R Squared = .220 (Adjusted R Squared = .181)
d R Squared = .167 (Adjusted R Squared = .126)
e R Squared = .499 (Adjusted R Squared = .475)
f R Squared = .367 (Adjusted R Squared = .336)
g R Squared = .645 (Adjusted R Squared = .627)
h R Squared = .133 (Adjusted R Squared = .091)
i R Squared = .104 (Adjusted R Squared = .060)
j R Squared = .053 (Adjusted R Squared = .006)
k R Squared = .825 (Adjusted R Squared = .816)
l R Squared = .905 (Adjusted R Squared = .901)
m R Squared = .477 (Adjusted R Squared = .452)
n R Squared = .315 (Adjusted R Squared = .282)
o R Squared = .164 (Adjusted R Squared = .123)
p R Squared = .188 (Adjusted R Squared = .149)
q R Squared = .546 (Adjusted R Squared = .524)
r R Squared = .184 (Adjusted R Squared = .144)
s R Squared = .120 (Adjusted R Squared = .077)
t R Squared = .798 (Adjusted R Squared = .788)
u R Squared = .076 (Adjusted R Squared = .031)

Appendix H. Pearson's Correlation Matrix of LPC and UPC Data

		PtEP	Fe2+	Sand	Clay	SRR	S2-	NH4+	%H20	%OM	Root Gr.	PO43-	SO4	Cl-	EOYB	δ34S	Decomp	C:N
PtEP	Pearson Correlation	1	-.038	-.035	.015	.003	.171*	-.024	.000	.022	-.013	-.056	-.039	.022	.071*	.036	.044	-.055
	Sig. (2-tailed)	.	.190	.222	.608	.911	.000	.407	.996	.454	.646	.054	.178	.447	.014	.219	.128	.060
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
Fe2+	Pearson Correlation	-.038	1	-.082*	.120*	.019	-.044	-.086*	.215*	.209*	.006	-.077*	.069*	-.039	.136*	.150*	.036	.038
	Sig. (2-tailed)	.190	.	.005	.000	.522	.130	.003	.000	.000	.838	.008	.018	.185	.000	.000	.219	.189
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
Sand	Pearson Correlation	-.035	-.082*	1	-.614*	.038	-.015	.227*	-.079*	-.181*	.017	-.027	.010	.016	-.509*	-.569*	.108*	-.440*
	Sig. (2-tailed)	.222	.005	.	.000	.192	.596	.000	.007	.000	.561	.359	.720	.577	.000	.000	.000	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
Clay	Pearson Correlation	.015	.120*	-.614*	1	.006	-.082*	-.165*	.437*	.600*	.060*	-.082*	.147*	.041	.458*	.512*	-.097*	.396*
	Sig. (2-tailed)	.608	.000	.000	.	.847	.005	.000	.000	.000	.040	.005	.000	.155	.000	.000	.001	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
SRR	Pearson Correlation	.003	.019	.038	.006	1	.031	.057*	.070*	.047	.063*	.037	.099*	.162*	.027	.062*	.022	-.053
	Sig. (2-tailed)	.911	.522	.192	.847	.	.284	.050	.016	.114	.030	.201	.001	.000	.347	.033	.439	.070
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
S2-	Pearson Correlation	.171*	-.044	-.015	-.082*	.031	1	-.184*	-.179*	-.180*	-.050	.234*	-.006	.049	.008	-.066*	.147*	-.136*
	Sig. (2-tailed)	.000	.130	.596	.005	.284	.	.000	.000	.000	.088	.000	.825	.091	.779	.022	.000	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188

NH4+	Pearson Correlation	-.024	-.086*	.227*	-.165*	.057*	-.184*	1	-.004	-.043	.027	-.103*	.178*	.119*	-.117*	-.080*	.182*	-.276*
	Sig. (2-tailed)	.407	.003	.000	.000	.050	.000	.	.878	.144	.348	.000	.000	.000	.000	.006	.000	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
H20	Pearson Correlation	.000	.215*	-.079*	.437*	.070*	-.179*	-.004	1	.911*	.150*	-.116*	.335*	.173*	.470*	.450*	-.085*	.391*
	Sig. (2-tailed)	.996	.000	.007	.000	.016	.000	.878	.	.000	.000	.000	.000	.000	.000	.000	.003	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
%OM	Pearson Correlation	.022	.209*	-.181*	.600*	.047	-.180*	-.043	.911*	1	.161*	-.122*	.311*	.104*	.546*	.560*	-.085*	.409*
	Sig. (2-tailed)	.454	.000	.000	.000	.114	.000	.144	.000	.	.000	.000	.000	.000	.000	.000	.004	.000
	N	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
Root Growth	Pearson Correlation	-.013	.006	.017	.060*	.063*	-.050	.027	.150*	.161*	1	-.006	.076*	.022	.035	.075*	-.158*	.204*
	Sig. (2-tailed)	.646	.838	.561	.040	.030	.088	.348	.000	.000	.	.831	.009	.450	.232	.010	.000	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
PO43-	Pearson Correlation	-.056	-.077*	-.027	-.082*	.037	.234*	-.103*	-.116*	-.122*	-.006	1	-.213*	.197*	-.103*	-.143	.057*	-.085
	Sig. (2-tailed)	.054	.008	.359	.005	.201	.000	.000	.000	.000	.831	.	.000	.000	.000	.000	.048	.004
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
SO4	Pearson Correlation	-.039	.069*	.010	.147*	.099*	-.006	.178*	.335*	.311*	.076*	-.213*	1	.485*	.319*	.343	-.081*	.175
	Sig. (2-tailed)	.178	.018	.720	.000	.001	.825	.000	.000	.000	.009	.000	.	.000	.000	.000	.005	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
Cl-	Pearson Correlation	.022	-.039	.016	.041	.162*	.049	.119*	.173*	.104*	.022	.197*	.485*	1	.239*	.187	.089*	-.010
	Sig. (2-tailed)	.447	.185	.577	.155	.000	.091	.000	.000	.000	.450	.000	.000	.	.000	.000	.002	.727
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
EOYB	Pearson Correlation	.071*	.136*	-.509*	.458*	.027	.008	-.117*	.470*	.546*	.035	-.103*	.319*	.239*	1	.732	.018	.430
	Sig. (2-tailed)	.014	.000	.000	.000	.347	.779	.000	.000	.000	.232	.000	.000	.000	.	.000	.536	.000

	tailed)																	
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
δ34S	Pearson Correlation	.036	.150*	-.569*	.512*	.062*	-.066*	-.080*	.450*	.560*	.075*	-.143*	.343*	.187*	.732*	1	-.181*	.350
	Sig. (2-tailed)	.219	.000	.000	.000	.033	.022	.006	.000	.000	.010	.000	.000	.000	.000	.	.000	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
Decomp	Pearson Correlation	.044	.036	.108*	-.097*	.022	.147*	.182*	-.085*	-.085*	-.158*	.057*	-.081*	.089*	.018	-.181	1	-.277
	Sig. (2-tailed)	.128	.219	.000	.001	.439	.000	.000	.003	.004	.000	.048	.005	.002	.536	.000	.	.000
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188
C:N	Pearson Correlation	-.055	.038	-.440*	.396*	-.053	-.136*	-.276*	.391*	.409*	.204*	-.085*	.175*	-.010	.430*	.350	-.277	1
	Sig. (2-tailed)	.060	.189	.000	.000	.070	.000	.000	.000	.000	.000	.004	.000	.727	.000	.000	.000	.
	N	1188	1188	1188	1188	1188	1188	1188	1188	1130	1188	1188	1188	1188	1188	1188	1188	1188

* Correlation is significant at the 0.05 level (2-tailed).