ABSTRACT

Freese, Robert Carl. Soil Development in Created Salt Marshes, Its Spatial Patterns, and Implications for Subsurface Water Flow. (Under the direction of Stephen W. Broome).

We examined soil development trends in a 28-year chronosequence of created salt marshes. Our objective was to determine whether created marshes reach ecological equivalence with natural marshes. Therefore, we studied soil properties that are likely indicators for ecological function. Marsh age is a good predictor of soil carbon and nitrogen levels, bulk density, macro-organic matter dry weight and nitrogen content of the 0 to 10 cm soil depth. Levels equivalent to the average natural marsh are predicted to occur within 22 years. Soil textural changes occur more slowly and are less closely predicted by marsh age. The 10 to 30 cm soil depth of created marshes does not change much with time and does not become equivalent to natural marshes within the time frame of this study.

We examined spatial patterns by comparing soil properties 1 m inland from the marsh edge with soil properties 15 m inland. There were no significant differences in the 4-year old marsh but the 11- and 29-year old marshes had higher levels of soil carbon and nitrogen, silt, clay, porosity at the 1 m position than at the 15 m position. Geomorphologic characteristics of created marshes appear to account for this trend. The 29-year old marsh has a gradient in soil morphology and classification from a weakly developed Typic Psammaquent soil 30 m from marsh edge to a Mollic Psammaquent at 15 m to a Mollic Endoaquent at 1 m. Reshaping created marshes to more closely resemble natural marshes would likely enhance soil development and ecological function of the inland part of these marshes.

Water tables and hydraulic properties of created marshes were studied to determine if there was greater flushing of nutrients from the soils of created marshes relative to natural

marshes. The amplitude of a tidal cycle relative to marsh elevation affects the hydraulic gradients and soil water flux across the marsh. Water tables in salt marshes contiguous with upland areas have higher flux than in marshes without associated uplands due to fresh water recharge. At low tensions, a larger volume of water is released from the soil of a natural marsh relative to a 4-year old created marsh. The highest levels of discharge and nutrient export occurred from the edge of the natural marsh.

SOIL DEVELOPMENT IN CREATED SALT MARSHES, ITS SPATIAL PATTERNS,

AND IMPLICATIONS FOR SUBSURFACE WATER FLOW

by

Robert C. Freese

A dissertation submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

DEPARTMENT OF SOIL SCIENCE

RALEIGH

2003

APPROVED BY:

Aziz Amoozegar	Theodore H. Shear
Michael J. Vepraskas	Stephen W. Broome (Chairman of Advisory Committee)

BIOGRAPHY

I was born in Worcester, Massachusetts on August 26, 1962. After high school, I vowed never to take another math or science class again. So as an undergraduate, I devoted myself to the study of humanities and social sciences and earned a Bachelor of Arts degree from Vassar College with a major in Anthropology. After living in New York City for several months, I longed to be outdoors and to understand the natural world better. Soil had long intrigued me for its ability to sustain life and human society and it seemed like a worthy subject of study. So in 1985, I moved to North Carolina, took classes and worked in various jobs until I was admitted to the Masters program in Soil Science at N.C. State University. There I studied the effects of tillage methods on infiltration and related soil physical properties. Afterwards, I mapped soil with SCS (now NRCS), mostly in the Piedmont and Coastal Plain of North Carolina. The patterns of soil on the landscape fascinated me for their effects on vegetation and land use and I found that work very satisfying and enjoyable. However, I wanted to see more of the world and to put my knowledge to greater use. So I volunteered with the U.S. Peace Corps in Thailand and worked as a Soil Conservation Extension Agent, an experience both satisfying and frustrating. I returned to work as a Soil Survey Project Leader in Duplin County, NC. Delineation of wetlands became a large part of my job and wetland restoration appealed to my desire to create a more harmonious relationship between our society and the natural world. I returned to graduate school in Soil Science at NCSU in 1998 but this time with a focus on salt marsh restoration under the direction of Dr. Stephen Broome. Upon completion of my Ph.D., I accepted a position with A.F. Clewell, Inc. restoring mined phosphate land in the Tampa, FL area.

ACKNOWLEDGEMENTS

I'd like to thank the chairman of my program committee, Dr. Stephen Broome, for his support in this project and for his patience in allowing me the time and freedom to explore the many intriguing aspects of salt marsh ecology, regardless of whether they were directly useful to me. It has been a satisfying process! I'd like to thank Dr. Ted Shear for inspiring me to pursue a career in restoration ecology, for his advice and input at various points in my program, and for his ability to see implications beyond a narrow frame of study. Dr. Michael Vepraskas has inspired me with his willingness to speak his mind and argue with others when it's something important. His advice on organization and interpretation of data were helpful in framing my study. Dr. Aziz Amoozegar has inspired me with his thorough, meticulous analysis of soil physical processes and he has helped me at several points in my handling of hydrologic data.

I'd like to thank Dr. Chris Craft for securing funding for this project and for his advice and encouragement over the past four years. Roberta Miller-Haraway helped me become computer literate and her help was essential in preparing many of my graphics. Dr. Marcia Gumpertz has been very helpful and patient with my many questions on statistical analysis and interpretation. Carleton Campbell was of great help in collection of field data and operation of the boat. I'd like to thank Andy Knapp, Ross Andrews, Eric Severson for their labor in the field, their companionship, and for reminding me not to take anything too seriously.

This research was supported by a grant from the U.S. Environmental Protection Agency's Science To Achieve Results (STAR) program through grant #8261111-01-0. Although the reseach described in this document has been funded wholly or in part by the

U.S. Environmental Protection Agency's Science To Achieve Results (STAR) program through grant #8261111-01-0, it has not been subjected to any EPA review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

TABLE OF CONTENTS **page**

LIST OF TABLES **page**

LIST OF FIGURES

Chapter 1. SOIL DEVELOPMENT IN A CHRONOSEQUENCE OF CREATED SALT MARSHES

ABSTRACT

Impacts to salt marsh wetlands are mitigated by creation of new salt marshes, often on sandy dredged material that lacks the characteristics of natural marsh soils. Soil indicators can be used to assess development of ecological functions in created marshes. We use a chronosequence of 10 created marshes from the North Carolina coast to examine long-term (28 year) trends in soil carbon, nitrogen and phosphorous pools, bulk density, particle size distribution and macro-organic matter (MOM) dry weight, N and P content, and carbon/nitrogen ratio. We use the following three statistical approaches to compare the soils of created and natural marshes and to thereby estimate time to equivalence with natural marshes: 1) paired t-tests, 2) contrasts of values predicted for created marshes of various ages vs. values for the average natural marsh, and 3) a bioequivalence test. Most properties in the 0-10 cm soil layer develop along clear trajectories toward convergence with the average natural marsh, particularly with respect to soil C, N, bulk density, MOM-N content and MOM dry weight. These properties become equivalent to those of the average natural marsh by 22 years. In contrast, trends in soil development of the 10-30 cm layer are generally weak and do not converge with the average natural marsh soil. However, since most functions involve biological activity, which is concentrated in the 0-10 cm layer, persistent soil differences in the 10-30 cm layer do not indicate impaired ecological function.

INTRODUCTION

Coastal salt marsh wetlands are valuable because they stabilize shorelines, provide wildlife habitat, and are used by commercially important fish. Ecological functions are processes that characterize and sustain an ecosystem. Some important salt marsh functions are high levels of primary and secondary production, sediment and nutrient accumulation, and biogeochemical transformations such as denitrification and sulfate reduction (Mitsch and Gosselink, 1993; Vernberg, 1993). These functions can contribute to the health of the larger estuarine ecosystem. Thus, when salt marshes are disrupted by road construction and other forms of development, there is a loss of function that potentially has wide impacts. Direct impacts to marshes are often mitigated by creation of new wetlands (Broome et al., 1988). However, it is unclear whether created marshes develop the full range of functions of natural marshes and what time scale is necessary for functional equivalency to occur.

Ecosystem development in created marshes is essentially a case of primary succession, a process generally limited by the absence of soil (Bradshaw, 1983). Created marshes in North Carolina are often established on dredged material which is a dense substrate that lacks the organic matter, silt, clay, nutrients and biological activity characteristic of natural marsh soils (Lindau and Hossner, 1981; Craft et al., 1988). Marsh soils develop by accretion of sediment and in situ biomass and thereby maintain their elevation as sea levels rise (Frey and Basan, 1978). Soil and ecological functions develop in tandem. For example, a dense plant canopy of *Spartina alterniflora* Loisel forms in as few as 3-5 years (Broome et al., 1986). The stems trap fine sediment (Gleason et al., 1979) and the roots add organic matter to the soil. These inputs increase the capacity of the soil to retain nutrients. It is likely that increased availability of soil nutrients also increases nutrient levels of the root-rhizome mat. This material is sometimes referred to as macro-organic matter (MOM). The MOM nutrient content in created salt marshes of North Carolina has been estimated comparable to natural marshes after 15 years (Craft et al., 1988) while total soil C, N, and P pools of these marshes develop more slowly. By contrast, soils of created salt marshes in southern California show little development 11 years after marsh creation (Zedler and Calloway, 1999) and are highly nitrogen deficient (Langis et al., 1991).

Soil invertebrates (infauna) are a particularly crucial aspect of marsh function because they sustain fish and shorebird populations. Development of the infaunal community in created marshes also follows a sequence related to soil formation. Invertebrate communities in newly created marshes have low densities composed mainly of surface dwelling organisms (Moy and Levin, 1991; Levin et al.,1996). However, the community becomes more abundant and diverse as soil detrital sources become available. This is demonstrated by the close correlation of infaunal densities with soil C, N, and MOM biomass (Craft, 2000). While infaunal densities similar to natural marshes can develop in as little as 8-15 years (Craft, in review), in other cases differences persist longer (Sacco et al., 1994). Soil physical factors such as texture also influence the distribution and abundance of various taxa (Sanders, 1958, Sarda et al., 1995).

The previous discussion suggests that there are soil prerequisites for ecological functions and these relationships are summarized in Table 1. While functions refer to processes, these soil properties are structural in the sense that they are measures taken at a single point in time. The relationship between the structure and function is not necessarily linear (Zedler and Lindig-Cisneros, 2000). A further limitation to the use of soil indicators is that there are functions unrelated to soil. Nonetheless, the relationship of soil to multiple functions and the ease with which these soil properties are measured makes them potentially useful indicators (Craft, 2000). The functions of created marshes may be evaluated by tracking the development of structural soil indicators toward a target level defined by natural marsh soil. Nearby natural marshes are ideal reference sites since they are likely to have a similar tidal regime, salinity, exposure and substrate type. Selection of a nearby reference marsh can eliminate confounding factors and reveal more clearly the progress of the created marsh toward maturity.

Objectives

Our first objective is to examine trends in soil properties of created marshes as a function of time since marsh creation. These trends show whether soil properties follow trajectories as the marsh develops and indicate whether marsh age can predict soil development. In lieu of measuring soil properties at a single site over an extended period, we studied a chronosequence of several created salt marshes of various ages.

A second objective is to compare created marshes with natural marshes to determine if soil properties reach equivalence with natural marsh soils and what length of time is needed for equivalence. Reference targets are necessary to infer equivalency and we compare two such targets: 1) a series of natural marshes, each of which is paired with one nearby created marsh, and 2) a single average of all natural marshes against which all created marshes are compared. In the latter case, we use two statistical approaches to compare means of created and natural marshes: 1) a difference test involving contrasts of means, and 2) a bioequivalence test. Bioequivalence procedures are applicable to research in which the main interest is whether two means are equal instead of the magnitude and significance of their difference (Berger and Hsu, 1996). Although developed originally for use in the pharmaceutical industry, they are used in the life sciences as well (Garrett, K.A., 1997).

MATERIALS AND METHODS

We selected ten created salt marshes from the North Carolina coast (Figure 1) that varied in age but had similar physiography (Table 2). For each site, we identified the nearest natural marsh. These ten natural marshes comprised our sample of reference marshes. For most created and natural marshes, we collected ten soil cores from the 0 to30 cm layer. We sectioned each core into surface (0 to10 cm) and subsurface (10 to 30 cm) layers. The 0 to 10 cm layer contains most of the plant roots and rhizomes and represents the zone where soil forming processes are most active. The 10 to 30 cm layer represents a relatively unaltered zone of soil. After the soil was air dried and sieved to remove large (> 2 mm diameter) roots, soil carbon and nitrogen content were determined using a Perkin-Elmer CHN elemental analyzer. Soils with a high content of shell fragments were treated with dilute HCl to remove inorganic carbon. Total phosphorous was measured in perchloric acid digests (Sommers and Nelson, 1972) using the method of Murphy and Riley (1962). The soil samples were analyzed for particle size distribution by the pipette method (Gee and Bauder, 1986) and bulk density by the core method (Blake and Hartge, 1986). Analysis of the soils of two 11-year old marshes (Harkers and Sneads Ferry sites) was limited to bulk density, soil C and N content. A second set of 10 cores was collected from the other 8 marshes for analysis of MOM dry weight and MOM-C, N and P by the above listed methods. However, MOM of the 1- and 3-year old marshes was insufficient for analysis of C and N.

Statistical analysis

We used SAS software (SAS, 1990) to perform regression analysis of mean soil properties of the created marshes against marsh age. We used the student's t-test to compare the soil and MOM properties of the paired created and natural marshes. We used the contrast option for general linear models (GLM) to determine the significance of the difference between the predicted values for the created marshes and the average value for all natural marshes. Use of predicted values rather than actual values makes it possible to test differences at ages for which actual data are not available. However, this comparison is meaningful only if the soil properties are closely related to marsh age ($r^2 > 0.5$, $p < 0.05$). Those soil properties having a non-linear relationship to marsh age (soil C and N) were first log transformed in order to linearize this relationship and to stabilize variances.

Bioequivalence testing requires selection of a maximum difference from the reference that can be tolerated yet still be considered equivalent. A difference of one standard deviation from the mean of all natural marshes was arbitrarily selected as a tolerance level. While that may appear to be a short coming of the approach, the use of 95% confidence coefficients in difference testing is similarly arbitrary. This t-test procedure is one sided since deficiency of a property with respect to the reference is of concern while excess is generally not. For soil properties that increase over time to approach the average natural marsh, t-tests are constructed in the following way:

$$t = \frac{(\hat{Y}_c - \hat{Y}_n) + \delta}{S(\hat{Y}_c - \hat{Y}_n)}$$

Where: $\hat{Y}_c - \hat{Y}_n$ = estimate of difference between the created and natural marshes
δ = tolerance level
$S(\hat{Y}_c - \hat{Y}_n)$ = standard error of estimate

The estimates of difference and standard error are obtained from the estimate option in the GLM procedure and are thus based on predicted rather than actual values for a given marsh age. The hypothesis tested is: H_o: $\mu_c \leq \mu_n - \delta$ (non-equivalence) vs. H_a: $\mu_c > \mu_n - \delta$ (equivalence) where μ_c = mean for the created marsh and μ_n = mean for the natural marsh. For properties that decrease with time to approach the average natural marsh, the sign of δ is reversed. The decision criterion is to reject H_o if $t > t_{.95,\, df}$ and conclude in favor of H_a. The t-tests are conducted for different marsh ages beginning at year = 28, the age of the oldest marsh in the chronosequence and the one most likely to be equivalent. If the test does not reject H_o, then there is no basis for concluding equivalence and no further testing is necessary. If the test rejects H_o then equivalence of the created and natural marshes for that age is concluded and the test is repeated for a slightly younger marsh. By testing sequentially younger ages in two year increments we determine the youngest age for which equivalence of the created and natural marshes occurs.

RESULTS

Soil Properties

Soil organic carbon/ total nitrogen content: The trends of C and N with marsh age are similar and may be discussed together. Most N in these marshes is present in the organic form, as indicated by the close correlation of C and N ($r = 0.98$). In the 0 to10 cm layer, the increase in C and N on a weight basis with marsh age (Figure 2a, d) is highly predictable ($r^2 > 0.75$) and significant ($p < 0.05$). The relationship best fits a quadratic equation and suggests an initially slow period of increase in C and N followed by an accelerating rate after about 15 years. The initial lag in C and N accumulation may be related to the gradual development of the root-rhizome mat, a major source of C and N to marsh soils. Although C and N levels must stabilize at some point, they do not appear to do so within the time frame of this study. However, when C and N on a volume basis (0-10 cm depth) are graphed against marsh age, the regression line appears to approach and level out near the asymptote suggested by the average natural marsh (Figures 2c, f).

In the 0 to10 cm layer, t-tests of paired created and natural marshes show that those marshes aged 1 to 13 and 28 years have significantly lower C and N levels than their references. The 24- and 26-year old marshes exceed or are not significantly different from their references. Although the 28-year old marsh actually has higher C and N levels than all other created marshes, it appears deficient with respect to its reference, a marsh with high organic matter soil (Histosol). In this case, it is more instructive to compare the created marshes with the entire sample of the population of natural marshes. Contrasts of predicted values of created marshes against the average natural marsh are significant for marshes aged 1 to18 years and not significant for older marshes. The bioequivalence test concludes equivalence at 22 years (Table 3).

In the 10 to 30 cm layer, there is a moderately predictable ($0.50 \geq r^2 \geq 0.75$) and significant trend of C and N accumulation on a weight basis (Figures 2b, e) but total pools are low relative to the 0 to10 cm layer. Since there are relatively few roots at this depth, substantial C and N accumulations are unlikely to occur until accretion buries the current C and N enriched surface layer. The t-tests of paired created and natural marshes show most created marshes have significantly lower C and N levels than their references except for the 8-, 11H- and 24-years old marshes which are not significantly different. The references for these three marshes are relatively young natural marshes with a thin capping of marsh soil over the basal sand. Contrasts of predicted levels of soil N in created marshes against that of the average natural marsh are significant for all ages. Contrasts for soil C are significant for ages 1-24 and not significant for older marshes. The bioequivalence test does not reject the null hypothesis of different mean C and N levels at 28 years (Table 3).

Soil total phosphorous: In the 0 to10 cm layer, the trend of phosphorous accumulation is moderately predictable and significant when graphed on a weight basis (Figure 2g), though the relationship is absent when graphed on a volume basis (Figure 2i). The t-tests of paired created and natural marshes show that the 3- and 8-year old created marshes have significantly lower P levels than their references while the 1- and 11-28-year old marshes are not significantly different. A flock of seagulls (*Larus spp*.) commonly feeds and nests at the 1-year old marsh. The resulting guano inputs may account for the slightly elevated P levels and the lack of significant difference from the reference. Phosphorous levels for the 8-year old reference site are very high. It is adjacent to the port of Morehead City (NC), a facility which receives barges carrying processed rock phosphate. This fertilizer material may have impacted the marsh and therefore, the site is not used to estimate P levels of the average natural marsh. Contrasts are significant for marshes aged 1-18 years but not significant for older marshes. The bioequivalence test does not reject the null hypothesis of different mean P content for year 28 (Table 3).

In the 10 to 30 cm layer, soil P content is poorly related to marsh age (Figure 2h). Two likely inputs of P to created marshes are deposition of clay particles with adsorbed P and deposition of guano from birds. These materials are added to the soil surface and accumulation of P below the surface occurs only as roots decay and as infauna burrow and mix the soil. However, since most roots and infauna are concentrated in the surface 0 to 10 cm, there is little opportunity for transport of P to the 10 to 30 cm layer. The t-tests of paired created and natural marshes show that the marshes aged 13-26 years are not significantly different from their references but in general there is little pattern with age. Soil P levels at this depth are variable and probably reflect parent material differences rather than soil development processes.

Sand content: In the 0 to10 cm layer, the decrease in sand content with marsh age is moderately predictable and significant (Figure 3a). The t-tests of paired created and natural marshes show that created marshes aged 1-13 and 28 years have significantly more sand than their references while the 24- and 26- year old marshes are not significantly different or lower in sand content. Contrasts are significant for ages 1-21 years and not significant for older marshes. The bioequivalence test does not reject the null hypothesis of different mean sand content at year 28 (Table 3).

In the 10 to 30 cm layer, sand content is poorly related to created marsh age (Figure 3b). The 13-year old marsh is excluded from analysis of particle size trends at this depth since it is on a graded upland with a sandy clay loam subsurface texture. The sand content of all other created marshes is > 85%. This shows that the texture of the subsurface layer of the created marshes undergoes little change from the original parent material. The t-tests comparing the paired created and natural marshes indicate that the 1-, 3-, 11-, 26-, 28- year old marshes have significantly greater sand content than their references while the 8-, 13- and 24-year old marshes are not significantly different.

Silt content: In the 0 to 10 cm layer, silt accumulation over time in created marshes is moderately predictable and significant (Figure 3c). The t-tests of paired created and natural marshes indicate the created marshes aged 1-13 and 28 years have significantly less silt than their references while the 24- and 26-year old created marshes are not significantly different. The 28-year old marsh has the highest mean silt content of any created marsh yet it appears deficient relative to its reference, a natural marsh in the Cape Fear estuary. This river has historically carried a high silt load, however, construction of a large dam about 30 years ago has undoubtably reduced the river's silt load. Thus, potential silt accumulation in the 28-year old marsh may be limited relative to its reference. Contrasts are significant for ages 1-22 years and not significant for older marshes. The bioequivalence test does not reject the null hypothesis of different mean silt contents at year 28 (Table 3).

In the 10 to 30 cm layer, silt content is poorly related to marsh age (Figure 3d). Like soil P, silt is added only to the soil surface and accumulation at the 10-30 cm depth is unlikely to occur until accretion buries the current silt enriched surface layer. The t-tests of paired created and natural marshes show most created marshes have significantly lower silt levels than their reference marshes. However, the 8- and 24-year old marshes are not significantly different from their references.

Clay: Relative to sand and silt, clay content is weakly related to marsh age and the relationship is not significant for either depth (Figures 3e, f). In the 0 to 10 cm layer, t-tests of paired created and natural marshes show that most created marshes have significantly lower clay content than their reference marshes with the exception of the 13- and 26-year old marshes which are not significantly different and the 24-year old marsh which has higher clay content. In the 10 to 30 cm layer, most created marshes have significantly lower clay content than their references except the 8- and 24-year old marshes which are not significantly different.

Soil Bulk Density: In the 0 to 10 cm layer, the decrease in bulk density with age of the created marshes is highly predictable and significant (Figure 4a). The regression equation predicts a 0.03 g cm^{-3} decrease per year. While newly created marshes have mean bulk densities typical of upland soils (1.4 g cm^{-3}), the 26- and 28-year old marshes have mean bulk densities less than the average for all natural marshes (0.73 g cm^{-3}). Some factors likely to cause this decrease are the development of a root-rhizome mat, increases in soil organic matter and activities of large numbers of fiddler crabs, *Uca spp*. The t-tests of paired created and natural marshes show significantly higher bulk densities for created marshes aged 1-13 years. Exceptions are the Sneads Ferry and Harkers marshes (11F and 11H) which are paired to reference marshes with unusually dense substrates. Bulk densities in the 24 to 28 year old marshes are lower or not significantly different from their references. Contrasts are significant for marshes aged 1-16 years and not significant for older marshes. The bioequivalence test concludes equivalence at 18 years (Table 3).

In the 10 to 30 cm layer, the trend of decreasing bulk density (Figure 4b) is also highly predictable and significant although the rate of decrease (0.017g cm^{-3} yr^{-1}) is only half that predicted for the 0 to 10 cm layer. In general, t-tests comparing the paired created and natural marshes indicate that the soils of created marshes at the 10 to 30 cm depth remain denser than those of their reference marshes. However, due to the variability of reference marshes, the 8-, 11-(Sneads Ferry and Harkers sites) and 24-year old marshes have bulk densities not significantly different from their references. Contrasts are significant for years 1-22 and not significant for older marshes. The bioequivalence test does not reject the null hypothesis of different means (Table 3).

Macro-Organic Matter Properties

MOM dry weight: In the 0 to10 cm layer, the increase in MOM biomass with marsh age is highly predictable and significant (Figure 4c). The t-tests of paired created and natural marshes show that the 1-, 3-, 11-, and 28-year old marshes accumulate significantly less MOM than their references while the other marshes are not significantly different from (ages 8, 13 and 24 years) or exceed (age 26 years) their references. Contrasts are significant for ages 1-8 years and not significant for older marshes. The bioequivalence test concludes equivalent MOM accumulation by year 22 (Table 3).

In the 10 to 30 cm layer, the increase in MOM biomass with marsh age is also highly predictable and significant (Figure 4d). The t-tests of paired created and natural marshes show that the created marshes aged 1, 3, 11, and 13 years produce significantly less MOM than their references while those aged 8 and 24-28 years are not significantly different. Contrasts are significant for ages 1-11 years and not significant for older marshes. The bioequivalence test concludes equivalent MOM accumulation by year 26.

MOM total nitrogen: The increase in MOM-N levels with marsh age is significant and highly predictable in the 0 to 10 cm layer and moderately predictable in the 10 to 30 cm layer (Figures 5a, b). In both layers, t-tests of paired created and natural marshes show that MOM-N levels of the 8-, 11-, and 13-year old marshes are significantly lower than the references while those of the 24- to 28-year old marshes are not significantly different. Contrasts are significant for marshes aged 1-19 years (0 to 10 cm layer) or 1-20 years (10 to 30 cm layer) but non-significant for older marshes. In the 0 to 10 cm layer, the bioequivalence test does not reject the null hypothesis of different means at year 28 while in the 10 to 30 cm layer it concludes equivalence at 26 years.

MOM total phosphorous: In the 0 to 10 cm layer, the decrease in MOM-P content with age of the created marshes is moderately predictable and significant (Figure 5c). This could reflect increased availability of N in the maturing marshes which increases plant growth, thereby diluting the MOM-P concentration. It could also reflect the greater proportion of live roots in the MOM of newly created marshes relative to that of mature marshes. Live roots of some marsh plants have higher P levels than dead root material, an observation confirmed by Craft et al. (1988). MOM-P levels in the reference for the 8-year old marsh are highly elevated relative to other natural marshes possibly due to deposition of P fertilizer material from the adjacent Morehead City port. Thus, this site is not used to estimate a value for the average natural marsh. Even with this site removed, MOM-P trends relative to the average natural marsh are ambiguous. Created marshes initially appear to have higher levels than the average natural marsh but over time decline to a level lower than the reference. Natural marshes of the area may not be suitable references with respect to MOM-P, possibly due to a longer history of anthropogenic impacts. While excess N is readily removed by denitrification, excess P accumulates in marsh soils. In the 10 to 30 cm layer, MOM-P levels are not related to age of the created marshes (Figure 5d) and appear to reflect site differences rather than soil development processes. The average for the created marshes is similar to the average for the natural marshes.

Results of t-tests of paired created and natural marshes are similar for the two layers. MOM-P levels in the 8-, 13-, and 24-year old created marshes are significantly lower than their references while the 1(10 to 30 depth), 3-, 11-, 26-, and 28-year old created marshes are not significantly different. Only the 0 to 10 cm layer of the 1-year old created marsh has significantly greater MOM-P levels than its reference. Again, this may be related to heavy seagull use of this marsh.

Carbon/ Nitrogen ratio trends

MOM Carbon/ Nitrogen ratio: In the 0 to 10 cm layer, the decrease in MOM C/N with marsh age is moderately predictable but not significant (Figure 6a). The t-tests of paired created and natural marshes show that the marshes aged 8-, 11-, and 13-years have significantly higher MOM C/N levels than their references while older marshes are either not significantly different or less than their references.

Soil Carbon/Nitrogen ratio: In the 0 to 10 cm layer, mean soil C/N of the created marshes ranges from 8.9 in the 1-year old marsh to 16.9 in the 28-year old marsh (Figure 5b). Snead's Ferry marsh (11 years old) has an unusually high value of 24.5 due to the presence of woody debris, and this marsh was removed from the trend analysis. The 1- and 3-year old marshes were also removed from the trend analysis because all soil samples were at the detection limit for nitrogen and the C/N estimates were thus skewed. Even after removing these three sites from the analysis, there was little relationship between soil C/N and marsh age. This reflects the fact that carbon and nitrogen are accumulating at approximately the same rate in the soils of created marshes. The t-tests of paired marshes show that the 1-, 3-, 11-(Swansboro), 13- and 28-year created marshes have significantly lower soil C/N than their references. The 8-, 11-(Harkers), 24- and 26-year old created marshes exceed or are not significantly different than their references.

DISCUSSION

Soil development in the 0 to 10 cm layer of created marshes follows clear trajectories with time. Most soil and MOM properties approach and eventually equal the levels characteristic of natural marshes. In the 0 to 10 cm layer, age is a particularly good predictor of soil C and N, bulk density, MOM-N and biomass. In the 10-30 cm layer, trends in these properties are generally weaker but still significant. Significant trends in soil-P, sand, silt and MOM-P also occur in the 0 to 10 cm layer but not in the 10 to 30 cm layer.

These findings differ from some previous studies that indicated created marshes do not become similar to natural marshes with time. Some researchers suggest that site differences such as substrate and salinity account for more variation among created marshes than does marsh age (Moy and Levin, 1991, Sacco et al., 1994). In some cases, the short time frame hampers these studies. In other cases, there are regional differences in rates of soil development that lead Zedler and Calloway (1999) to reject the idea that soil properties of created marshes in California converge over time with those of natural marshes. On the other extreme, Lindau and Hossner (1981) predict that created marshes in Texas can develop soil properties comparable to natural marshes in just 2-5 years. Regional differences may explain why Streever (2000) did not find evidence that created marshes become similar to natural marshes with time since his study combined data sets from across a large region. Therefore, the findings of this study can be extended to regions outside the southeastern U.S. only with caution. But while rates of soil development are likely to differ between regions, the existence of trajectories on some time scale is probably constant across regions.

In some cases, the use of paired reference marshes can explain variation among created marshes. Though the soil of the Pine Knoll marsh (24 years old) appears deficient in

C, N, and silt relative to other older created marshes, it is paired with a nearby natural marsh which also fails to accumulate C, N and silt due to its exposure to frequent, high energy waves. In this case, the created marsh compares favorably with the reference. However, in another case, the Snows Cut marsh (28 years old) bears little resemblance to its reference and is actually more similar to other created marshes. Thus, the use of average values from several natural marshes can be a better reference when assessing soil development trends and predicting time to equivalence. Table 3 summarizes the results of three methods of assessing time to equivalence and lists soil/MOM properties in the approximate chronological order in which equivalence occurs. The paired t-tests provide information about specific marshes but tell us little about overall trends. Relative to the other statistical approaches, they underestimate time to equivalence for soil-P and bulk density and overestimate it for soil C and N. The use of contrasts of predicted values for the created versus the hypothetical average natural marsh provides more precise estimates of time to equivalence. The theoretical basis for bioequivalence tests is more appropriate than that of standard difference testing. Our bioequivalence test generally confirms the results of the contrasts but produces slightly more conservative estimates of time to equivalence. However, its failure to conclude equivalence in some cases is due to large standard errors for those models.

In the 0 to 10 cm layer, bulk density is the first soil property to reach equivalence and this occurs in 17-18 years. Soil nutrient pools are slower to develop. Carbon and nitrogen reach equivalence in 19-22 years. Soil P levels are more difficult to predict and are highly affected by site characteristics. Nonetheless, equivalent P levels may be predicted to occur in about 20-30 years. Soil texture changes more slowly than soil nutrient pools with sand reaching equivalence in 22-30 years and silt taking somewhat longer. In the 10 to 30 cm layer, soil properties do not change much with time. Bulk density is the only property at this depth that shows a strong trend toward convergence with natural marsh soils and equivalence may be predicted to occur in 23-30+ years. In contrast to soil properties, MOM dry weight and N content develop toward convergence with the natural marsh with similar rapidity in both the 0 to 10 and 10 to 30 cm layers. This occurs within 20-26 years.

This study confirms that total (0-30 cm) soil nutrient pools are slow to develop and are probably dependent on accretion in response to rising sea levels. However, when the 0 to 10 and 10 to 30 cm layers are considered separately, we find that soil nutrient pools of the 0 to 10 cm layer develop about as quickly as MOM dry weight and N levels. Since most functions involve the biological activity concentrated in the 0 to 10 cm soil layer, persistent differences in the soils of the 10 to 30 cm layer are not likely to affect ecological function. Indeed, if young natural marshes (references for 8-, 11H-, and 24-year marshes) are used as the standard, then it is likely that the 10 to 30 cm layer of created marshes would be equivalent.

A previous study of soil development in created marshes indicated that soil C/N ratio declines with time (Craft, 2001), however, this study finds no change in soil C/N with time. The MOM C/N ratio decreases sharply (from 80 to 50) as created marshes age. Although this trend is not significant ($p > 0.05$), it suggests that the *Spartina alterniflora* plants become less N stressed over time and that the nutritional quality of the MOM increases. Presumably, the capacity of these created marshes to sustain deposit feeding infauna increases as well.

REFERENCES

Berger, R.L. and J.C. Hsu. 1996. Bioeqivalence trials, intersection-union tests, and equivalence confidence sets. Statistical Science. 4:283-319.

Blake, G.R. and K.H. Hartge. 1986. Particle size analysis. p. 363-376. *In* A. Klute (ed.) Methods of soil analysis: physical and mineralogical methods. Agron. Monogr. 9. ASA, CSSA and SSSA, Madison, WI.

Bradshaw, A.D. 1983. The reconstruction of ecosystems. Journal of Applied Ecology. 20:1-17.

Broome, S.W., E.D. Seneca and W.W. Woodhouse, Jr. 1986. Long-term growth and development of transplants of the salt-marsh grass *Spartina alterniflora*. Estuaries 9:63-74.

Broome, S.W., E.D. Seneca and W.W. Woodhouse, Jr. 1988. Tidal salt marsh restoration. Aquatic Botany 32:1-22.

Craft, C.B. 2000. Co-development of wetland soils and benthic invertebrate communities following salt marsh creation. Wetlands Ecology and Management. 8:197-207.

Craft, C.B. 2001. Soil organic carbon, nitrogen and phosphorous as indicators of recovery in restored Spartina marshes. Ecological Restoration. 19(2):87-91.

Craft, C.B., S.W. Broome and E.D. Seneca. 1988. Nitrogen, phosphorus and organic carbon pools in natural and transplanted marsh soils. Estuaries 11:272-280.

Craft, C., P.M. Megonigal, S.W. Broome, J. Cornell, R.C. Freese, J. Stevenson, L. Zheng, J.N. Sacco. The pace to ecosystem development of constructed Spartina alterniflora marshes. Ecol. Appl.(In press).

Frey, R.W. and P.B. Basan. 1978. Coastal salt marshes. P.101-170. *In* R.A. Davis (ed.)Coastal sedimentary environments. Springer-Verlag, New York.

Garrett, K.A.. 1997. Use of statistical tests of equivalence (bioequivalence tests) in plant pathology. Phytopathology 87(4): 372-374.

Gee, G.W. and J.W.Bauder. 1986. Particle size analysis. p. 383-412. *In* A. Klute(ed.) Methods of soil analysis: physical and mineralogical methods. Agron. Monogr. 9. ASA, CSSA and SSSA, Madison, WI.

Gleason, M.L., D.A. Elmer, N.C. Pien, J.S. Fisher. 1979. Effects of stem density on sediment retention by salt marsh cord grass, *Spartina alterniflora* Loisel. Estuaries 2(4): 271-273.

Langis, R., M. Zalejko and J.B. Zedler. 1991. Nitrogen assessments in a constructed and a natural salt marsh of San Diego Bay. Ecological Applications 1:40-51.

Levin, L.A., D. Talley and G. Thayer. 1996. Succession of macrobenthos in a created salt marsh. Marine Ecology Progress 141:67-82.

Lindau, C.W. and L.R.Hossner. 1981. Substrate characterization of an experimental marsh and three natural marshes. Soil Science Society of America Proceedings 45:1171-1176.

Mitsch, W.J. and J.G. Gosselink. 1993. Wetlands. 2nd edition. Van Nostrand Reinhold, New York.

Moy, L.D. and L.A. Levin. 1991. Are *Spartina* marshes a replaceable resource? A functional approach to evaluation of marsh creation efforts. Estuaries 14(1):1-16.

Murphy, J. and J.P.Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27:31-36.

Sacco, J.N., E.D.Seneca and T.R. Wentworth. 1994. Infaunal community development of artificially established salt marshes in North Carolina. Estuaries 17(2): 489-500.

Sanders, H.L. 1958. Benthic studies in Buzzards Bay. I. Animal-sediment relationships. Limnology and Oceanography 3(3):245-258.

Sarda, R., K. Foreman and I. Valiela. 1995. Macroinfauna of a southern New England salt marsh: seasonal dynamics and production. Marine Biology 121:431-445.

SAS Institute. 1990. SAS user's guide. SAS Institute, Cary, North Carolina, USA.

Sommers, L.E. and D.W. Nelson. 1972. Determination of total phosphorous in soils: a rapid perchloric acid digestion procedure. Soil Science Society of America Proceedings 36:902-904.

Streever, W.J. 2000. *Spartina alterniflora* marshes on dredged material: a critical review of the ongoing debate over success. Wetlands Ecology and Management 8:295-316.

Vernberg, F.J. 1993. Salt marsh processes: a review. Environmental Toxicology and Chemistry 12:2167-2195.

Zedler, J.B. and J.C. Calloway. 1999. Tracking wetland restoration: do mitigation sites follow desired trajectories? Restoration Ecology 7(1):69-73.

Zedler, J.B and R. Lindig-Cisneros. 2000. Functional equivalency of restored and natural salt marshes. Pp565-582. *In* M.P. Weinstein and D.A. Kreeger (ed.) Concepts and controversies in tidal marsh ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Table 1-1. Relationship of ecological functions with potential soil indicators.

Ecological Function	**Soil Based Indicator**
Plant productivity	Soil reserves of N and P
Nutrient retention	Clay, humus content, CEC
Infaunal productivity	Soil and MOM organic C and N
Habitat suitability for infauna	Bulk density, soil texture
Rates of nutrient mineralization	Carbon/ Nitrogen ratio
Denitrification, SO_4^- reduction	Soil organic carbon

Table 1-2. Site characteristics of created and natural *Spartina alterniflora* marshes.

Site[1]	Size[2] (ha)	Age[2] (years)	Tidal range[3] (meters)	Salinity range[3] (ppt)	Geomorphic position[3]	Soil Classification[4]
1. DOT	0.9	1	1	20-30	back barrier flats	Typic Psammaquent
2. Consultant	1.0	3	1	17-32	back barrier flats	Typic Hydraquent
3. Port	1.0	8	1	18-30	back barrier flats	Typic Hydraquent
4. Swansboro (S)	0.4	11	1.1	20-30	riverine	Typic Psammaquent
5. Harkers Is. (H)	0.4	11	1	20-30	back barrier flats	Typic Hydraquent
6. Snead Ferry (F)	0.4	11	1.1	20-30	back barrier flats	Typic Psammaquent
7. Dill's Creek	0.3	13	1	14-33	submerged upland	Typic Hydraquent
8. Pine Knoll	0.3	24	1	20-30	back barrier flats	Typic Psammaquent
9. Marine Lab	0.2	26	1	20-30	back barrier flats	Typic Hydraquent
10.Snow's Cut	0.8	28	1.2	5-20	riverine	Typic Medisaprist

[1] Marshes were constructed for shoreline stabilization (8), dredge spoil stabilization (9, 10), research (3 – 6), mitigation on dredge spoil (1, 2) and mitigation on graded upland soil (7).
[2] Created marshes only
[3] Both created and natural reference marshes
[4] Natural reference marshes only. Soils of created marshes classify as Typic Psammaquents (Carteret series), except Dills Creek which classifies as a fine-loamy, Aquic Udorthent (series unknown).

Table 1-3. Comparison of the results of three methods to estimate years required for created marshes to become equivalent to natural marshes. ne = not bioequivalent or bioequivalence not detected

0-10 cm depth	t-tests[1]	contrasts[2,3]	bioequivalence[2]	10-30 cm depth	t-tests[1]	contrasts[2,3]	bioequivalence[2]
MOM dry weight	8	8	22	MOM dry weight	8	12	26
Bulk density	11	17	18	Bulk density	8	23	ne
Soil-C	24	19	22	Soil-C	8	25	ne
Soil-N	24	19	22	Soil-N	8	>28	ne
Soil-P	1	19	ne	Soil-P	1	.	.
Soil C/N	8	17	28	Soil C/N	3	18	ne
MOM-N	24	20	ne	MOM-N	24	21	26
MOM C/N	24	.	.	MOM C/N	24	.	.
Sand	24	22	ne	Sand	8	.	.
Silt	24	24	ne	Silt	8	.	.

1 t-tests compare means of paired created and natural marshes. Year shown is the age of the youngest marsh for which non-significant differences ($p > 0.05$) are found.
2 contrasts and bioequivalence tests compare the predicted values for the created marshes with the average for all natural marshes. Estimates are omitted for those properties which do not have a predictable ($r^2 \geq 0.50$) and significant ($p \leq 0.05$) relation to age of created marsh.
3 Year shown is the age of the youngest marsh for which non significant differences ($p > 0.05$) are found.

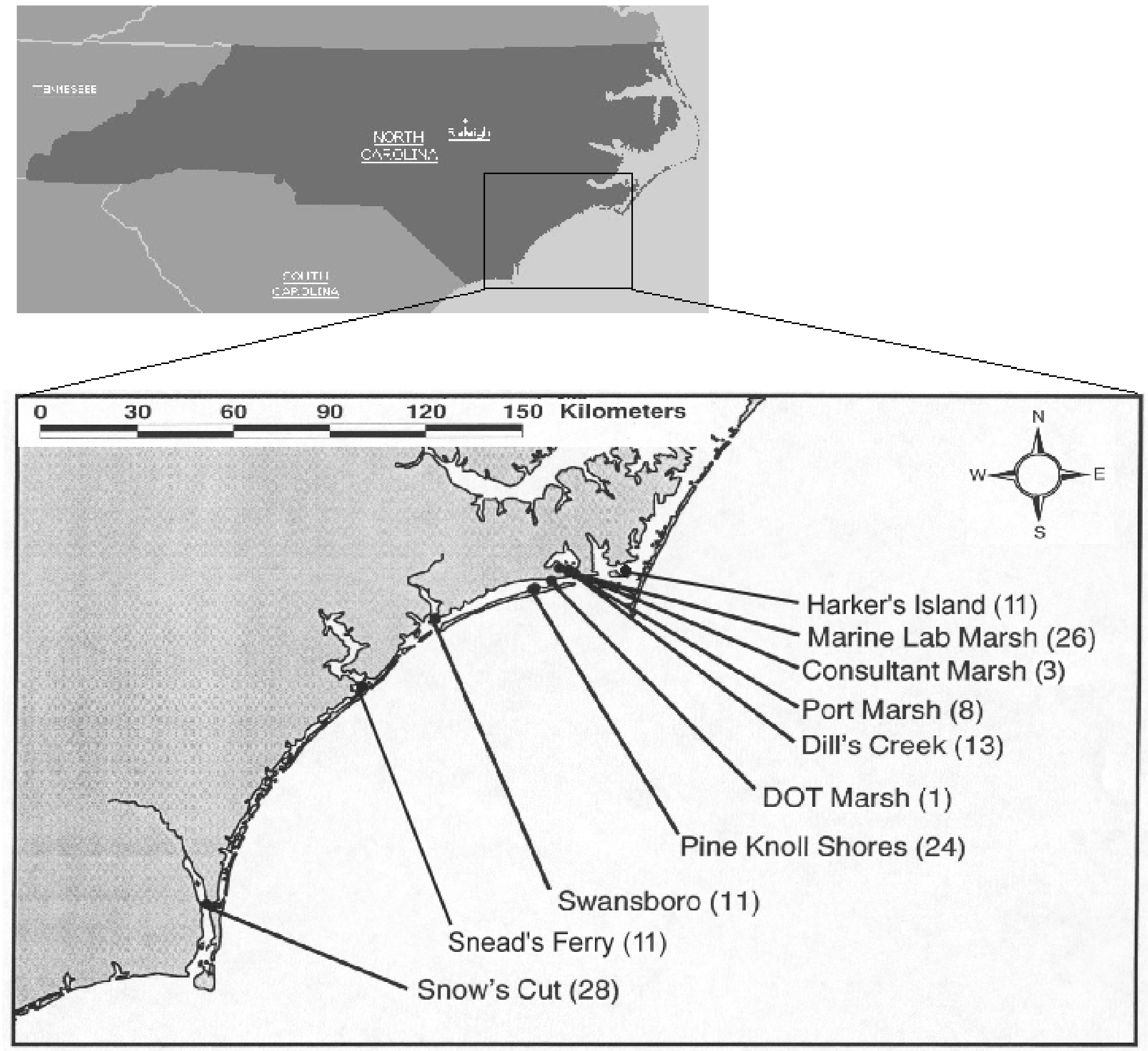
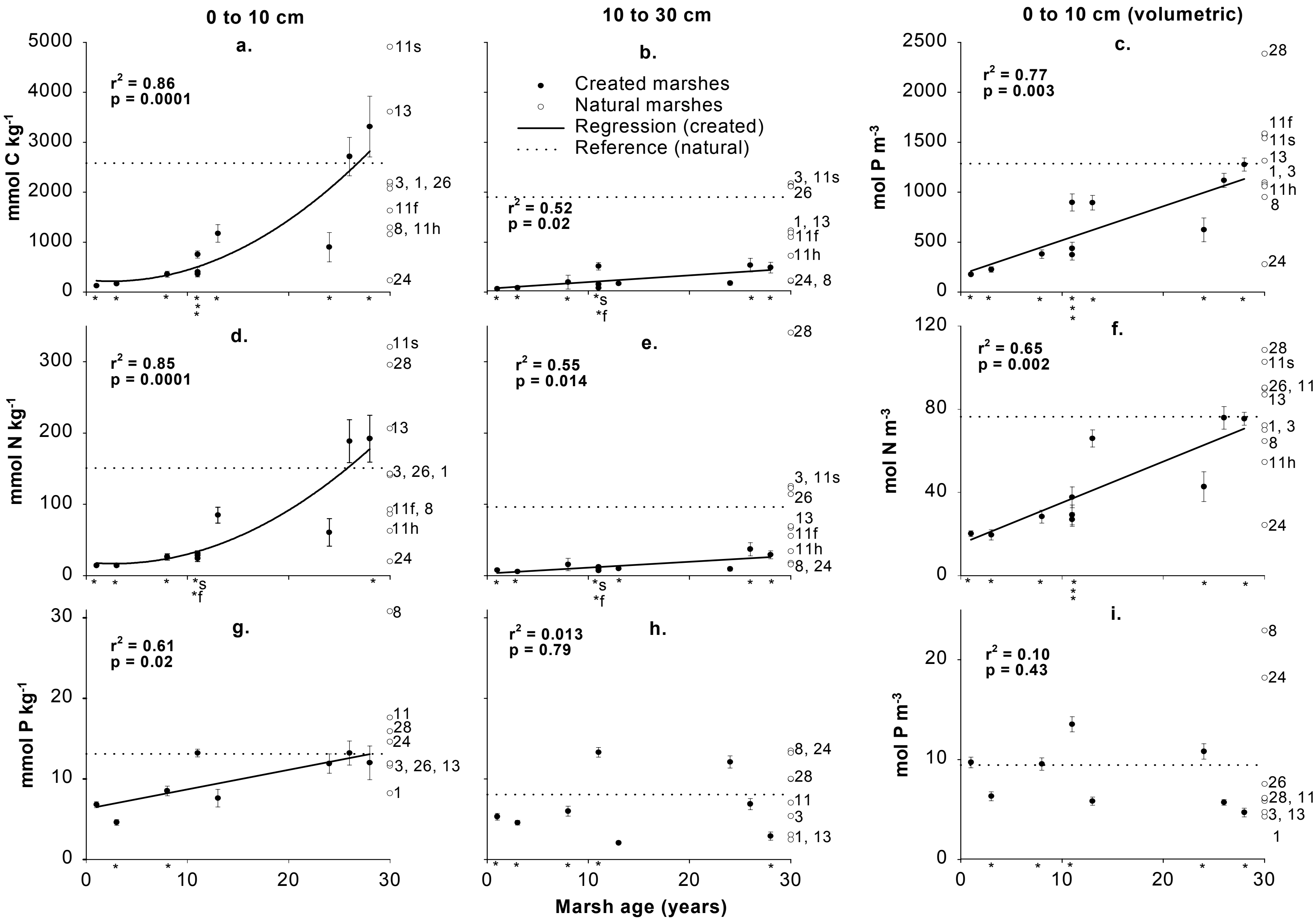


Figure 1-1. Locations of study sites. Each site includes one created and one natural (reference) marsh.

Figure 1-2. Means and standard errors for soil carbon (a-c), nitrogen (d-f), and phosphorous (g-i) content as a function of age of created marshes. Due to scale limitations, the carbon levels of the reference marsh paired with the 28-year old marsh are not shown. This marsh soil had 6570 mmol kg^{-1} in the 0 to 10 cm layer and 7920 mmol kg^{-1} in the 10 to 30 cm layer. The means of the natural reference marshes are shown at year 30. Numbers to the right of each graph show the age of the created marsh with which that reference marsh is paired. The presence of an asterisk below the x-axis indicates a significant ($p < 0.05$) difference between the created marsh of that age and its paired natural marsh.


0 to 10 cm
10 to 30 cm
0 to 10 cm (volumetric)
a.
b.
c.
d.
e.
f.
g.
h.
i.
mmol C kg-1
mmol N kg-1
mmol P kg-1
mol P m-3
mol N m-3
mol P m-3
Marsh age (years)
Created marshes
Natural marshes
Regression (created)
Reference (natural)
r2 = 0.86
p = 0.0001
r2 = 0.52
p = 0.02
r2 = 0.77
p = 0.003
r2 = 0.85
p = 0.0001
r2 = 0.55
p = 0.014
r2 = 0.65
p = 0.002
r2 = 0.61
p = 0.02
r2 = 0.013
p = 0.79
r2 = 0.10
p = 0.43
11s
13
3, 1, 26
11f
8, 11h
24
3, 11s
26
1, 13
11f
11h
24, 8
28
11f
11s
13
1, 3
11h
8
24
11s
28
13
3, 26, 1
11f, 8
11h
24
28
3, 11s
26
13
11f
11h
8, 24
28
11s
26, 11f
13
1, 3
8
11h
24
8
11
28
24
3, 26, 13
1
8, 24
28
11
3
1, 13
8
24
26
28, 11
3, 13
1
*s
*f

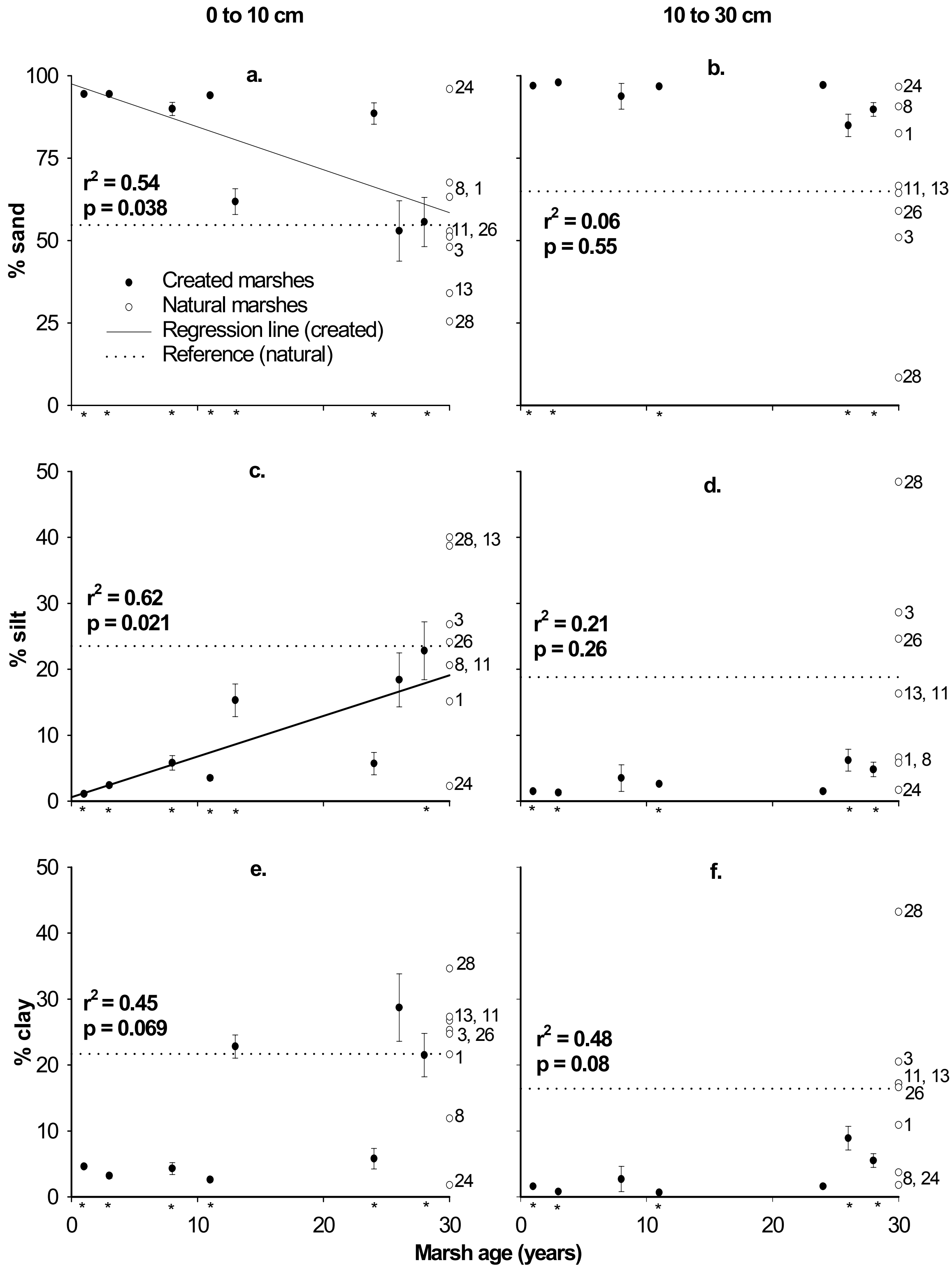


Figure 1-3. Means and standard errors of sand, silt, and clay as a function of age of created marshes. Mean sand, silt, and clay of reference marshes are shown at marsh age = 30 years. The ages of the created marshes with which they are paired are shown to the right. The presence of an asterisk below the x-axis indicates a significant ($p < 0.05$) difference between the created marsh of that age and its paired natural marsh.

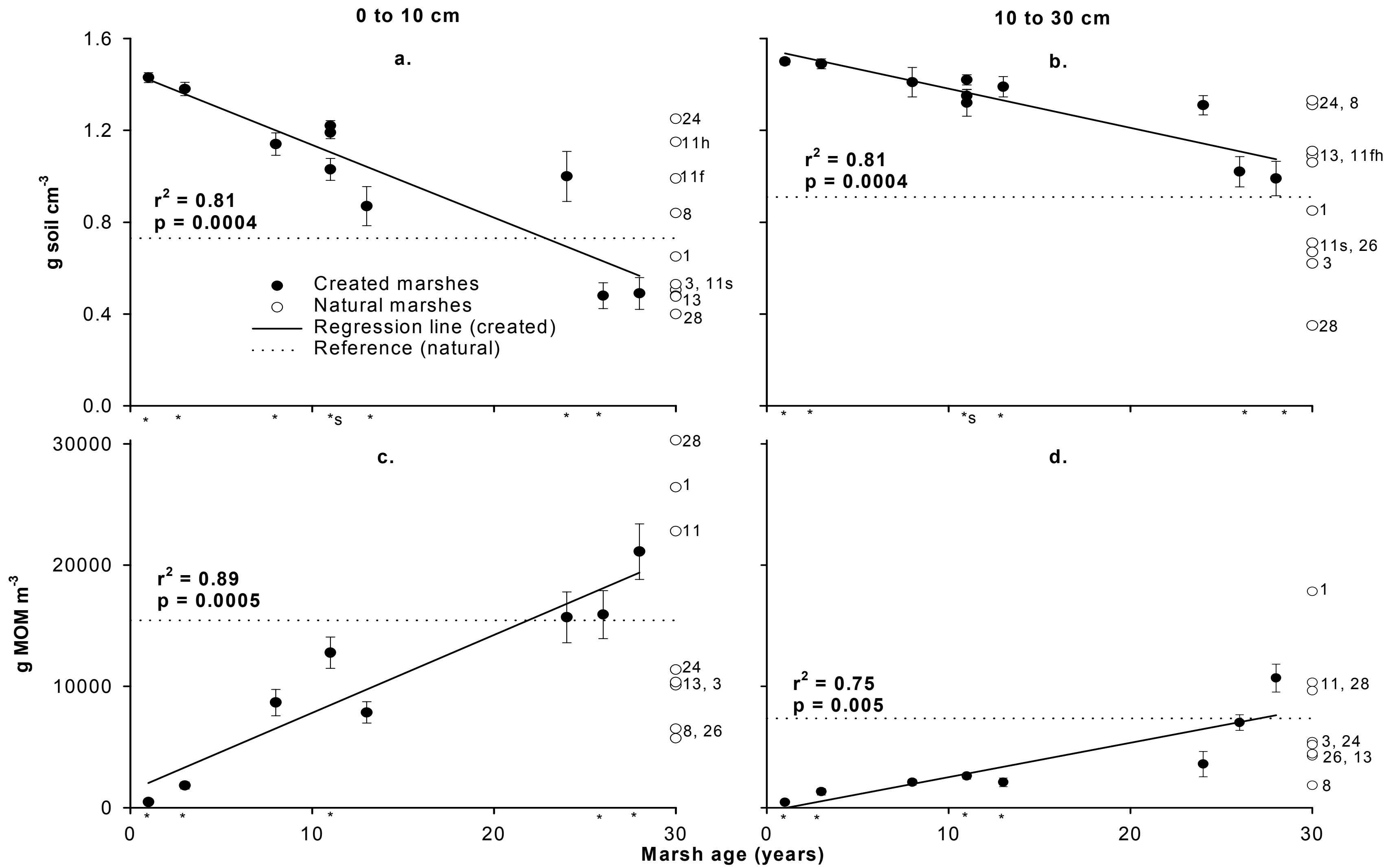


Figure 1-4. Means and standard errors for soil bulk density and MOM dry weight as a function of age of created marshes. Mean bulk density and MOM dry weight for natural marshes are shown at marsh age = 30 years. The ages of the created marshes with which they are paired are shown to the right of each graph. The presence of an asterisk below the x-axis indicates a significant ($p < 0.05$) difference between the created marsh of that age and its paired natural marsh.

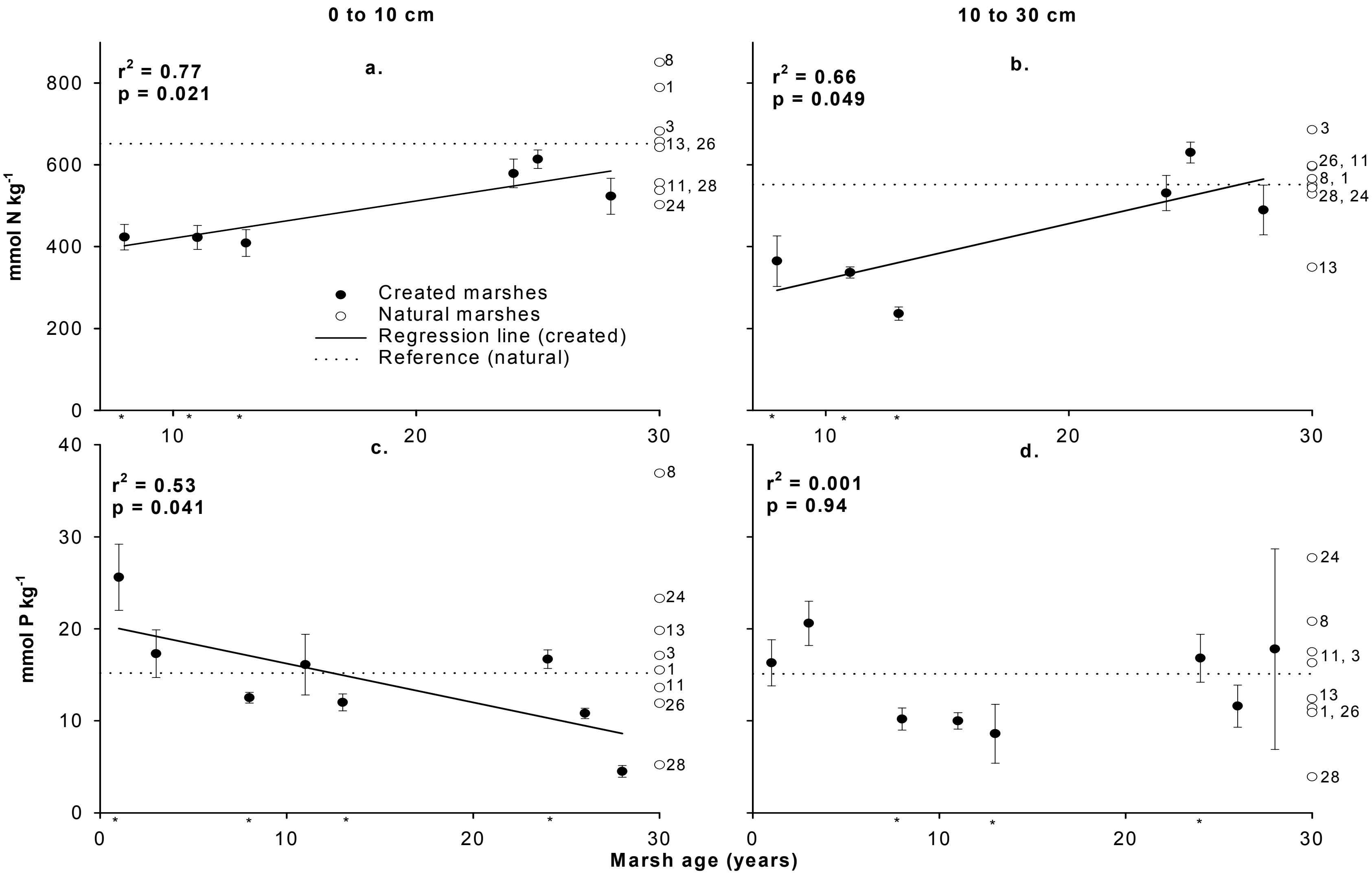


Figure 1-5. Means and standard errors for MOM nitrogen and phosphorous content as a function of age of created marshes. Means for natural marshes are shown at marsh age = 30 years. The ages of the created marshes with which they are paired are shown to the right of each graph. The presence of an asterisk below the x-axis indicates a significant ($p < 0.05$) difference between the created marsh of that age and its paired natural marsh.

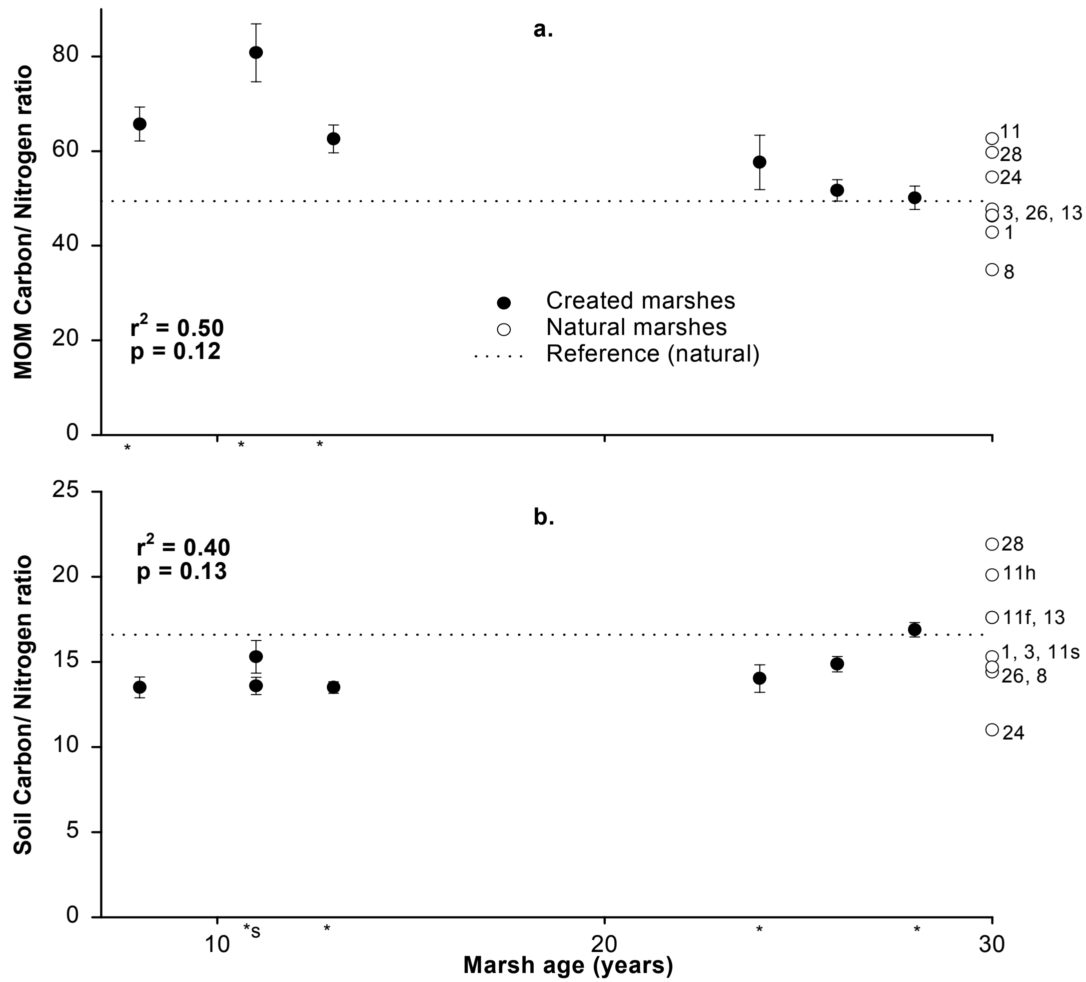


Figure 6. Means and standard errors of carbon/ nitrogen ratios in the 0 to 10 cm depth as a function of age of created marshes. Carbon/ nitrogen ratios of natural marshes are shown at marsh age = 30 years. The ages of the created marshes with which they are paired are shown to the right of each graph. The presence of an asterisk below the x-axis indicates a significant ($p < 0.05$) difference between the created marsh of that age and its paired natural marsh.

Chapter 2. SPATIAL PATTERNS OF SOIL AND VEGETATION IN CREATED *SPARTINA ALTERNIFLORA* LOISEL MARSHES

ABSTRACT

One of the characteristic features of salt marshes is the distinct zonation that occurs with respect to plant species and morphology, infaunal community, and soil characteristics. This study documents zonation of soil and vegetation in three created salt marshes of various ages located in the Newport River estuary of North Carolina. Since soil features are potential indicators for ecological function, this study helps assess the functional contributions of the zones in developing created salt marshes. Five soil cores were collected from edge and inland positions within three created marshes of various ages (4, 11, and 29 years old) and one natural marsh. The soil was analyzed for carbon, nitrogen, phosphorous, bulk density, texture, hydraulic conductivity, and porosity. The MOM (macro-organic matter) was analyzed for carbon, nitrogen, phosphorous, and dry weight. Aboveground biomass, stem height, and stem density of edge and inland positions were measured. The geomorphology and soil morphology across these two positions was described. The edge soils of the natural marsh were higher in bulk density, sand, MOM-N, MOM-P and lower in soil carbon and clay than the inland soils. There were no spatial differences in the 4 year old DOT marsh. Many of the spatial differences observed in the natural marsh were reversed in the 11 year old Port marsh and the 29 year old Marine Lab marsh. This appears related to the geomorphology of created marshes which have low elevation edges and high elevation inland areas. In contrast, natural marshes often have high elevation berms at marsh edge and

a flat, low elevation marsh plain inland. The soil of the inland areas of the created marshes classifies as a Typic Psammaquent, an immature soil that lacks the characteristics of the Mollic Endoaquent soils of the nearby natural marsh. Relative to the Marine Lab marsh, the areal extent of mature soils is greater in the Port marsh due to the construction of a tidal creek. This feature runs through the middle of the site and maximizes the proportion of “edge” at this site.

INTRODUCTION

The spatial patterns of vegetation in natural salt marshes have long been documented. This patterning is most evident as bands of vegetation of different morphology or species. For example, *Spartina alterniflora* plants growing along tidal creeks are tall and highly productive with low stem density. Further inland, *S. alterniflora* plants are shorter and less productive with dense stem growth (Adams, 1963; Valiela et al., 1978). Most research indicates that these spatial differences are due to environmental rather than genetic factors. Fertilization experiments show that nitrogen limitations are one factor since N fertilization partially converts short form plants into tall form (Valiela and Teal, 1974, Broome et al., 1975). However, in some cases N levels in the soil are greater in the short Spartina areas than in the tall form areas (Mendelssohn, 1979). Thus, additional factors such as soil salinity, drainage and redox potential may limit or interact to limit growth (Howes et al., 1986; Anderson and Treshow, 1980; Cooper, 1982; Wiegert et al., 1983). Higher salinity levels inland may cause plants to divert N toward production of osmotica, substances by which the plants maintain suitable osmotic potential. Howes et al. (1986)

suggests that nitrogen limitation is an indirect cause of the short growth form. Their research indicated that redox potential explains most variation in plant yield along a transect from marsh edge to center. They suggested that NH_4 uptake is controlled by soil O_2 status as well as NH_4 concentration. By increasing either of these factors N uptake and plant growth may be increased. Soil drainage also controls O_2 status. The stagnant soil water conditions that prevails in the zones away from the marsh edge (Gardner, 1973; Mendelssohn and Seneca, 1980) may also allow toxic levels of salts and hydrogen sulfide to accumulate and thereby inhibit plant growth.

The soil invertebrate (infauna) population of salt marshes also varies spatially. Sarda et al. (1995) found three distinct assemblages of infauna within a natural marsh in New England. The assemblages were distributed along gradients of varying soil texture and organic matter with greatest production occurring in sandy, high organic matter areas of the marsh. In created marshes there is generally greater infaunal density at low and medium elevations than at high elevations (Moy and Levin, 1991; Levin et al.,1996). In a natural marsh, Levin et al. also observed greater density of epifauna at low relative to high elevations.

Salt marsh soils develop spatial patterns due to the depositional processes. Sediment deposition is affected by the dense plant canopy which slows tidal currents and causes larger, heavier particles to settle at the marsh edge while finer particles settle toward the marsh center. In one study, over 80% of suspended material disappeared from floodwaters within 12 m of a tidal creek (Stumpf, 1983). One study showed sediment deposition rates at the marsh edge that were approximately twice that of the marsh interior (Leonard, 1997). These processes contribute to the formation of levees which are a common feature along tidal creeks and marsh edges (Frey and Basan, 1978). Trapping of clay on plant stems is a process that may be important in its deposition in the marsh interior. Samples across a 25 m transect of soil in a North Carolina salt marsh showed a gradient of increasing silt and organic matter from the edge to the marsh interior (Yelverton and Hackney, 1986). Episodic processes such as storms also affect soil patterns within salt marshes (Stumpf, 1983), particularly when the marshes are adjacent to barrier islands where overwashing of sand is an ongoing process. Gradients of soil porewater chemistry also exist in salt marshes. In two young salt marshes, Osgood et al. (1993) found that hydrogen sulfide and ferrous iron increased while redox potential decreased in a transect from high to low elevation areas. Porewater NH_4 and P increased from high to low elevation areas but factors such as soil texture, salinity and pH did not vary significantly with elevation.

Created salt marshes have been used to stabilize shorelines and dredged material for over 30 years. More recently, they have been constructed to mitigate damage to natural marshes that occurs during development. The ecological functions of created marshes have been studied with respect to vegetation establishment, infaunal community, and soil and macro-organic matter (MOM) properties. Soil nutrient pools, texture and bulk density have been proposed as one set of indicators for ecological function (Craft et al., in press). While overall levels of most soil properties of the 0 to 10 cm layer approach and eventually equal those of natural marshes (see chapter 1), spatial variability of these properties within created marshes has been little studied. Lindau and Hossner (1981) observed the development of spatial differences in a 16-month old created marsh. Clay, organic matter, total soil nitrogen and extractable phosphorous accumulated more rapidly at low relative to high elevations. Elevation had the dominant effect on measured soil parameters while fertilizer application and plant species were relatively unimportant. In a brackish water marsh, Craft et al. (2002) showed faster rates of change in bulk density, porosity, organic C and N within a low elevation, *S. alterniflora* marsh relative to a higher elevation *S. patens* marsh. Above ground biomass in the *S. patens* marsh developed slowly, not reaching equivalence to a natural *S. patens* marsh after 15 years.

The general goal of this study is to document spatial patterns in soil development and vegetation within a chronosequence of three created salt marshes. We hypothesize that these properties do not develop uniformly. By studying a chronosequence of marshes, we can consider the effect of marsh age on spatial variability. Additional considerations are summarized in the following questions: How do these patterns differ from those occurring in a nearby natural marsh? Assuming soil and vegetative properties are indicators for ecological function, what are the implications of such spatial differences on ecological functions of created marshes? What are some possible causes for differences in spatial distibution of soil properties between created and natural marshes?

Our first objective is to compare soil and vegetative properties between two positions (edge and inland) and between two soil depths (0-10 cm and 10-30 cm) of four *S. alterniflora* salt marshes. Our second objective is to compare the soil and vegetative properties at these two positions with properties of an “average” North Carolina salt marsh, a composite reference derived from measurements of 10 natural marshes described in a another study (Craft et al, in press).

MATERIALS AND METHODS

Four marshes in the Newport River estuary near Morehead City, North Carolina were selected. Three of the marshes are created while one is natural in origin. The three created marshes were selected to represent a range of marsh ages. Only one natural marsh was selected for study since there are a number of existing studies that document spatial patterns in natural marshes. The one natural marsh was selected based on its proximity to the three created marshes and because its soil and MOM characteristics in the 0 to 30 cm depth were typical among 10 natural marshes previously studied (see chapter 1). In that study, this natural marsh was the reference site for the then 1-year old DOT marsh. Some characteristics of the four marshes and positions within them are described in Table 1. Position is defined here as distance of the sampling site from the marsh – open water edge. The positions selected for study were located at the following distances from this edge: 1 meter (edge) and 15 meters (inland). Due to the greater width of the Marine Lab marsh, a third position (upland margin) was studied at this site at a distance of 30 meters from the edge. All positions were located within the regularly flooded *Spartina alterniflora* marsh.

The locations of the four marshes relative to one another are shown in Figure 1. The 4-year old DOT marsh was constructed on an intertidal sand flat in Bogue Sound,1.4 km west of Atlantic beach bridge. The 11-year old Port marsh was constructed on a sandy, dredged material disposal island 0.25 km north of the Port facility of Morehead City. This marsh differed from the other created marshes in that it was constructed with a channel through its center to mimic the geomorphology of a natural marsh. The edge position was located along this channel rather than along the open water of the estuary. The 29-year old

Marine Lab marsh was constructed on another sandy dredged material disposal island ("Radio Island") located 0.15 km north of NC Highway 70.

In July 2001, the soil at each position in the four marshes was sampled by taking five soil cores (8.5 cm diameter) from 0-30 cm depth. These cores were collected at evenly spaced intervals in a 50 m transect parallel to the marsh edge and at distances inland of 1, 15, and 30 (Marine Lab site only) meters. Cores were sectioned into 0 to 10 and 10 to 30 cm layers. Soil samples were obtained from these cores by collecting the soil passing through a 2 mm sieve. The remainder of the core was rinsed on a 2 mm sieve to obtain a clean sample of root material, also referred to as macro-organic matter (MOM). Soil samples were air-dried while MOM samples were dried at 70 °C prior to grinding. Carbon and nitrogen content of both soil and MOM were determined with a Perkin-Elmer CHN elemental analyzer. Soil samples with shell fragments were pre-treated with dilute HCl to remove the inorganic carbon. Soil total phosphorous was determined by digesting the soil in concentrated sulfuric acid and measuring P concentration of the extract colorimetrically on a Lachat spectrophotometer. MOM phosphorous was determined by dry-ashing the root material, treating it with 6N HCl and analyzing the filtrate by inductively coupled plasma (ICP) spectrometer. Particle size distribution was determined by the pipette method (Gee and Bauder, 1986) and bulk density by the core method (Blake and Hartge, 1986). Redox potential readings were taken in July 2001 near the sites from which the soil cores were obtained. At each site, five platinum tipped electrodes were inserted into the soil to a depth of 10 cm. The electrodes were allowed to equilibrate for at least 5 minutes prior to reading. Since a calomel reference electrode was used a correction factor of 245 was added to each reading to make it relative to the standard hydrogen electrode. The five readings from each site were averaged and treated as a single observation. No temperature or pH corrections were made.

An additional set of smaller (100 cm^3 volume) soil cores was collected at the same time for determination of soil moisture retention characteristics. These cores were taken from the same sites as the larger cores and two depths were sampled: the top of root zone (0-4 cm) and a subsoil zone (20-24 cm). Each core was placed on a porous plate in a temperature and pressure controlled chamber. Water was gradually added to the cores until saturation was reached. The cores were then desaturated by applying sequentially greater pressures and measuring water outflow through the porous plate at each pressure level (Danielson and Sutherland, 1986). The water content remaining at the final pressure was obtained by oven drying the core. Total porosity and macroporosity (pores > 1mm in diameter) were determined from the resulting water release curve and expressed as a fraction of the total soil volume.

We measured *in situ* lateral hydraulic conductivity of the root zone (0 – 20 cm depth) and subsurface zone (30-50 cm depth) by the piezometer method (Amoozegar and Wilson, 1999), a technique whereby water is pumped from a piezometer and the rate of water reentry recorded. Well screen with 0.04 mm slots allowed water to enter the cavity from the surrounding soil. We measured vertical hydraulic conductivity at these same sites using a piezometer without well screen, open only on the bottom. This design largely eliminates lateral flow. We took between 3 and 5 of each measurement at each position in each marsh.

Elevation readings were made near the sites where each soil core was obtained. These readings were referenced to the low water level for that day. The National Oceanic and Atmospheric Administration (NOAA) issues tide predictions which were used to estimate the elevation of those low water marks relative to a common datum ("mean lower low water"). Marsh surface elevations were adjusted to that common datum. An additional 150-250 elevation readings of the marsh surfaces were made within the study area of each marsh. These elevation readings and their coordinates on an x-y plane were entered in the Surfer 3D graphing program (Golden Software, Inc., Golden, CO) in order to portray the geomorphology of the four marshes.

Detailed soil profile descriptions were made at each position to a depth of 1 meter. Soil samples from each horizon were collected for particle size distribution and pH. The classification of each pedon was determined to the subgroup level using the NRCS keys to soil taxonomy (Soil Survey Staff, 1996).

Foliar weight, stem height, and stem density were measured in September, 2001. Five measurements were taken from each position near the sites from which the soil cores were obtained. Stem density was measured as the number of stems in a 0.25 m^2 quadrat. Stem height was estimated as the average of the 5 tallest stems within the quadrats. Aboveground biomass was then harvested, dried and weighed.

Statistical Analysis

We used SAS software to compare means of soil properties between positions and between soil depths. The study design is split-plot in nature with position (1 m vs. 15 m) as the whole plot unit and soil depth (0-10 cm vs. 10-30 cm) as the sub-plot unit. A general linear model describes each of the soil properties as a function of these four terms: position, soil core within position, soil depth, and position x depth interaction. This model assumes equal variances between depths. Where this assumption is not met, we test differences between positions by separate ANOVA tests for each depth. We also test differences in vegetative characteristics between positions by ANOVA.

We used one-sided, 95% confidence intervals to compare the means for each of the positions within the three created marshes with the mean of the composite of ten natural marshes. For properties in which accumulation is the desired trend (MOM dry weight, soil and MOM nutrient pools, silt, clay), we compare the upper confidence interval (UCI) endpoint for the created marshes with the lower confidence interval (LCI) for the natural. For properties in which a decreasing level is the desired trend (bulk density, sand, MOM C/N) we compare the LCI endpoint for the created marsh position with the UCI endpoint for the natural marsh. If there was no intersection of these confidence intervals, then their means were judged different. If intersection of confidence intervals occurred then the null hypothesis of equal means was not rejected.

RESULTS

Comparison of Edge and Inland Positions for Each Marsh

The Single Natural Marsh

The position effect is significant for soil carbon, clay, macroporosity, MOM dry weight, and MOM nitrogen (Table 2). These properties are greater inland than at marsh edge. The position effect is also significant for bulk density and MOM-P but these properties are greater at marsh edge than inland.

Depth effects are significant for bulk density and sand. These properties increase with soil depth. Significant depth effects also occur for silt and MOM-N which decrease with soil depth. There are no significant interactions of marsh position and soil depth. The standing crop of above ground biomass is greater at marsh edge than inland (Table 6). This confirms observations in the literature concerning spatial patterns of biomass production. Differences in stem density and stem height between positions are not significant. This is in contrast to observations in the literature.

The 4-year old DOT Marsh

There are no significant position effects for any of the soil and MOM properties (Table 3). Significant depth effects occur for soil-C, soil-N, silt, clay, MOM-N,P, and total soil porosity. These properties decrease with depth. Significant depth effects also occur for bulk density and sand which increase with depth. There are no significant interactions of depth and position. Stem height at marsh edge is significantly taller than inland but differences in above-ground biomass and stem density between positions are not significant (Table 6).

The 11-year old Port Marsh

Silt, clay and total porosity have significant position effects and are greater at marsh edge than inland (Table 4). Sand and bulk density also have significant position effects and are greater inland than at marsh edge. Variances for soil-C, soil-N, MOM-P, and MOM-C/N are unequal between depths thus the split-plot analysis of both position and depth is not appropriate. The analysis of variance (ANOVA) for position differences indicates that mean soil C and N at marsh edge are greater than inland for the 0 to10 cm depth but that these differences are not significant at the 10 to 30 cm depth.

The MOM dry weight, clay, and total porosity have significant depth effects. These properties decrease with soil depth. Bulk density and sand also have significant depth effects and these properties increase with soil depth. The significant interaction term for total porosity indicates that the position effect is greater at the 0 to10 cm depth than at the 10 to 30 cm depth. *Spartina* stem height is significantly taller at marsh edge than inland (Table 6). Stem density is significantly less at marsh edge than inland. These spatial differences in vegetation are typical of natural marshes. In contrast to the literature, above ground biomass production is not significantly different at marsh edge and inland. However, some dieback in plants at the marsh edge was evident and probably affected the comparison.

The 29-year old Marine Lab Marsh

Bulk density, MOM dry weight, and sand have significant position effects. These properties are greater inland than at marsh edge (Table 5). Silt, clay, MOM-N,P, and soil porosity also have significant position effects and are greater at marsh edge than inland. Unequal variances between depths occur for soil-C and soil-N. For these parameters, we perform separate ANOVA tests for each depth (Table 5). As with the Port marsh, the soil of the 0 to 10 cm depth has significantly greater C and N at the marsh edge than inland while position differences are not significant at the 10 to 30 cm depth.

Significant depth effects occur for bulk density and sand. These properties increase with soil depth. The MOM dry weight, soil-P, silt, clay, MOM-N, and total porosity also have significant depth effects and these properties decrease with soil depth. Significant position-soil depth interactions occur for MOM dry weight, sand, silt, clay and indicate that position differences are more pronounced at the 0 to 10 cm depth than at the 10 to 30 cm depth. A significant position x depth interaction for total porosity indicates more pronounced differences at the 10 to 30 than at the 0 to10 cm depth. A significant interaction term for macroporosity is not accompanied by significant effects for either position or depth. This indicates that position differences for macroporosity are reversed at the two depths. Macroporosity of the 0-10 cm depth is greater inland than at marsh edge but at the 10-30 cm depth macroporosity is greater at marsh edge than inland. Above ground biomass production and stem height are both significantly greater at marsh edge than inland while stem density is significantly greater inland than at marsh edge (Table 6). These spatial differences in vegetation correspond to those observed in the literature for natural marshes.

Comparison of Properties of the Composite Natural Reference Marsh with those of Edge and Inland Positions from Created Marshes

Soil Nutrient Pools

In the 0 to 10 cm depth of the Marine lab marsh, intersection with the confidence interval of the composite natural (reference) marsh occurs for both the edge and upland margin positions (Figure 2a, c). This suggests that neither this marsh's edge nor its inland have levels significantly different from that of the reference. Confidence intervals in the DOT and Port marshes, however, fail at both positions to intersect that of the reference.

This indicates that these marshes, regardless of position, have significantly lower soil C and N levels than the reference. Thus, spatial differences in soil C and N with respect to the reference are not significant.

In the 10 to 30 cm depth of the Port and Marine lab marshes, confidence intervals for mean soil C and N intersect those of the reference for marsh edges but fail to intersect it for inland positions (Figure 2b, d). This indicates that at this depth the marsh edges are equivalent to the reference but the inland sites are not. This suggests deeper soil development at the edges of these older marshes relative to their inland areas. In the 10 to 30 cm depth of the DOT marsh, confidence intervals fail to intersect that of the reference for both positions. This indicates that this marsh has significantly lower soil C and N than the reference, regardless of position.

The mean soil P of the reference has narrow confidence intervals and suggests relatively consistent levels (Figure 2 e, f). In the created marshes, soil-P levels are somewhat higher at marsh edge than inland. However, the confidence intervals in all marshes for all positions and at both depths intersect those of the reference. Thus, differences between created marshes and the reference are not significant for either position.

The soils at the edge of the Port marsh have elevated soil C and N levels at 10 to 30 cm due to the presence of an Ab (buried A) horizon which occurs at depths as shallow as 25 cm. This organic rich horizon is the remains of a marsh that existed at this site prior to its use for disposal of dredge material. The resulting high variability in soil characteristics accounts for the wide confidence interval at the Port marsh edge position. At the inland position, the buried A horizon is deeper and was never sampled when collecting cores. Due to the greater depth to this horizon, it is unlikely that the nutrients in the soil of the former marsh are available to the plants growing at this position in the created marsh.

Soil Texture

All comparisons of particle size classes of created marsh positions with the reference are similar (Figure 3a-f). They indicate that the soils from the edges of the Port and Marine Lab marshes are not significantly different from that of the reference. The soils from the edge of the youngest marsh (DOT) and from all inland positions are significantly higher in sand and lower in silt and clay relative to the reference.

When created marshes are viewed in chronological sequence, their sand content at the edge appears to decrease while sand content inland remains constant. Similarly, silt and clay increase at the marsh edge but little accumulation occurs inland. The texture of even the oldest marsh at the upland margin position does not develop textures any heavier than loamy sand (>70% sand). This contrasts with spatial patterns in natural marshes in which silt and clay increase from marsh edge to inland (Yelverton and Hackney, 1986).

MOM N, C/N, P

It may be possible to assess the condition of plants in the created marshes by comparing the nutrient status of the MOM with that of the composite natural reference marsh. The means of MOM-N for the DOT and Marine lab marshes have confidence intervals which intersect that of the natural reference for both positions. In the Port marsh, neither position intersects that of the reference (Figure 3a). Carbon/ Nitrogen ratio is another indicator of the nutritional status of the MOM and in this case only the edge position at the Marine Lab marsh intersects that of the reference (Figure 3c). The Port marsh edge had a mid-summer die-back of many *Spartina* plants and this unhealthy, though probably temporary condition, may be reflected in the high MOM C/N ratio.

Based on confidence intervals for MOM-N of the 10-30 cm depth, neither position in the Marine Lab marsh nor the edge position in the Port marsh are significantly different from the reference (Figure 4b). Both positions in the DOT marsh and the inland position in the Port marsh are significantly lower in MOM-N than the reference. These same patterns occur for MOM C/N (Figure 4d). Again, some of the core samples for the 10 to 30 cm depth in the Port marsh included part of the Ab horizon and this greatly increased sample variability. With respect to MOM-P, the confidence intervals for all positions in all created marshes and for both depths intersect with that of the reference (Figure 4e, f). This suggests that MOM-P in all cases is not significantly different from that of the reference.

Soil Bulk Density and MOM Dry Weight

The confidence intervals around the mean bulk density of the 0 to 10 cm depth for the created marsh positions intersect that of the composite reference marsh in the case of the Marine Lab (both positions) and Port marsh (edge only). These positions are therefore not significantly different from the reference while the DOT marsh (both positions) and Port marsh (inland) have significantly higher bulk density than the reference. The pattern is similar at the 10 to 30 cm depth except the Marine Lab marsh (inland) has significantly denser soil than the reference. This difference between depths may be related to the high MOM production in the soil of the Marine Lab at the 0 to 10 cm depth and the much lower MOM production at the 10 to 30 cm depth.

Spatial patterns in MOM accumulation with respect to the reference are inconsistent.

The confidence intervals around mean MOM accumulation of the 0 to 10 cm depth (Figure 5c) for the created marsh positions intersect that of the composite reference marsh in the case of the Marine Lab (both positions) and Port marsh (edge only). These positions are not significantly different from the composite natural marsh while MOM accumulation in the DOT marsh (both positions) and Port marsh (inland only) is significantly lower. In the 10 to 30 cm layer (Figure 5d), the confidence intervals around mean MOM accumulation intersect with that of the reference in the case of the DOT marsh (inland only) and the Marine Lab marsh (both positions).

Soil Morphology and Classification of Salt Marsh Soils

The Single Natural Marsh

The soils of the natural salt marshes of the Newport River estuary are mapped as Carteret sand (Typic Psammaquents) toward the barrier islands and as Hobucken muck (coarse-loamy, Typic Hydraquents) toward the outlet of the river (Goodwin R.A., 1984). However, map units for salt marsh areas were poorly defined at the time of mapping since little human interest in these soils was anticipated. The soil descriptions given below indicate that the typical natural marsh chosen for this study has soils better classified as Mollic Endoaquents. This re-classification is justified by two factors: 1) sufficient organic matter accumulation in the epipedon (A1 and A2 horizons) to result in dark colors of Munsell value 3 or less, and 2) sufficient accumulation of silt and clay in at least one horizon of the control section (25 to 100 cm) to qualify as a sandy loam or finer textural class. It was assumed that these soils do not qualify as Sulfaquents since their pH remains near neutral after drying. Nor do they qualify as Hydraquents due to the shallowness of the loamy material. The two descriptions suggest relatively little morphological variation between the soils of the marsh edge and center in this natural marsh.

Typical pedon from marsh center (Mollic Endoaquent):

A1- 0 to 20 cm; greenish black (5GY 2.5/1) sandy loam (71% sand, 12% silt, 17% clay); weak medium granular structure; very friable; many fine roots; few coarse shell fragments; neutral; clear smooth boundary.

A2- 20 to 36 cm; dark greenish gray (5GY 3/1) sandy loam (80% sand, 9% silt, 11% clay); weak medium granular structure; very friable; common fine roots; few coarse shell fragments; neutral; clear smooth boundary.

Cg- 36 to 100 cm; dark greenish gray (5GY 4/1) sand (98% sand, <1% silt, 2% clay); single grained; loose; neutral.

Typical pedon from marsh edge (Mollic Endoaquent):

A1- 0 to 8 cm; greenish black(10Y 2.5/1) sandy loam(70% sand, 14% silt, 16% clay); weak medium granular structure; very friable; many fine roots; common coarse shell fragments; neutral; clear smooth boundary.

A2- 8 to 33 cm; dark greenish gray (10Y 3/1) sandy loam (68% sand, 14% silt, 18% clay); weak medium granular structure; very friable; common fine roots; common coarse shell fragments; neutral; clear smooth boundary.

Cg- 33 to 100 cm; greenish gray (10Y 5/1) sand (98% sand, <1% silt, 2% clay); single-grained; few fine roots; neutral; clear smooth boundary.

The 4-year old D.O.T. Marsh

The soils described as typical of marsh edge and inland both classify as Typic Psammaquents and fit the criteria for the Carteret series. However, there are some important morphological differences between them. The A1 horizon at marsh edge has a slightly darker color than at the inland site indicating a faster rate of organic matter accumulation. This horizon, however, is of insufficient thickness to qualify as a mollic epipedon. The pedon from the inland site has an A1 horizon with very high sand content which decreases in the A2 horizon. The pedon at the inland site also has redoximorphic iron concentrations within the A1 and A2 horizons, a feature generally absent in the peraquic conditions of most salt marshes. This suggests relatively well aerated conditions. The marsh edge which is lower in elevation and more frequently flooded lacks these iron concentrations.

Typical pedon from inland portion of marsh (Typic Psammaquent):

A1- 0 to 10 cm; dark greenish gray (5GY 4/1) sand (97% sand, <1% silt, 3% clay); common fine prominent brown (10YR 4/3) iron concentrations; weak fine granular structure; very friable; common fine roots; few very fine shell fragments; neutral; clear smooth boundary.

A2- 10 to 23 cm; dark greenish gray (5GY 4/1) sand (90% sand, 4% silt, 5% clay);

few fine prominent (10YR 4/3) iron concentrations; weak fine granular structure; very friable; few fine roots; few very fine shell fragments; neutral; clear smooth boundary;

Cg- 23 to 100 cm; greenish gray (10GY 5/1) sand (93% sand, 3% silt, 4% clay); single-grained; loose; few very fine shell fragments; neutral; clear smooth boundary.

Typical pedon from marsh edge(Typic Psammaquent):

A1- 0 to 5 cm; dark greenish gray (10GY 3/1) sand (91% sand, 4% silt, 5% clay); weak fine granular structure; very friable; common fine roots; few very fine shell fragments; neutral; clear smooth boundary.

A2- 5 to 10 cm; dark greenish gray (10GY 4/1) sand (95% sand, 1% silt, 4% clay); weak fine granular structure; very friable; few fine roots; few very fine shell fragments; neutral; clear smooth boundary.

Cg- 10 to 100 cm; greenish gray (5GY 5/1) sand (97% sand, <1% silt, 3% clay); single grained; loose; few very fine shell fragments; neutral.

The 11-year old Port Marsh

In this marsh there is a clear difference in soil morphology between marsh edge and inland. While both positions have developed a greenish black color in the A1 horizon, this horizon is thicker and of finer texture at the marsh edge. The developing soils of the Port marsh are underlain by an Ab (buried A) horizon at depths ranging from approximately 25 to 40 cm. The presence of this fine-textured horizon alters the soil classification at the inland site from what would otherwise be a Typic Psammaquent to a Typic Endoaquent. Similarly, this horizon alters the classification of the marsh edge soil from what would otherwise be a Mollic Psammaquent to a Mollic Endoaquent.

Typical pedon from inland part of the marsh (Typic Endoaquent):

A1- 0 to 8 cm; greenish black (10GY 2.5/1) loamy sand (87% sand, 5% silt, 8% clay); weak fine granular structure; very friable; many fine roots; few very fine shell fragments; neutral; clear smooth boundary.

Cg- 8 to 43 cm; greenish gray (10GY 5/1) sand (98% sand, <1% silt, 2% clay); single grained; loose; few fine roots; few very fine shell fragments; neutral; clear smooth boundary.

2Ab- 43 to 76 cm; dark greenish gray (10Y 3/1) loam (46% sand, 34% silt, 20% clay); massive; friable; slightly sticky and moderately plastic; many fine roots; neutral; gradual smooth boundary;

2Cg- 76 to 100 cm; dark greenish gray (10Y 3/1) loamy sand (87% sand, 6% silt, 7% clay); massive; very friable; neutral.

Typical pedon from marsh edge (Mollic Endoaquent):

A1- 0 to 15 cm; greenish black (5GY 2.5/1) sandy loam (70% sand, 16% silt, 14% clay); weak fine granular structure; very friable; few fine roots; few coarse shell fragments; neutral; clear smooth boundary.

Cg- 15 to 33 cm; greenish gray (5GY 5/1) sand (96% sand, 1% silt, 2% clay); single grained; loose; neutral; clear smooth boundary.

2Ab- 33 to 64 cm; dark greenish gray (10Y 3/1) sandy loam (59% sand, 26% silt, 15% clay); massive; friable; slightly sticky and moderately plastic; neutral; gradual smooth boundary.

2Cg1- 64 to 81 cm; dark greenish gray (10Y 3/1) loamy sand (88% sand, 5% silt, 7% clay); massive; very friable; neutral; clear smooth boundary.

2Cg2- 81 to 100 cm; dark greenish gray (10Y 4/1) sand (92% sand, 3% silt, 5% clay); single grained; loose; neutral.

The 29-year old Marine Lab Marsh

In this marsh the soils at three positions along a transect were described. This revealed that there is a gradient in soil morphology from Typic Psammaquent at the upland margin to Mollic Psammaquent at the inland position to Mollic Endoaquent at marsh edge. Thickness of the A1 horizon and silt/clay content increase as distance from the marsh edge decreases. The soil becomes developmentally older as the marsh edge is approached. The textural class of the A1 changes progressively from loamy sand at upland margin to sandy loam at inland position to clay loam at marsh edge. At the upland margin, the A1 horizon has a color value of 3 but its thickness is less than the 15 cm required for a Mollic epipedon. At the inland position, the thickness of the A1 horizon is sufficient to qualify as a Mollic epipedon but the sandy loam material does not occur within the control section and therefore the pedon still classifies as a Psammaquent. At the edge position, both the thickness of the dark colored epipedon and the presence of fine-textured material within the control section cause this pedon to classify as a Mollic Endoaquent.

Typical pedon from upland margin (Typic Psammaquent):

A1- 0 to 10 cm; dark greenish gray (10Y 3/1) loamy sand (86% sand, 5% silt, 9% clay); weak fine granular structure; very friable; many fine roots; neutral; gradual smooth boundary.

A2 – 10 to 18 cm; dark greenish gray (10Y 4/1) loamy sand; clear smooth boundary.

Cg- 18 to 100 cm; greenish gray (10Y 5/1) sand (95% sand, 4% silt, 1% clay); single-grained; loose; neutral.

Typical pedon from inland position (Mollic Psammaquent)

A1 – 0 to 18 cm; dark greenish gray (10Y 3/1) sandy loam; many fine roots; neutral; gradual smooth boundary.

A2 – 18 to 28 cm; dark greenish gray (10Y 4/1) loamy sand; common fine roots; neutral; clear smooth boundary.

Cg – 28 to 100 cm; greenish gray (10Y 5/1) sand; few fine roots; neutral; clear smooth boundary.

Typical pedon from marsh edge (Mollic Endoaquent):

A1- 0 to 23 cm; dark greenish gray (10Y 3/1) clay loam (24% sand, 37% silt, 39% clay); weak medium granular structure; very friable; common fine roots; common coarse shell fragments; neutral; gradual smooth boundary.

A2- 23 to 38 cm; dark greenish gray (10Y 4/1) sandy loam(65% sand, 17% silt, 18% clay); weak medium granular structure; very friable; common fine roots; few fine shell fragments; neutral; clear smooth boundary.

Cg- 38 to 100 cm; greenish gray (10Y 5/1) sand; single grained; loose; few fine shell fragments; neutral.

GEOMORPHOLOGY

The Single Natural Marsh

Figure 6 shows three of the distinctive features of the geomorphology of natural salt marshes. The first is the presence of a berm that follows the marsh edge and which also occurs discontinuously along the small tidal channel that meanders through this section of marsh. These berms form the highest elevation points in the marsh and are believed to develop by the accumulation of sediment carried by tidal currents. The *Spartina* stems slow the tidal currents and cause the heavier particles to drop from suspension. The second feature is the marsh plain, a flat, low lying expanse having minor undulations. During the flood stage of the tidal cycle it is one of the first portions of the marsh to be inundated as water moves up the tidal channel and out across the marsh plain. This tidal channel is the third distinctive feature of the natural marsh. Its outlet is narrow (approximately 1 meter wide) with steep slopes where it dissects the berm. The head of the creek is wider (approximately 3 meters wide) and grades gradually into the surrounding marsh plain. It forms the stem of a well defined dendritic drainage pattern.

The DOT Marsh

The topography of the DOT created marsh is irregular and undulating with numerous isolated depressions which in many cases are unvegetated (Figure 7). Mounds of high ground occur inland at approximately 15-20 meters from marsh edge. These mounds differ from the berm of the natural marsh in terms of their location relative to marsh edge, irregular distribution, and extremely coarse soil texture. These characteristics suggest that the mounds are not the result of deposition from tidal currents but rather are the result of storm deposition, a force powerful enough to carry sand inland a great distance. Indeed, the mitigation report for this marsh mentions considerable sand accretion in the wake of hurricane Bertha and attributes this accretion to placement of a line of “biologs” which stabilize the site (NC Department of Transportation, 1996). This marsh is located in the middle of a sound and is more exposed than any of the other marshes. Thus, its seemingly random swells and swales may be an expression of the unusually dynamic location of this marsh. Despite the young age of this marsh, there is some indication of development of a drainage network.

The DOT marsh has the highest elevation of the four marshes studied. Tidal gage data from one month indicates that one of the high elevation points underwent flooding only 16% of the time. This infrequent and shallow flooding regime has potential implications for the development and ecological functions of this marsh community. Seagulls (*Larix spp*.) are extremely prevalent here and nest on these high elevation mounds. It is also likely that the isolation of this marsh island affords them protection from predators. Colonization of high elevation areas in the marsh by sea lavendar (Limonium spp.) also suggests that these sites may over time develop more of the characteristics of a high marsh community. The infrequent flooding regime also means that there is less opportunity for deposition of fine sediment and that the soils here are likely to remain sandy.

The Port and Marine Lab Marshes

The topography of the Port and Marine Lab marshes (Figures 8 and 9) is similar and consists of a smooth surface in which the lowest elevation and most frequently flooded areas are at the marsh edge. These areas grade gradually into the uplands and result in the highest marsh elevations occurring inland. The smooth topography results from the grading process when the marsh was established. Despite the age of these marshes, the topography has changed little except for accretion at the marsh edges. Based on thickness of the pedogenic horizons over the basal sand (parent material or C horizon), it appears that the Port marsh edge has accreted as much as 15 cm of soil since establishment while accretion at the inland area of the Port marsh could be as much as much as 8 cm though based on the coarser texture of the surface horizon, it is probably much less. The Marine Lab marsh edge has accreted as much as 38 cm since establishment while the inland and upland margin may have accreted as much as 18 and 28 cm, respectively. Not all of this material represents new deposition. Some of the sand is reworked parent material that has been mixed with the newly deposited sediment by the burrowing activity of fiddler crabs (*Uca spp*.).

These two marshes differ from the natural marsh in that they show neither the development of a drainage network nor the formation of berms at the marsh edge. As with the DOT marsh, location and exposure of the marsh may determine geomorphology. These marshes are more sheltered than the DOT marsh and the lower energy tidal currents probably carry little sand. Their location is somewhat nearer the mouth of the Newport River and thus riverine rather than oceanic influences may predominate. Lack of a drainage network means that the process of flooding at these sites is somewhat different from that in the natural marsh. The flood water enters and leaves the marsh as a uniform sheet of water rather than in distinct channels. Research suggests that these channels are important conduits for fish to access the marsh surface (Desmond et al., 2000). The presence of a berm at the marsh edge may also retain flood water longer since it constrains water to leave via a narrow channel. This increases foraging opportunities for fish on the marsh plain. Longer retention of flood water also provides increased opportunity for deposition of silt and clay which results in the fine textured soils that characterize the inland portion of many natural marshes.

DISCUSSION

The edge soils of the natural marsh are higher in bulk density, sand, MOM-N, MOM-P, and lower in soil carbon and clay than the inland soils. Many of these relationships are reversed in the Port and Marine Lab marshes. The edge soils of those marshes are higher in soil carbon, soil nitrogen, silt, clay, porosity and lower in bulk density and sand than the inland soils. Evidently, there are different rates of soil development at different positions in created marshes. Based on the characteristics of the C horizon, we assume that the soil in these marshes at the time of establishment was sandy and homogeneous and that all spatial differences in soil characteristics are due to different rates of pedogenic processes. Lack of spatial differences in soil development at the DOT marsh probably indicates that insufficient time has passed for different rates of soil development to become evident. Given the 29 years age of the Marine lab marsh, it appears that these spatial differences can persist for considerable time.

There are spatial differences in the vegetation of created marshes and they have many of the characteristics attributed to natural marshes. The DOT marsh has taller stem growth at marsh edge than inland. The Port marsh has taller stem growth and lower stem density at marsh edge than inland. The Marine Lab marsh has taller stems, lower stem density, and higher biomass at marsh edge than inland. However, it is ironic that the single natural marsh in this study exhibits only one of the spatial patterns often attributed to natural marshes. It has greater biomass production at marsh edge than inland. However, given the much larger size of the natural marsh relative to the created marshes it may be that spatial patterns in vegetation in this natural marsh only become evident over distances greater than 15 meters.

The edge positions in the Port and Marine Lab marshes readily accumulate fine sediment while the inland positions fail to accumulate silt and clay. One explanation for this difference is that the inland positions are higher in elevation and are flooded for shorter durations than the edge. Therefore, less time is available per tidal cycle for deposition of fine sediment. However, the elevational differences between positions are generally slight and result in only a 2% decrease in flooding duration between edge and inland positions of the Port Marsh. Therefore, other factors besides elevation are probably involved. The absence of a berm at the marsh edge may mean that tidal water ebbs more quickly from the gently sloping inland part of the marsh and therefore silt and clay are not deposited there.

The inland areas of the Port and Marine Lab marshes also have less soil C than the marsh edge. This is surprising because the major source of C to marsh soils is the *Spartina* MOM. The MOM accumulation at the inland positions in these created marshes is greater or not significantly different from that at the marsh edge. Therefore, if MOM accumulation is not different between positions then there may be some process that preferentially removes C from the soil at the inland part of the marsh. Faster oxidation of MOM is one possible explanation but the lack of significant differences in redox potential between the positions (Table 7) suggests that the positions are equally anaerobic. Another possible explanation is that carbon is more readily flushed from the sandy soils of the inland marsh than from the finer textured soils at the marsh edge. Differences in soil N are more difficult to account for as there are several potential sources of nitrogen to created marshes. Some possible sources of nitrogen are N-fixing cyanobacteria at the marsh surface, heterotrophic N fixing bacteria within the rhizospheres of plant roots, nitrogen in tidal water, and atmospheric inputs. Again, different subsurface flow rates between positions could be an explanation.

It is difficult to determine whether position (horizontal distance) or elevation (vertical distance) exerts a greater influence on the development of soil properties within created marshes. In the Port and Marine Lab marshes these variables are closely correlated and the Pearson correlation coefficients are equal to 0.95 and 0.97 for the two respective marshes. The correlation is weaker in the DOT marsh where $r = 0.41$. For comparison, the natural marsh has a correlation of position and elevation of – 0.56.

The marsh edge soil eventually develops the morphology and classification of nearby natural marshes, but the inland soil remains developmentally younger. Soil morphology and classification are thus potential tools for assessing the development of created marshes. In this study area, the morphology of Mollic Endoaquents are a standard against which nearby created marshes can be compared. Among the positions of the three created marshes, only the edge soils of the Marine Lab marsh meet the criteria. In other areas of the estuarine system, different soil classifications are appropriate standards. For instance, in the Newport River system, true examples of Carteret sand (Typic Psammaquents) are most likely to occur in back barrier island settings. These marshes are historically subject to overwash of sand from the barrier islands and due to their longer distance from rivers, they have very low inputs of silt and clay. On the other extreme, true examples of Hobucken muck (Typic Hydraaquents) are more likely to occur near the outlet of the river in relatively sheltered settings with more inputs of silt and clay than of sand. The created marshes in this study are located in an intermediate zone represented by the intermediate characteristics of Mollic Endoaquents.

The geomorphology of the created marshes is the reverse of that of the natural marsh. Despite their differences, they all have low elevation edges and high elevation interiors. The inland parts of these marshes slope gently and have little to no drainage system. Although the Port marsh was constructed with a large channel through it, no secondary channels have developed within the study area. The processes that lead to development of a drainage system are unclear, however, construction of marshes with flatter interiors with greater micro-relief might encourage rivulets to form which could develop into channels. These channels would be "hot spots" for exchange of water and organisms with the marsh plain. There would be more edges in a marsh with this design and diversity of habitats would increase. Likewise, construction of a berm at marsh edge would cause ebbing water to break through the berm at discrete points. These outlets might then be fed by developing channels in the marsh plain.

While the DOT marsh is still relatively new, the Port and Marine Lab sites have been in place long enough to be evaluated. Both the Port and Marine Lab sites show spatial differences in soil development that indicate that part of the marsh is not developing toward the desired standard. This portion is the area of each marsh that still classifies as a Typic Psammaquent soil. However, the proportions of this soil type are different in the two marshes. Visual estimates suggest that about 50% of the Marine Lab marsh has soil meeting this criterion while less than 25% of the Port marsh would meet it. This difference between the two marshes appears to be due to the construction of a tidal creek through the middle of the Port marsh which maximizes the extent of "edge" such that few places in the marsh are more than 10 meters from open water. Thus, the inclusion of a tidal creek in the project design appears to have increased the areal extent of soil development.

There is a temptation to over-engineer marsh creation projects. Ultimately, some of the developing marsh's characteristics will be a function of its location relative to various sediment sources. In the case of the DOT marsh, the low *Spartina alterniflora* marsh that was planted to replace a brackish *Juncus roemerianus* marsh may ultimately develop into a high salt marsh with yet another suite of species. Understanding and working with the processes operative at a site will increase the effectiveness of wetland creation efforts.

REFERENCES

Adams, D.A. 1963. Factors influencing vascular plant zonation in North Carolina salt marshes. Ecology 44(3):445-456.

Amoozegar, A. and G.V. Wilson. 1999. Methods for measuring hydraulic conductivity and drainable porosity. p.1149-1206. *In* R.W. Skaggs and J. Van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, SSSA, Madison, WI.

Anderson, C.M. and M Treshow. 1980. A review of environmental and genetic factors that affect height in Spartina alterniflora Loisel.(salt marsh cordgrass). Estuaries 3(3):168-176.

Blake, G.R. and K.H. Hartge. 1986. Bulk density. p. 363-376. *In* A. Klute (ed.) Methods of soil analysis: physical and mineralogical methods. Agron. Monogr. 9. ASA, CSSA and SSSA, Madison, WI.

Broome, S.W., W.W. Woodhouse,Jr, and E.D. Seneca. 1975. The relationship of mineral nutrients to growth of Spartina alterniflora in North Carolina: II. The effects of N, P, and Fe fertilizers. Soil Science Society of America Proceedings 39:301-307.

Cooper, A. 1982. The effects of salinity and waterlogging on the growth and cation uptake of salt marsh plants. The New Phytologist 90:263-275.

Craft, C., S.Broome, and C. Campbell. 2002. Fifteen years of vegetation and soil development after brackish-water marsh creation. Restoration Ecology 10(2):248-258.

Craft, C., P.M. Megonigal, S.W. Broome, J. Cornell, R.C. Freese, J. Stevenson, L. Zheng, J.N. Sacco. The pace to ecosystem development of constructed Spartina alterniflora marshes. Ecol. Appl.(In press).

Danielson, R.E. and P.L. Sutherland. 1986. Porosity. p. 443-462. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9 (part 1) ASA and SSSA, Madison, WI.

Desmond, J.S., J.B. Zedler, G.D. Williams. 2000. Fish use of tidal creek habitats in two southern California salt marshes. Ecological Engineering 14:233-252.

Frey, R.W. and P.B. Basan. 1978. Coastal salt marshes. P.101-170. *In* R.A. Davis (ed.) Coastal sedimentary environments. Springer-Verlag, New York.

Gardner, L.R. 1973. The effect of hydrologic factors on the pore water chemistry of interstitial marsh sediments. Southeast Geology 15:17-28.

Gee, G.W. and J.W.Bauder. 1986. Particle size analysis. p. 383-412. *In* A. Klute(ed.) Methods of soil analysis: physical and mineralogical methods. Agron. Monogr. 9. ASA, CSSA and SSSA, Madison, WI.

Goodwin, R.A. 1978. Soil Survey of Carteret County, North Carolina, U.S. Department of Agriculture, Soil Conservation Service.

Howes, B.L., R. W. Howarth, J.M. Teal, and I. Valiela. 1981. Oxidation-reduction potentials in a salt marsh: Spatial patterns and interactions with primary production. Limnology and Oceanography 26(2):350-360.

Howes, B.L., J.W.H. Dacey, and D.D. Goehringer. 1986. Factors controlling the growth form of Spartina alterniflora: feedbacks between above-ground production, sediment oxidation, nitrogen and salinity. Journal of Ecology 74:881-898.

Leonard, L.A. 1997. Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina. Wetlands 17(2):263-274.

Levin, L.A., D. Talley, and G. Thayer. 1996. Succession of macrobenthos in a created salt marsh. Marine Ecology Progress Series 141:67-82.

Lindau, C.W. and L.R. Hossner. 1981. Substrate characterization of an experimental marsh and three natural marshes. Soil Science Society of America Journal. 45:1171-1176.

Mendelssohn, I.A. 1979. Nitrogen metabolism in the height forms of Spartina alterniflora in North Carolina. Ecology 60:574-584.

Mendelssohn, I.A. and E.D. Seneca. 1980. The influence of soil drainage on the growth of salt marsh cordgrass *Spartina alterniflora* in North Carolina. Estuarine and Coastal Marine Science 11:27-40.

Moy, L.D. and L.A. Levin. 1991. Are Spartina marshes a replaceable resource? A functional approach to evalueation of marsh creation efforts. Estuaries 14(1): 1-16.

NC Department of Transportation. 1996. As-built report of wetland mitigation, Bridges Street extension, Morehead City. Permits and Wetland Mitigation Unit, Raleigh, NC

Osgood, D.T. and J.C. Zieman. 1993. Spatial and temporal patterns of substrate physicochemical parameters in different-aged barrier island marshes. 37:421-436.

Sarda, R., K. Foreman, and I. Valiela. 1995. Macroinfauna of a southern New England salt marsh: seasonal dynamics and production. Marine Biology 121:431-445.

Soil Survey Staff. 1996. Keys to soil taxonomy, seventh edition. U.S. Department of Agriculture, Natural Resources Conservation Service.

Stumpf, R.P. 1983. The process of sedimentation on the surface of a salt marsh. Estuarine, Coastal and Shelf Science. 17: 495-508.

Valiela,I. and J.M. Teal. 1974. Nutrient limitation in salt marsh vegetation. *In* Ecology of Halophytes (Ed. R.J. Reimold and W. H. Queen). Academic Press, New York.

Valiela, I., J.M. Teal, and W.G. Deuser. 1978. The nature of growth forms in the salt marsh grass Spartina alterniflora. 112:461-469.

Wiegert, R.G., A.G. Chalmers, and P.F. Randerson. 1983. Productivity gradients in salt marshes: the response of Spartina alterniflora to experimentally manipulated soil water movement. Oikos 41:1-6.

Yelverton, G.F. and C.T. Hackney. 1986. Flux of dissolved organic carbon and pore water through the substrate of a Spartina alterniflora marsh in North Carolina. Estuarine, coastal and shelf science 22:255-267.

TABLES

Table 2-1. Some characteristics of study marshes and positions within marshes.

Marsh	Age (years)	Width (m)	position	distance	Soil classification	Elevation (m)	Flooding
DOT	4	40 - 72	inland	15	Typic Psammaquent	0.943 - 1.296	14%
			edge	1	Typic Psammaquent	0.973 - 1.104	38%
Port	11	25 - 37	inland	15	Typic Endoaquent	0.704 - 0.744	65%
			edge	1	Mollic Endoaquent	0.407 - 0.552	67%
Marine Lab	29	36 - 46	upland margin	30	Typic Psammaquent	0.901 - 0.956	
			inland	15	Mollic Psammaquent		
			edge	1	Mollic Endoaquent	0.501 - 0.645	
Natural			inland	15	Mollic Endoaquent	0.868 - 1.048	43%
			edge	1	Mollic Endoaquent	0.999 - 1.115	41%

Table 2-2. Means and standard errors (SE) for soil properties of Natural marsh. The last set of columns are the significance of position and depth factor effects for split-plot design. Bolded p-values indicate a significant ($p < 0.05$) factor effect.

		0-10 cm		10-30 cm		p-values		
variable	position	mean	SE	mean	SE	position	depth	posxdep
Soil-C (mmol kg^{-1})	inland	2168	306	1474	167	**0.05**	0.25	0.32
	edge	1027	403	1149	202			
Soil-N (mmol kg^{-1})	inland	131.4	15.7	80	9.93	0.055	0.12	0.22
	edge	69	22.7	69.6	9.83			
Soil-P (mmol kg^{-1})	inland	10.6	0.75	5.28	0.84	0.459	0.002	0.21
	edge	7.9	1.99	5.35	1.03			
sand (%)	inland	67.7	2.86	79.9	3.4	0.1	**0.042**	0.15
	edge	84.2	5.66	83.6	3.1			
silt (%)	inland	16.1	1.57	8.5	1.9	0.39	**0.026**	0.12
	edge	8.3	2.83	9	2.5			
clay (%)	inland	16.2	1.34	11.5	1.6	**0.021**	0.088	0.2
	edge	7.5	2.77	7.4	1.3			
Ksat-lateral (m d^{-1})	inland	1.097	0.606	3.748	0.343	0.805	**0.004**	0.205
	edge	0.262	0.039	5.041	1.660			
Ksat-vertical (m d^{-1})	inland	1.152	0.416	10.698	2.288	0.315	**0.005**	0.315
	edge	0.684	0.363	16.129	4.806			
Total porosity	inland	0.66	0.017	0.67	0.033	0.053	0.97	0.76
	edge	0.56	0.056	0.56	0.03			
Macroporosity	inland	0.021	0.01	0.068	0.019	**0.036**	0.15	0.054
	edge	0.019	0.007	0.011	0.007			
Bulk density (g cm^{-3})	inland	0.61	0.03	0.81	0.05	**0.031**	**0.013**	0.16
	edge	0.93	0.11	1	0.09			
MOM dry wt.(g m^{-3})	inland	23647	3465	15940	2876	**0.0004**	0.25	0.17
	edge	7718	957	8465	1515			
MOM-N (mmol kg^{-1})	inland	678	35.1	438	30.2	**0.007**	**0.005**	0.06
	edge	824	64.9	760	74.4			
MOM-C/N	inland	41.2	0.64	41.9	1.1	0.32	0.4	0.71
	edge	38.4	2.66	40.3	2			
MOM-P (mmol kg^{-1})	inland	16	1.31	10.2	0.76	**0.028**	0.18	0.94
	edge	24.9	6.94	18.5	1.97			

Table 2-3. Means and standard errors (SE) for soil properties of DOT marsh. The last set of columns are the significance of position and depth factor effects for split-plot design. Bolded p-values indicate a significant ($p < 0.05$) factor effect.

		0-10 cm		10-30 cm		p-values		
variable	position	mean	SE	mean	SE	position	depth	posxdep
Soil-C (mmol kg^{-1})	inland	360	35.7	108	9.48	0.86	**< 0.0001**	0.36
	edge	342	49.1	140	29.7			
Soil-N (mmol kg^{-1})	inland	27.1	3.91	7	0*	0.68	**0.0034**	0.63
	edge	22.8	5.34	7	0*			
Soil-P (mmol kg^{-1})	inland	11.7	0.58	7.74	0.74	0.27	0.003	0.14
	edge	10	0.47	8.22	0.62			
sand (%)	inland	86	1.67	93.3	0.54	0.71	**0.0002**	0.84
	edge	85.7	1.69	92.5	0.98			
silt (%)	inland	8	0.82	4.2	0.21	0.47	**0.0001**	0.58
	edge	8.5	1.16	5.2	0.74			
clay (%)	inland	5.9	0.88	2.5	0.33	0.79	**0.0004**	0.96
	edge	5.8	0.64	2.3	0.45			
Ksat-lateral (m d^{-1})	inland	3.140	0.392	6.628	0.838	0.077	0.096	0.146
	edge	3.315	1.162	3.605	0.727			
Ksat-vertical (m d^{-1})	inland	12.341	2.770	4.863	1.558	0.187	0.075	0.195
	edge	6.111	1.912	4.670	2.026			
Total porosity	inland	0.45	0.013	0.406	0.02	0.55	**0.05**	0.61
	edge	0.48	0.042	0.409	0.01			
Macroporosity	inland	0.008	0.004	0.008	0.007	0.82	0.63	0.56
	edge	0.012	0.005	0.006	0.004			
Bulk density (g cm^{-3})	inland	1.22	0.03	1.53	0.03	0.99	**< 0.0001**	0.94
	edge	1.22	0.08	1.54	0.02			
MOM dry wt.(g m^{-3})	inland	4889	658	3693	618	0.071	0.19	0.44
	edge	2878	871	2546	384			
MOM-N (mmol kg^{-1})	inland	526	35	343	13.7	0.74	**0.001**	0.72
	edge	530	59.3	317	17.9			
MOM-P (mmol kg^{-1})	inland	21.7	3.56	15.4	2.26	0.58	**0.006**	0.54
	edge	25	3.7	16	0.89			
MOM-C/N	inland	66	4.15	88.4	2.7	0.29	**0.0001**	0.62
	edge	62	5.19	81.3	3.92			

Table 2-4. Means and standard errors (SE) for soil properties of Port marsh. The last set of columns are the significance of position and depth factor effects for split-plot design. Bolded p-values indicate a significant ($p < 0.05$) factor effect. P-values preceded by * indicate that separate ANOVA tests were performed by depth.

		0-10 cm		10-30 cm		p-values		
variable	position	mean	SE	mean	SE	position	depth	pos*depth
Soil-C (mmol kg^{-1})	inland	245	39.7	26.6	1.6	* **0.014**	(0-10 cm)	
	edge	766	281	519	422	* 0.31	(10-30 cm)	
Soil-N (mmol kg^{-1})	inland	7.1	0	7.1	0	***0.005**	(0-10 cm)	
	edge	61.4	21.8	30	21.4	* 0.37	(10-30 cm)	
Soil-P (mmol kg^{-1})	inland	9	0.86	7.28	0.3	0.0014	<0.0001	**0.002**
	edge	14.82	0.83	8.62	0.35			
Bulk density (g cm^{-3})	inland	1.24	0.05	1.61	0.01	**0.002**	**0.0007**	0.38
	edge	0.82	0.16	1.34	0.14			
sand (%)	inland	93.8	0.7	97.3	0.2	**0.007**	0.072	0.26
	edge	74.2	9.6	87.6	7			
silt (%)	inland	3.3	0.7	1.6	0.2	**0.022**	0.25	0.58
	edge	13.2	4.4	8.4	5.2			
clay (%)	inland	2.9	0.9	1.1	0.2	**0.0028**	**0.01**	0.06
	edge	12.6	5.4	4	1.8			
Ksat-lateral (m d^{-1})	inland	7.247	1.29	8.693	0.722	**0.033**	0.57	0.187
	edge	2.914	1.39	.	.			
Ksat-vertical (m d^{-1})	inland	19.873	0.68	5.605	2.224	**0.013**	**0.032**	.
	edge	8.235	2.348	.	.			
Total porosity	inland	0.51	0.04	0.4	0.01	**0.006**	**0.0004**	**0.033**
	edge	0.72	0.1	0.44	0.05			
Macroporosity	inland	0.022	0.017	0.001	0.003	0.25	0.82	0.33
	edge	0.02	0.027	0.034	0.025			
MOM dry wt.(g m^{-3})	inland	7654	1341	1773	416	0.85	**< 0.0001**	0.98
	edge	7482	3237	1558	670			
MOM-N (mmol kg^{-1})	inland	447	60.9	393	27	0.37	0.99	0.51
	edge	463	45.3	520	151			
MOM-P (mmol kg^{-1})	inland	11.8	2.2	11.3	0.73	*0.096	(0-10 cm)	
	edge	15.4	4	35.1	24	*0.38	(10-30 cm)	
MOM-C/N	inland	69.9	8.1	68.2	6.8	*0.36	(0-10 cm)	
	edge	66.1	1	76.7	20.7	*0.71	(10-30 cm)	

Table 2-5. Means and standard errors (SE) for soil properties of Marine Lab marsh. Bolded P-values indicate a significant factor effect (p>0.05) for position or depth. P-values preceded by * indicate that separate ANOVA tests were performed by depth
.

		0-10 cm		10-30 cm		p-values		
variable	position	mean	SE	mean	SE	position	depth	pos*depth
Soil-C (mmol kg^{-1})	upland margin	1733	177	286	23.5	* **0.027**	(0-10 cm)	
	inland	2583	336	328	44.6			
	edge	2769	341	1154	448	* 0.12	(10-30 cm)	
Soil-N (mmol kg^{-1})	upland margin	107	10.1	7.1	0	***0.007**	(0-10 cm)	
	inland	177	24.1	17.1	1.7			
	edge	210	27.1	85.7	34.8	*0.087	(10-30 cm)	
Soil-P (mmol kg^{-1})	upland margin	15.2	0.81	7.76	0.29	0.074	**<0.0001**	0.4
	inland	.	.	.	.			
	edge	20.6	2.84	12	1.78			
Bulk density (g cm^{-3})	upland margin	0.69	0.04	1.19	0.027	**0.011**	**<0.0001**	0.32
	inland	0.59	0.037	1.25	0.093			
	edge	0.47	0.05	0.85	0.13			
sand (%)	upland margin	84.9	1.3	95.0	0.29	**0.0031**	**0.0002**	**0.014**
	inland	67.1	4.4	94.2	0.40			
	edge	37.6	10.3	67.6	8.45			
silt (%)	upland margin	6.0	0.9	3.5	0.13	**0.0036**	**0.0015**	**0.011**
	inland	11.3	1.7	2.4	0.24			
	edge	29.1	5.1	15.4	3.99			
clay (%)	upland margin	9.2	0.6	1.6	0.26	**0.0029**	**<.0001**	**0.02**
	inland	21.5	2.79	3.5	0.21			
	edge	33.3	5.3	17	4.47			
Ksat-lateral (m d^{-1})	upland margin	2.476	0.499	5.172	2.161	0.057	0.14	0.714
	edge	0.83	0.383	2.513	0.706			
Ksat-vertical (m d^{-1})	upland margin	6.311	1.767	8.505	3.575	0.91	0.483	0.627
	edge	4.733	4.139	9.494	1.38			
Total porosity	upland margin	0.72	0.01	0.41	0.02	**0.021**	**0.0001**	**0.042**
	edge	0.74	0.04	0.59	0.05			
Macroporosity	upland margin	0.05	0.016	0.004	0.002	0.55	0.29	**0.046**
	edge	0.01	0.004	0.027	0.014			
MOM dry wt.(g m^{-3})	upland margin	28797	2011	7588	1247	**0.0002**	**0.0005**	**0.011**
	inland	17009	1507	6137	801			
	edge	14025	2140	8442	1838			
MOM-N (mmol kg^{-1})	upland margin	550	58.6	470	37.6	**0.009**	**0.05**	0.6
	inland	.	.	.	.			
	edge	775	74.7	645	26			
MOM-P (mmol kg^{-1})	upland margin	15.8	1.4	14.7	0.73	**0.01**	0.14	0.4
	inland	.	.	.	.			
	edge	21.8	2.3	18	0.49			
MOM-C/N	upland margin	49.8	1.42	51.3	1.52	0.62	0.14	0.31
	inland	.	.	.	.			
	edge	45.5	3.79	52.9	3.11			

Table 2-6. Comparison of foliar characteristics between positions in 4 marshes.

marsh	variable	position	mean	SE	p-value
Natural	foliar dry wt (g m^{-2})	inland	478	44	**0.04**
		edge	636	48	
	stem density (# stems m^{-2})	inland	189	27	0.81
		edge	198	22	
	mean stem height (cm)	inland	100	10	0.23
		edge	116	6.8	
DOT	foliar dry wt (g m^{-2})	inland	494	71	0.1
		edge	778	133	
	stem density (# stems m^{-2})	inland	226	24	0.52
		edge	252	30	
	mean stem height (cm)	inland	68	2	**0.002**
		edge	109	6.6	
Port	foliar dry wt (g m^{-2})	inland	539	69	0.24
		edge	673	79	
	stem density (# stems m^{-2})	inland	304	36	**0.02**
		edge	189	18	
	mean stem height (cm)	inland	80	2	**< 0.0001**
		edge	115	2.4	
Marine Lab	foliar dry wt (g m^{-2})	upland margin	515	24	**0.0002**
		edge	967	65	
	stem density (# stems m^{-2})	upland margin	264	11	**0.0001**
		edge	173	8	
	mean stem height (cm)	upland margin	69	3.9	**<.0001**
		edge	144	7.2	

Table 2-7. Redox potential at positions in three marshes.

Marsh	position	Eh (mv)	SE	p-value
D.OT	inland	23	29	ns
	edge	5	50	
Marine Lab	inland	-64	11	ns
	edge	-58	21	
Natural	inland	-79	18	ns
	edge	-54	26	

Figure 2-1. Locations of four study marshes. (Image courtesy of U.S. Geologic Survey.)

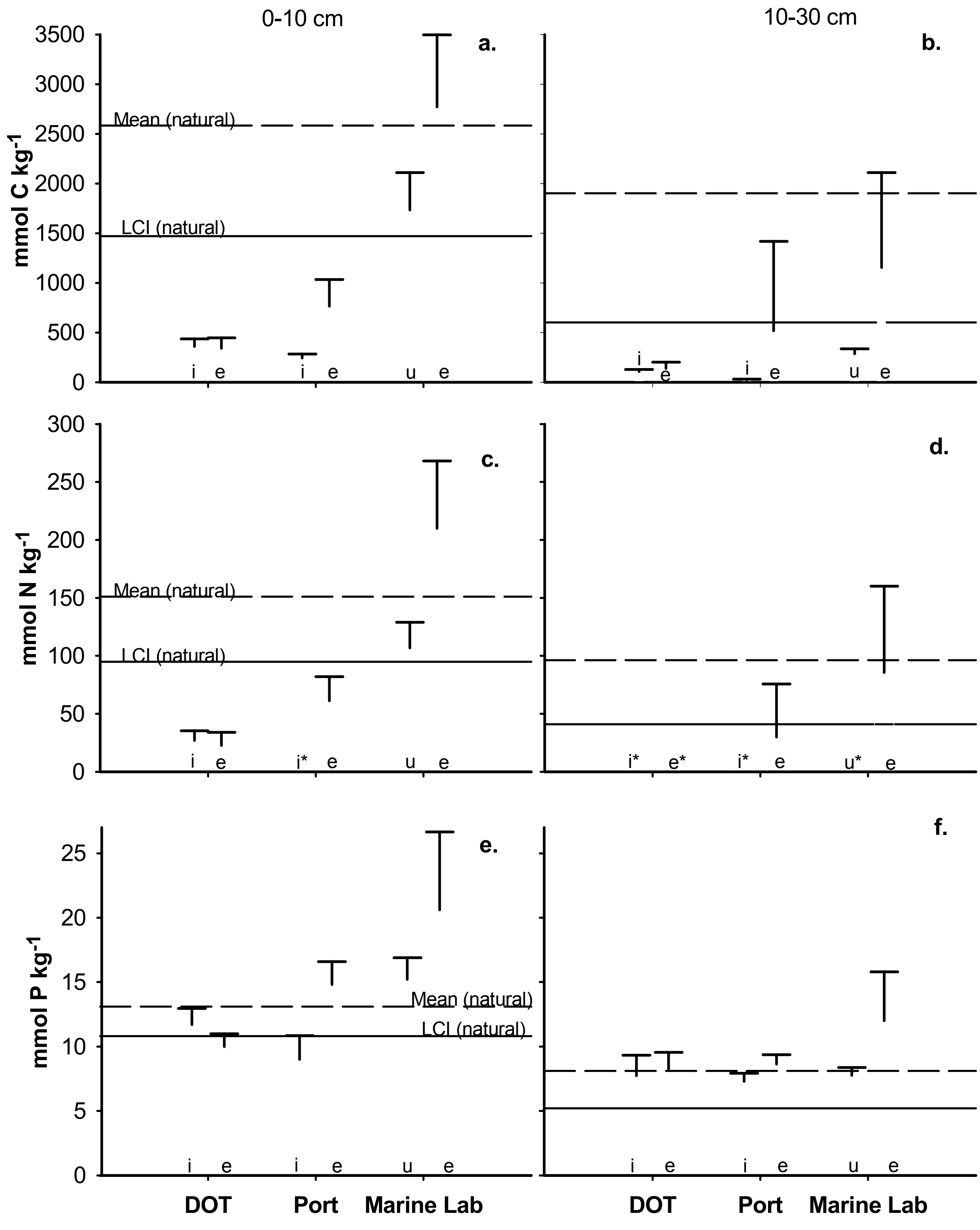


Figure 2-2. Upper confidence intervals (UCI) for soil C,N,P of three created marshes relative to the lower confidence interval (LCI) of the composite natural marsh. Horizontal bar of "T" shows the UCI endpoint, base of "T" shows the mean,e = edge, i = inland, u = upland margin positions. "*" indicates nitrogen levels below detection limit.

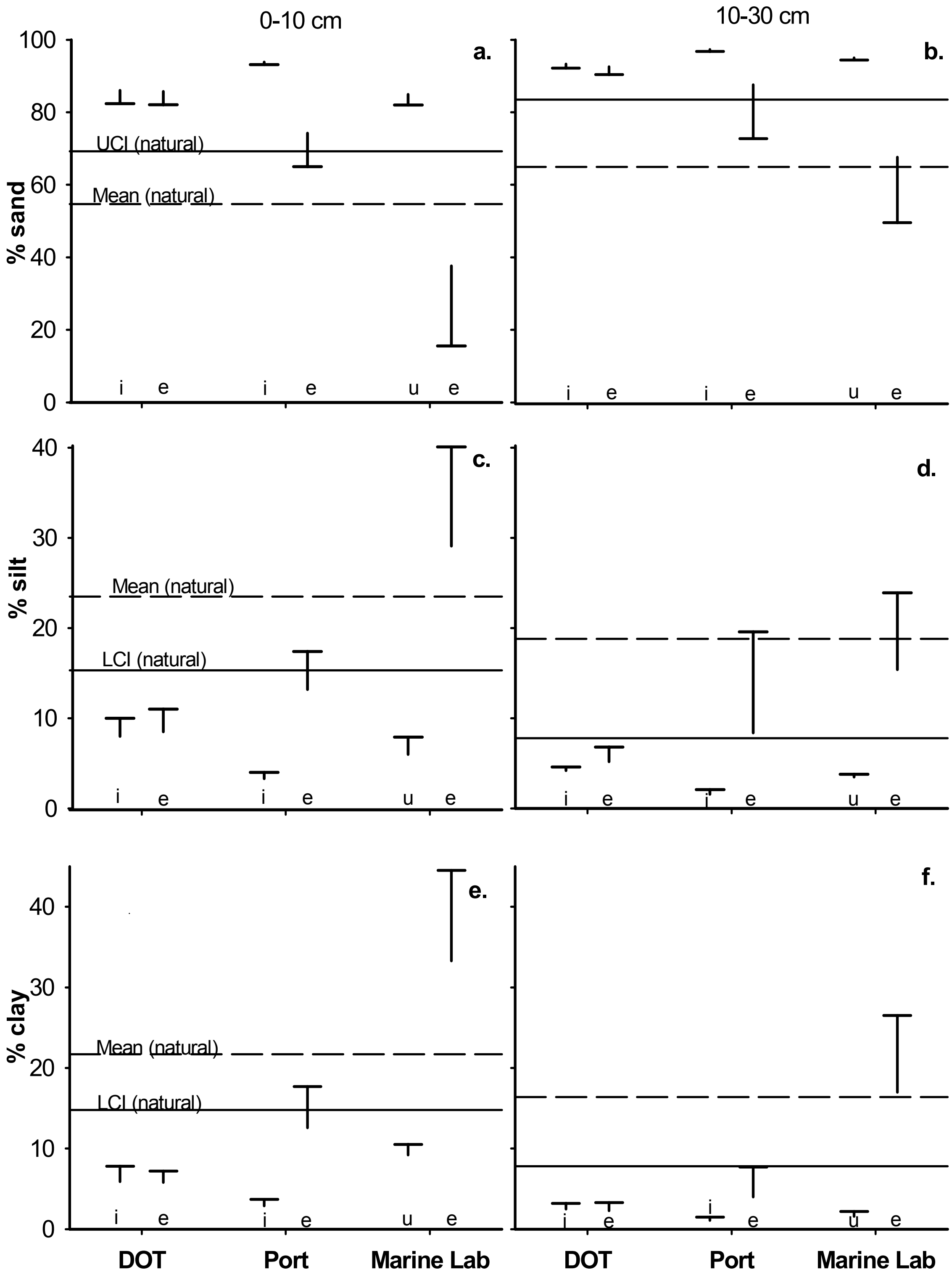


Figure 2-3. Lower/ upper Confidence Intervals (LCI/ UCI) for mean sand, silt, clay of created marshes relative to LCI/ UCI for composite natural marsh. Horizontal bar of inverted "T" shows the LCI endpoint for positions in created marshes,e =edge, i = inland, u = upland margin positions.

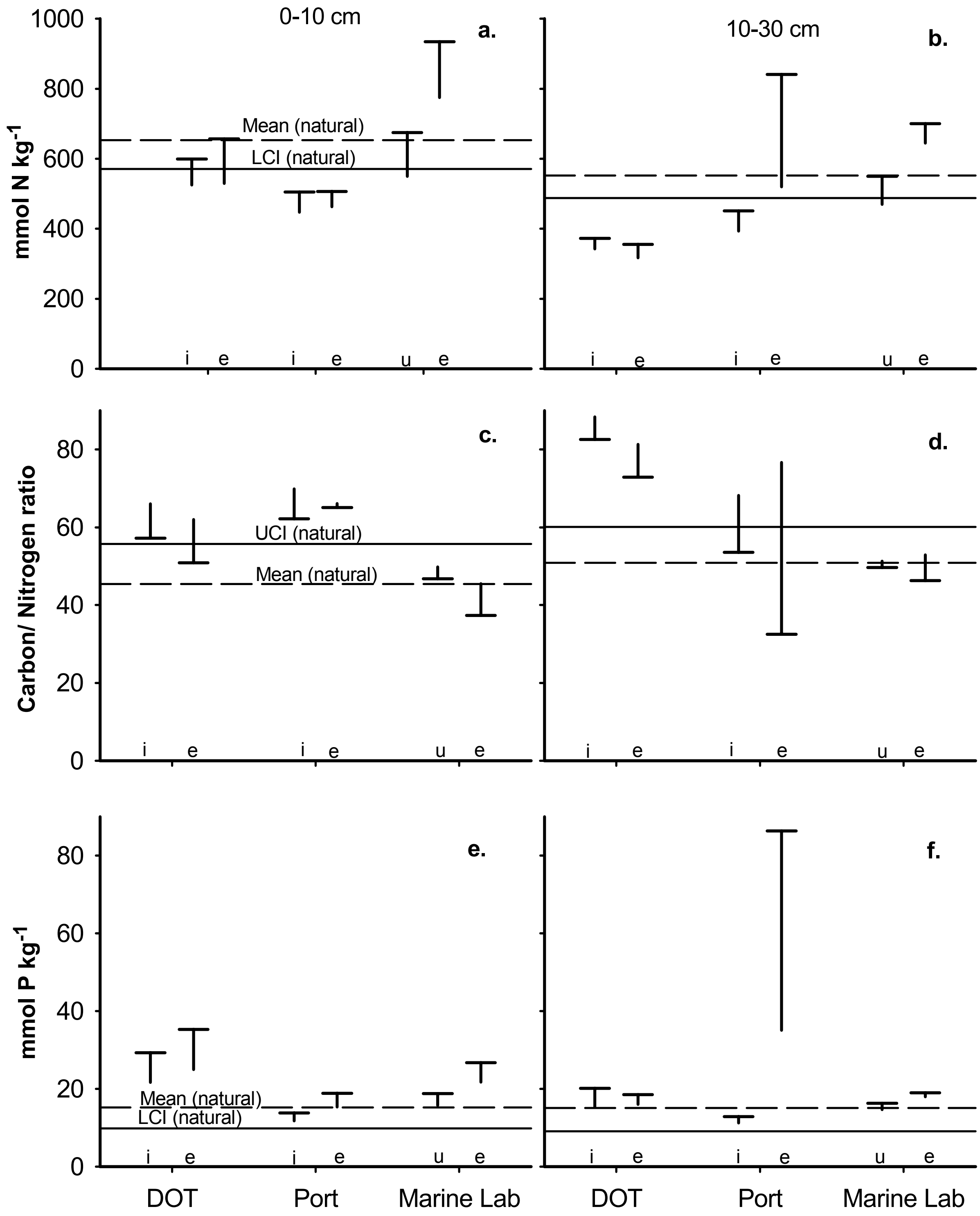


Figure 2-4. Upper/ lower confidence intervals for MOM-N, C/N, P of created marshes relative to LCI/ UCI of composite natural marsh. Horizontal bar of "T" shows the UCI endpoints. Horizontal bar of inverted "T" shows LCI endpoints.

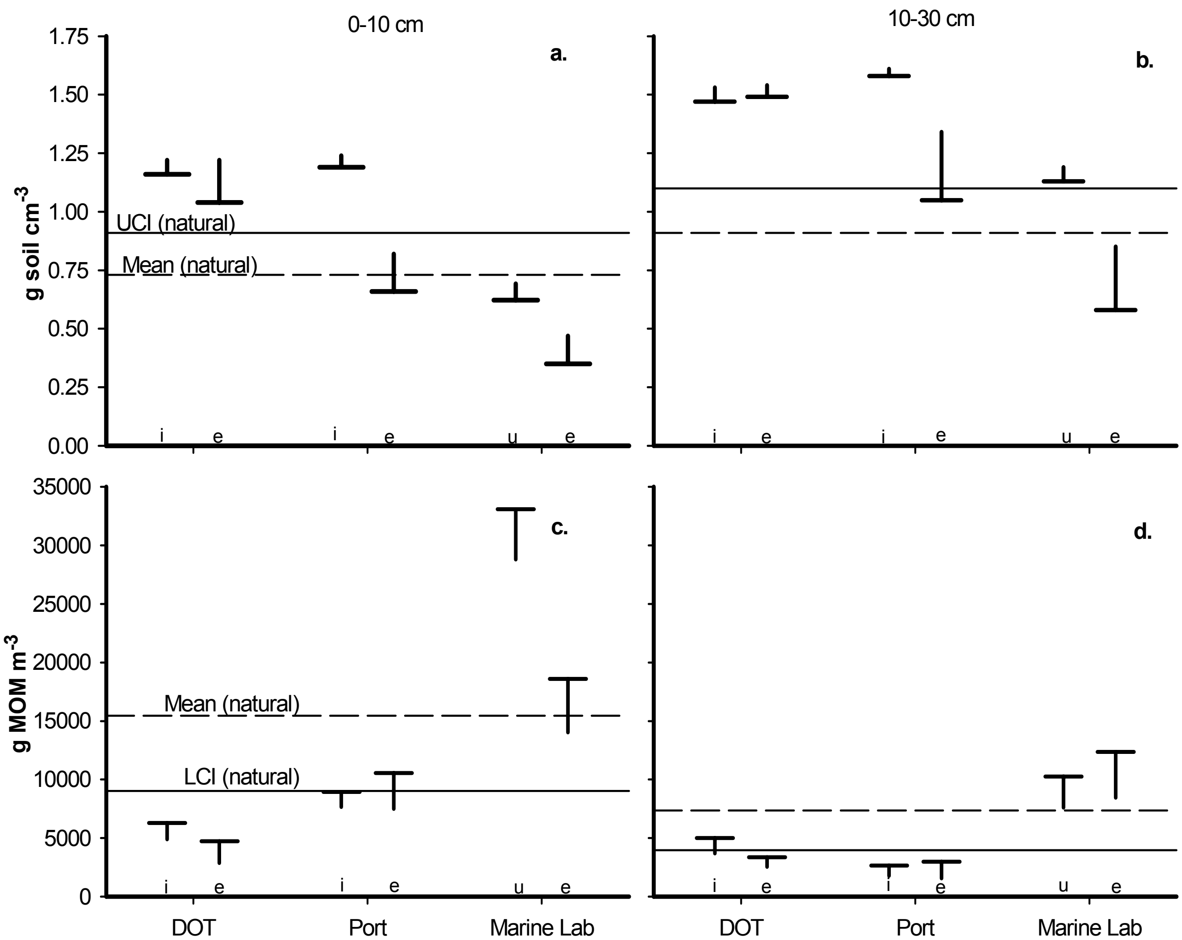


Figure 2-5. Lower/ upper confidence intervals for bulk density and MOM dry weight of created marshes relative to upper/ lower confidence interval of composite natural marsh. Horizontal bar of inverted "T" shows LCI endpoints, horizontal bar of "T" shows UCI endpoints,
e = edge, i = inland, u = upland margin.

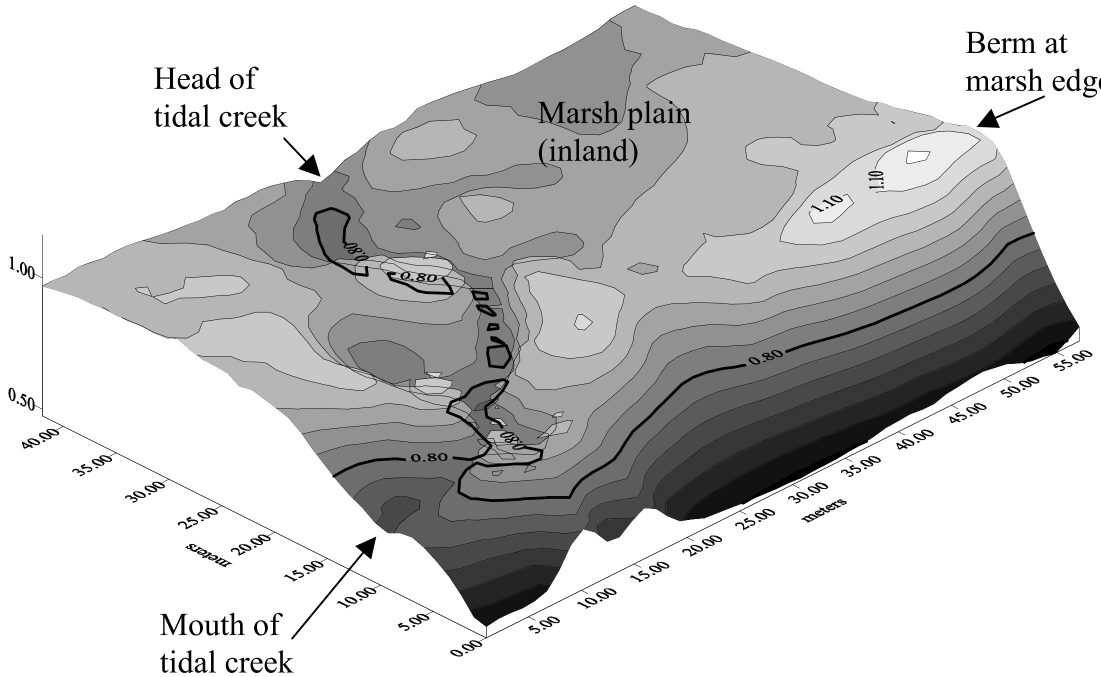


Figure 2-6. Overlay of contour and surface maps for study site in Natural marsh. The 0.80 m contour line is the marsh edge and approximate seaward limit of vegetation.

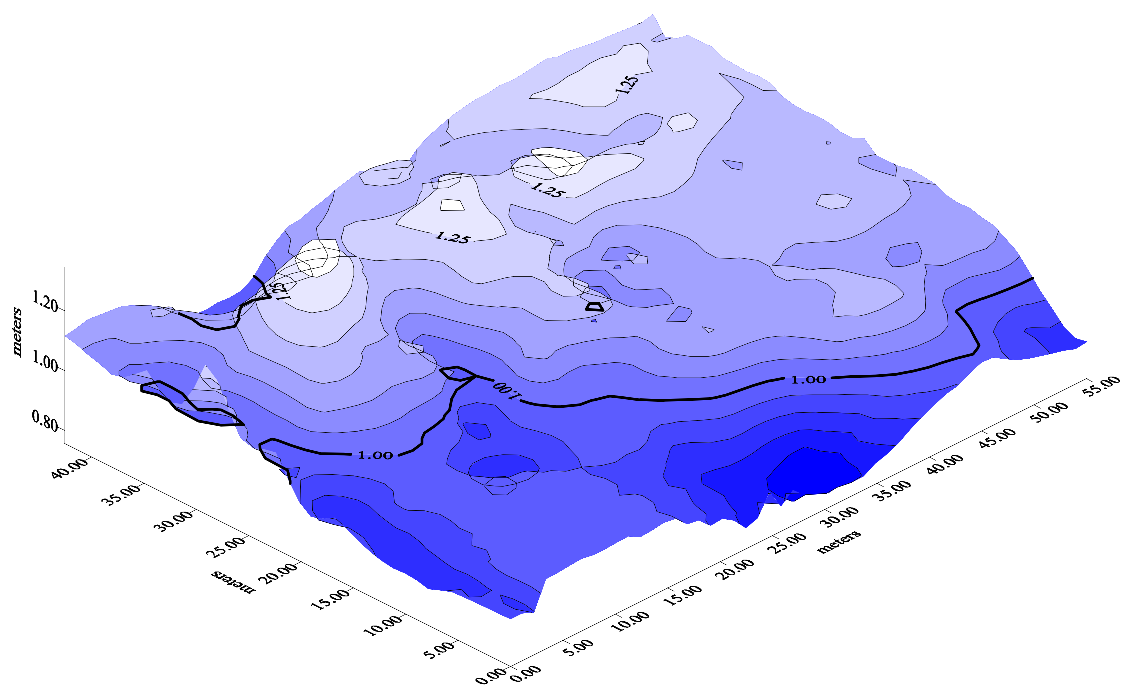


Figure 2-7. Overlay of contour and surface maps for study site in D.O.T. marsh. The 1.00mcontour line is the marsh edge and approximate seaward limit of vegetation.

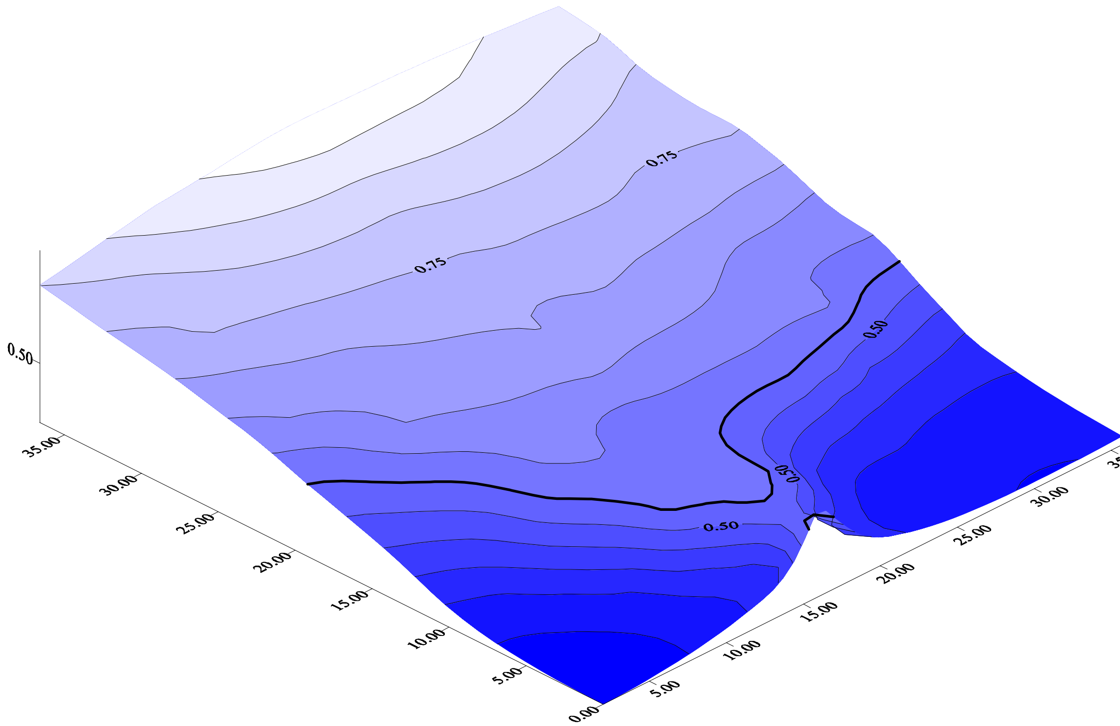


Figure 2-8. Overlay of contour and surface maps for study site in Port marsh. The 0.55 m contour line is the marsh edge and approximate seaward limit of vegetation.

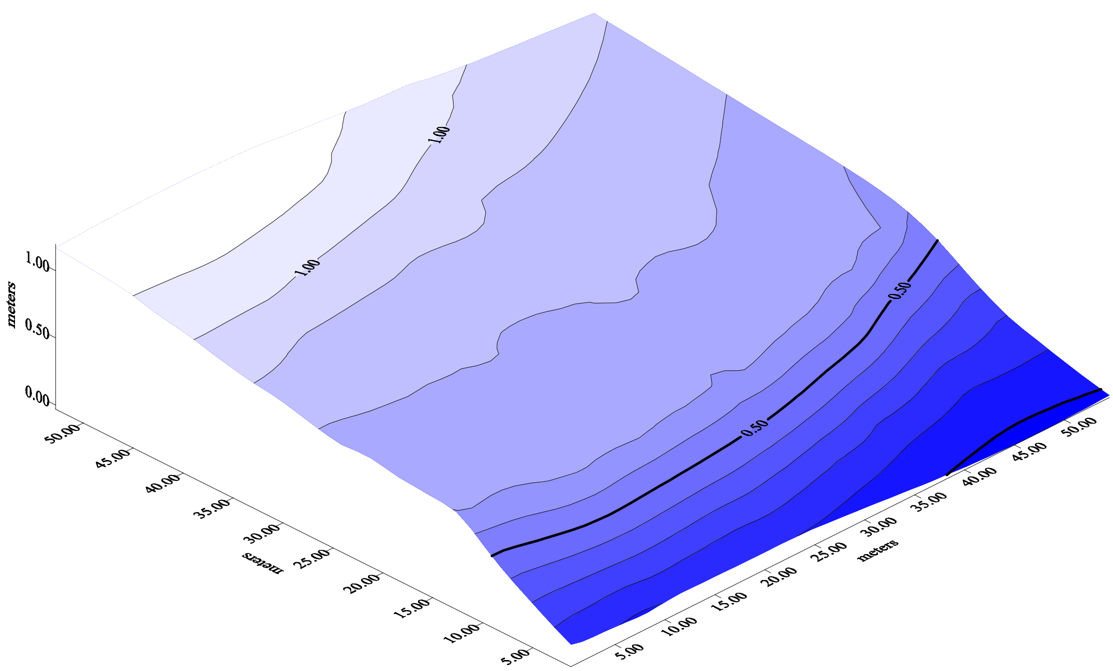


Figure 2-9. Overlay of contour and surface maps for study site in Marine Lab marsh. The 0.50 m contour line is the marsh edge and approximate seaward limitation of vegetation.

Chapter 3: HYDROLOGIC PATTERNS IN CREATED AND NATURAL SALT MARSHES

ABSTRACT

Tidal fluctuation drives salt marsh hydrology and determines the degree of drainage that occurs. Drainage is a mechanism for export of nutrients such as carbon, nitrogen, and phosphorous to estuaries. Salt marshes are believed important to estuarine nutrient cycles. Retention of nutrients, particularly nitrogen, is important to the development of the ecological functions of newly created salt marshes. This study was designed to characterize the hydrology and nutrient export from one natural and three created salt marshes. A series of water table monitoring wells was established along a transect in each marsh and two tidal cycles were selected for study which represented high and low water conditions. Hydraulic gradients and water table fluctuations of the edge and inland zones of the four marshes were highly affected by the different water levels of the two tidal cycles. Seasonal differences were less important. The two created marshes adjacent to uplands had higher soil water flux than the highest levels recorded in the natural marsh. Freshwater discharge from these uplands appears to play a role in maintaining high soil water flux throughout the period the marsh surface is exposed. Soil water flux on a created marsh island without uplands was more erratic, particularly at low water levels. Due in part to differences in moisture release characteristics of soils from a natural and created marsh, the highest discharge of water and nutrients on a square meter basis occurred from the edge zone of the natural marsh. Discharge and nutrient export from the inland zones of both marshes was low. Due to the

number of factors involved in determining nutrient export, it is probably not possible to generalize about nutrient export from created versus natural marshes.

INTRODUCTION

The hydrology of salt marsh wetlands is dominated by the rise and fall of tides. Tidal fluctuations on the Atlantic coast of the United States are semidiurnal, having two high tides and two low tides on most days. Other factors also affect marsh hydrology. For example, precipitation affects marsh hydrology if it occurs when tides are low and after substantial drainage has occurred (Carr and Blackley, 1986). Where marshes are contiguous with uplands, groundwater inflow also affects marsh hydrology at their upland margin (Gardner, 1973). However, in general, these other sources of water are of minor importance compared with the effect of twice daily surface inundation by tides. The regularity of this process makes salt marsh hydrology relatively simple to describe and eliminates the need for the long-term monitoring that characterizes many hydrologic studies of wetlands.

Interest in salt marsh hydrology is motivated by several factors. One of these is to understand the role of the marshes in the nutrient cycles of coastal waters. Nixon (1980) summarized early research on this topic and concluded that marshes tend to export dissolved nutrients to the estuary. Discharge of subsurface water is one export mechanism. Tidal fluctuation serves as the "pump" which at high tide adds new water to the marsh and at low tide allows drainage of water enriched in nutrients. Mineralization via sulfate reduction is the process by which nutrients are released to the soil pore water. Jordan and Correll (1985) estimated a seepage volume at the creek bank of 30 liters per meter length of creek bank, per tidal cycle. They contend that this accounts for less than half of the observed export of dissolved nutrients. Yelverton and Hackney (1986) estimated net flux of dissolved organic carbon (DOC) from a sandy North Carolina salt marsh and concluded that < 1% of net primary production was exported as DOC.

Gardner (1973) conducted an early study of salt marsh hydrology with respect to pore water chemistry. He observed that the water table at low tide in a South Carolina salt marsh is essentially horizontal and stagnant in most of the marsh and that only within about 3 meters of the marsh edge does it slope toward the creek and discharge. The fine textured soils of the marsh interior prevent rapid flux of substances into or out of the system. Harvey et al. (1987) studied pathways of pore water drainage and replacement from salt marshes and found that flow takes place only when the marsh surface is exposed and that it is predominantly horizontal in the form of lateral drainage to a tidal creek. Vertical fluxes were not important in discharge. Replacement of drainage water occurred by vertical infiltration of tidal water and lateral flow from marsh areas further inland. In contrast, Carr and Blackley (1986) found that upwelling of water from the underlying coarse sediments was a significant process controlling water table fluctuation, particularly during the low amplitude neap tides that did not flood the marsh surface. Hemond and Fifield (1982) studied the subsurface flow regime 15 meters from marsh edge and found that it was dominated by upward flow of groundwater in response to evapotranspirational demand. Their sensitivity analysis showed that permeability of the peat soil was the most important factor influencing subsurface flow in the marsh interior.

Nuttle and Harvey (1987) separate a Massachusetts salt marsh into three distinct hydrologic zones: a creekbank zone within 2.5 meters of the marsh edge with a dynamic subsurface hydrology in which lateral flux oscillates in response to tides. A transition zone occurs from 2.5 to 15 meters. In this zone, lateral flow there is less dynamic and is driven by alternating periods of daily surface flooding (spring tides) and periods without surface flooding (neap tides). A third zone occurs inland at distances greater than 15 meters from the marsh edge. The water table in this zone does not respond to tidal fluctuation and no lateral flow occurs. Removal of water from this zone occurs solely by evapotranspiration. They conclude that the magnitude and extent of lateral drainage from salt marshes is controlled by four factors: the morphology of the marsh which includes both topography and overall elevation, the time between successive flooding events, the hydraulic properties of the soil, and rate of evapotranspiration.

Salt marsh hydrology is also important because flow of water through the soil can affect marsh productivity in several ways. It removes toxins such as hydrogen sulfide and excess salts which can otherwise inhibit plant growth. It can also deliver new supplies of nutrients in dissolved or particulate form. However, in other cases, it could remove essential plant nutrients.

Creation of new marshes to mitigate for those damaged by development has become a common practice in coastal areas. Surface hydrologic characteristics such as the duration, depth and frequency of flooding are considered in the design of created marshes. This is important because inundation must be often enough to ensure the exchange of water, materials, organisms, and nutrients between marsh and estuary during most tidal cycles. However, subsurface hydrologic characteristics are less often considered and few studies exist that describe it. This is surprising since proper subsurface hydrology is necessary to the development of hydric soils, hydrophytic plant communities and the associated faunal populations.

The hydrology of created marshes has implications for biogeochemical cycles of the estuarine system. Thompson et al. (1995) found that denitrification rates in a 1 to 3 year old created marsh were two orders of magnitude lower than in an adjacent natural marsh. Nitrification and denitrification were also less closely coupled in the created marsh. This difference was hypothesized to be due to more oxygenated soils and to higher flux rates which flush NO_3^- from the sandy soils of the created marsh. One of the goals of this study is to test their hypothesis of higher flux rates in the soils of created marshes.

As described in the previous chapter, there are soil and geomorphologic differences between natural and created salt marshes which could affect subsurface hydrology. The high elevation interiors and low elevation edges of created marshes may create a hydraulic gradient that promotes water flow and the flushing of nutrients. This could explain the nutrient impoverishment of inland portions of created marshes relative to marsh edges, a trend documented in the previous chapter. Flushing of nitrogen is of particular concern since salt marshes are nitrogen limited ecosystems. Therefore, a relatively closed nitrogen cycle is necessary to maintain productivity. Rapid subsurface flow of water potentially flushes N from soils and could "short circuit" this cycle.

Another goal of this study is to describe subsurface hydrologic characteristics of one natural and three created salt marshes. Hydraulic conductivity and hydraulic gradient are important because they determine the rate at which water moves through the soil (soil water flux). Water table depth and soil water release characteristics are important because they may be used to estimate drainage volume per tidal cycle and thereby to assess nutrient export.

MATERIALS AND METHODS

Sites

The four marshes in this study are located in the Newport River estuary near Morehead City, North Carolina. Some of their characteristics are described in Table 1 of the previous chapter. In addition, a limited number of hydrologic characteristics of a second natural marsh, adjacent to the 11-year old Port marsh, were studied to provide a greater range of information about reference marshes.

Water Table Monitoring Wells and Hydraulic Gradients

A transect of three monitoring wells was established in each of the five marshes. The monitoring wells consisted of 5 cm diameter polyvinyl chloride (pvc) pipes which were inserted into the soil to a depth of 0.75 m. The pipes were screened over most of this length. The cavity between the pipe and soil was filled with coarse sand to ensure that changes in soil water levels were registered quickly. The top of the cavity was sealed with bentonite clay and grout to prevent surface water from flowing directly through the coarse sand and into the well. The top of the pipe was 0.9 m above the marsh, a height generally sufficient to prevent flooding of the ultra-sonic data logger (Infinities USA, Inc.) that was positioned on top of the pipe and which recorded water levels in these wells. The monitoring wells were installed at distances from the marsh edge of 0.5, 4, and 15 m. However, at the Marine Lab marsh, the wells were installed at distances of 1, 6, and 21 m due to the greater width of this marsh. Data loggers recorded water levels in the wells at 20 minute intervals throughout the course of one month. Water level readings were adjusted to make them relative to a common datum. The datum selected is known as “mean lower low water” (MLLW). Tidal cycles have a diurnal inequality (Thurman, 1997) in which one of the two daily low tides is usually substantially lower than the other. The mean of the lower of these low tides is the mean lower low water datum. This benchmark was determined at each site by marking the low water level for a certain day and then using NOAA tide tables which show height of each low water relative to MLLW. A correction factor for particular places along the coast was used to adjust for local tidal characteristics. The DOT and Natural marshes were corrected to the MLLW at Atlantic Beach Bridge, a landmark located 1.4 km to the east. The Marine Lab and two Port marsh sites were corrected to the MLLW at Gallant Channel, a site located 1-2 km to the northeast.

Near the DOT and Port marshes, data loggers were installed in the open water of the estuary. They recorded the rise and fall of tides at the same 20 minute intervals at which the other data loggers monitored marsh water tables. The tide gage data loggers were installed on screened pipes secured to posts located several meters offshore from the marshes. Tidal cycles during the periods of study did not show the anticipated pattern in which there are periods of large tidal amplitude (spring tides) alternating with periods of low tidal amplitude (neap tides). Instead, we observed periods in which both high and low tides were relatively high and other periods in which both high and low tides were relatively low (Figure 1). Based on these data, we selected a limited number of tidal cycles for study, those that represented either end of a range of tidal conditions. Characteristics of the selected tidal cycles are shown in Table 1. A limited number of data loggers meant that marsh hydrology could not be monitored at all marshes simultaneously. However, the regularity of tidal processes means that there is a great deal of similarity between tidal cycles in terms of tidal stage (falling tide, low tide, rising tide, high tide) and in the patterns of flow observed.

The first period of hydrologic monitoring took place at the DOT and Natural marshes from March 15 to April 18, 2000. Although some seasonal variation in tidal range occurs, most variation in lunar tides occurs over the course of one month (Thurman, 1997). A second monitoring period in these two marshes took place from June 9 to July 12, 2000, in order to determine if there were any pronounced seasonal differences in hydrology. However, dense algal and barnacle growth on the pipes in the open water during this latter period made the tide gage readings unreliable. Water table readings were monitored at the two Port marshes (natural and created) from August 15 to October 4, 2000. However, a tropical storm on August 30 damaged the data loggers at the natural marsh resulting in an incomplete record for that site. Water table levels in the Marine Lab marsh were monitored from November 14 to December 14, 2001.

Marsh surface elevations readings relative to MLLW were made at one meter intervals along the monitoring well transect and extended from the open water of the estuary (or tidal creek) to a distance inland of about 20 meters. This enabled us to compare water levels within the monitoring well transect to both the MLLW datum and to the marsh surface as shown in Figures 2-12. The water table readings in the transect were also used to calculate the slope of the water table (hydraulic gradient) throughout the tidal cycle from high to low and back to high tide. The hydraulic gradient for the edge zone of the marsh was calculated as the difference in water levels between the 0.5 and the 4 meter monitoring wells divided by the distance between them (3.5 m). The hydraulic gradient for the inland zone was calculated as the difference in water levels between the 4 and 15 m monitoring wells divided by their distance (11 m).

Soil Water Flux

The hydraulic gradient between the 0.5 to 15 m wells was averaged for each hour that the marsh surface was exposed on selected dates. Lateral hydraulic conductivity measurements, mentioned in the previous chapter, were used to estimate soil water flux in accordance with Darcy's law where:

$$Q/a = -K(\nabla H / \nabla L)$$

Q = outflow rate (units: $L^3\ T^{-1}$)

a = cross-sectional area perpendicular to path of flow (L^2)

Q/a = soil water flux ($L\ T^{-1}$)

K = hydraulic conductivity ($L\ T^{-1}$)

ΔH = change in hydraulic head (L)

ΔL = change in distance (L)

$\Delta H / \Delta L$ = hydraulic gradient ($L\ L^{-1}$)

Piezometers and Pore Water Sampling

We installed between 9 and 11 nests of piezometers at each marsh for the purpose of sampling the soil pore water at various depths. One-half of the piezometers were screened at the 5 to 20 cm soil depth, one-half were screened at the 35 to 50 cm depth. We conducted pore water sampling at three times of the year (August, November, April) in order to assess seasonal differences in soil water chemistry. We sampled during ebb tide after water had receded from the soil surface but while the soil was still draining. The piezometers were emptied and then allowed to refill before collecting the water using a vacuum pump. For comparison, samples of estuarine water were taken at a distance of approximately 50 m from the marsh edge. Only one estuarine water sample was taken for the DOT and Natural marshes, at a distance midway between these marshes. Five drops of 6N HCl were immediately added to the bottles to prevent NH_3 volatilization and to inhibit microbial activity. The samples were placed on ice within an hour of completing the sampling. Particulate material was removed in the lab by filtering the water samples through a 0.45 µm membrane filter. They were kept cold until analyzed for NO_3^-, NH_4^+, total nitrogen, total phosphorous and ortho-phosphate. Total N was determined by kjeldahl digestion while the other determinations were made with a Lachat spectrometer. Nitrate levels at virtually all times were below the detection limit of 0.1 mg L^{-1} and are thus not reported.

Drainage Volume and Nutrient Export Determinations

We collected 10 cores from two soil depths in each marsh and used them to determine water release characteristics by a procedure mentioned in the previous chapter. The two sets of water release curves shown in Appendix A are composites of five cores taken from similar positions within the DOT and Natural marshes. We used this relationship between soil water content and pressure head in conjunction with water table data to determine the drainage volume for those two marshes. The procedure, which is described in Appendix A, assumes that complete saturation occurs when the marsh is flooded and that the soils drain to equilibrium at low tide. For each monitoring well position, this procedure produces an estimate of the drainage volume per square meter of marsh surface area for one tidal cycle. This procedure requires the assumption that the soil drains to equilibrium. This is not always a good assumption, especially in cases where the marsh surface is exposed for only a brief period (2-3 hours). In those cases, this procedure may overestimate drainage volume. However, in other cases where the marsh surface is exposed for several days and where water tables stabilize for long periods, this approach is valid. We used this approach to estimate drainage volume from the DOT and Natural marshes only since they are isolated marsh islands with no associated uplands. The Port and Marine Lab marshes have adjoining uplands that contribute flow to the marsh water tables. Our approach would severely underestimate drainage volume in those marshes.

We used a separate procedure to calculate drainage volume via lateral flow to the creekbank for the Port marsh. This procedure is demonstrated in Appendix B. The unique feature of the Port marsh which makes this procedure suitable is the presence of a dense, sticky, plastic Ab horizon starting at a depth of 33 to 43 cm. This horizon is an aquitard since it limits flow across the horizon and therefore allows us to define the lower boundary of flow in this system. Confining layers are absent in the other marshes. Piezometer measurements confirm that the layer underlying the Ab is a confined aquifer since its soil water pressure is consistently greater (by about 20 cm) than the layers overlying the Ab.

An estimate of the nutrients exported per tidal cycle is made by multiplying the drainage volume from the marsh, in liters, by the nutrient concentration of the soil water (mg L^{-1}) after first subtracting the nutrient concentration of the estuarine water. This allows us to calculate net export of nutrients that each marsh discharges to the estuary on selected tidal cycles.

RESULTS

Water Table Fluctuations and Hydraulic Gradients

In this study, hydraulic gradients are calculated such that water tables which slope toward the estuary (or tidal creek) are expressed as positive quantities while those that slope inland are negative quantities. The former condition is henceforth referred to as discharge since soil water is moving toward the open water and ultimately discharging into the estuary. A water table with a negative gradient is a condition henceforth referred to as recharge since water from the sound is entering the marsh and recharging its water table.

The Natural Marsh

Tides on March 20, 2000 are high and the marsh surface is exposed for only a brief period: 100 minutes at the 0.5 m edge, 200 minutes at the 4 m berm, and 180 minutes at the 15 m inland position. As the tide begins to fall at 13:00, head levels across the marsh are similar (Figure 2a) and the hydraulic gradients are near zero (Figure 2b) indicating that no subsurface flow is occurring. At low tide, head levels drop below the surface at the 4 m site while the 0.5 and 15 m sites remain saturated to the surface. Although the water level in the estuary at this time is below the marsh surface, the head level at the 0.5 m well is above the soil surface. This suggests that discharge of the water table is occurring there. By 16:00, head levels drop across the marsh fall to their lowest point in the tidal cycle even as rising water begins to inundate the surface. The steepest hydraulic gradients occur at this time in both the edge and inland zones, indicating maximal discharge of groundwater from the marsh. By 17:20, the marsh is flooded although head levels have not yet equilibrated. The head levels increase most rapidly at the 0.5 m well and a negative hydraulic gradient develops at the edge zone suggesting that the tidal water is forcing lateral flow inland simultaneously with surface infiltration. These hydraulic gradient patterns indicate that the edge zone undergoes alternating periods of discharge and recharge while the inland zone maintains a positive gradient throughout the tidal cycle which approaches zero only as the marsh floods.

In order to examine a range of conditions, a second tidal cycle is studied on a day of low water levels (April 12, 2000) when the marsh surface is exposed for a much longer period: 480 minutes at the 0.5 m well, 760 minutes at the 4 m well, and 620 minutes at the 15 m well. By 17:40, the falling tide has exposed the entire marsh surface. Drainage from the 4 m berm position occurs while the soils at the 0.5 m edge and 15 m inland sites remain saturated (Figure 3a). The water table at the 0.5 m well is above the soil surface, again indicating discharge. Low tide occurs at 21:20 and the water tables at the 0.5 and 4 m wells fall rapidly while the soil of the 15 m well remains saturated near the surface. These different rates of water table drop causes a relatively steep hydraulic gradient to develop inland which allows drainage from the marsh interior to occur (Figure 3b). This is reflected in water table levels at 0:40 for the 15 m well which fall 12 cm below the marsh surface relative to 0.6 cm on March 20. This indicates that tidal range on a given day has a large impact on the water volume that will drain from a marsh. The rising tide at 0:40 causes head levels at the 0.5 m well to rise even as head levels at 4 and 15 meter wells continue to fall. The hydraulic gradient at marsh edge becomes negative, indicating lateral recharge for this zone. Lateral discharge continues from the inland portion of the marsh until that surface is flooded by about 2:00. By 4:00, flood water covers the entire marsh and hydraulic gradients in both zones approach zero.

Another tidal cycle characterized by similarly low tidal levels occurred on June 13, 2000. Water tables fluctuation and magnitude of the hydraulic gradients was similar to that observed on the earlier date (Figures 4a,b). Apparently, this marsh is exposed for too brief a period for the high evapotranspiration rates that typically occur in the summer to have an observable impact on marsh water table levels. A high water tidal cycle occurred on July 1, 2000 (Figures 5a and b). A comparison of hydrologic patterns in mid-summer with those observed in the spring suggest that seasonal variation is less important than the variation caused by tidal range and amplitude.

The Created DOT Marsh

The higher elevation of this marsh relative to the natural marsh means that the created marsh surface is exposed longer than the natural marsh surface on all tidal cycles. On March 20, 2000, the inland portion of the marsh develops a positive hydraulic gradient (Figure 3b) early in the falling part of the tidal cycle (10:00 – 13:00). In contrast, the hydraulic gradient at the edge fluctuates around zero. This probably indicates variable rates of equilibration rather than alternating periods of recharge and discharge. At 11:40, the tide recedes from upper part of the marsh surface at 15 m though the soil there remains saturated (Figure 3a). Tide water drains from the entire marsh surface around 13:00 and the marsh edge immediately develops a strong positive hydraulic gradient, indicating discharge (Figure 3b). By low tide at 14:40, the hydraulic gradient of the inland portion of the marsh approaches zero indicating that this portion of the marsh has drained to near equilibrium and that little further drainage can occur. This equilibrium level appears related to the convex topographic feature on which the 15 m well is located. The initially rapid drop in the water table here probably occurred by lateral drainage and discharge of soil water at the edge of this feature. Further drop in the water table below the base of this mound is limited by rate of water movement to other discharge zones such as the marsh edge. At low tide, the water table at the 4 m well also begins to fall below the soil surface while the water table at the 0.5 m well remains above the surface, indicating discharge at the marsh edge.

At 17:00, the tide floods the marsh surface at the 0.5 and 4 meter wells, and head levels there increase in response while the head level at the 15 m well continues to decline slightly. Negative hydraulic gradient develop in both zones indicating that lateral flow is recharging the water table in addition to the infiltration that is occurring at the lower marsh elevations. Unlike the natural marsh, the inland part of this created marsh undergoes alternating periods of recharge and discharge.

Water tables on April 20th are relatively stable. During this period of low water levels, high tides only flood the 0.5 and 4 m wells and do not reach the 15 m well (Figure 7a). Most drainage at the 15 m well has occurred prior to the start of the current tidal cycle. Therefore, a more complete view of the hydrologic process may be seen by viewing the hydraulic gradients in the three days prior to the selected tidal cycle (Figure 7b). The hydraulic gradient in the inland portion of the marsh generally remains near zero, becoming negative only when innundation at the marsh edge forces lateral recharge. Water tables stabilize at the elevation of the marsh edge, a likely point of groundwater discharge. Further drainage is probably limited by the longer time required for movement of water to other, lower points of discharge. It may be that during these extended periods without innundation, evapotranspiration does become a significant factor in water table drawdown. Negative hydraulic gradients suggestive of recharge dominate at marsh edge (Figure 7b) despite the fact that tide levels are generally below the marsh surface and thus do not have a forcing effect on water tables. This may occur because groundwater flow is a 3 dimensional process and the transect of three monitoring wells may not always be in the predominant direction of flow. This is especially likely given the complex topography of this marsh which has numerous isolated depressions which hold large volumes of surface water at low tide. When this surface water becomes isolated by the receding tide, the pools may become sources for groundwater flow and the directions of flow may change from that which occurred at higher water levels. The weakness and erratic nature of these gradients suggest that there is no longer a single driving force controlling hydrology as occurs during more regular periods of flooding. Positive hydraulic gradients at the edge zone develop for brief periods following high tide as the water table at marsh edge discharges to the estuary.

Water table levels for a tidal cycle of low water levels (June 13, 2000) are similar to those observed on April 12 (Figures 8a and b). Again, negative hydraulic gradients dominate at marsh edge while slightly positive gradients dominate inland.

The Natural Port Marsh

Due to their low elevations, tides flood the natural and created Port marshes continuously during high water tidal cycles. Therefore, no drainage occurs at those times. Thus, we studied only one tidal cycle which occurred on a day of low water levels (August 27, 2000) and maximum drainage. By 10:00 that day, the falling tide had receded below the surface of the marsh (Figure 10a) and the soil at the 0.5 m well had begun to drain. The berm at marsh edge appears to constrain outflow from the marsh thereby retaining water on the inland part of the marsh surface for a longer period than would occur in the absence of a berm. This is evidenced by the shallow ponding at the 4 and 15 m wells at 10:00. During the 2.5 hours prior to low tide (12:20), the water table at the 0.5 m well drops rapidly causing a steep hydraulic gradient indicative of discharge (Figure 10b).

The maximum water table drop at the 0.5 m well occurs at low tide. The water table elevation is near the base of the steep slope that forms the marsh edge and this feature is a likely point of discharge for the water table. Further drop in the water table is limited by the longer flow path required to reach another point of discharge. This is another example of how local marsh geomorphology controls water table fluctuation. At low tide, surface water has drained from the marsh interior but the water table remains at the surface. The water table here conforms to the configuration of the marsh surface which is essentially level. Therefore no hydraulic gradient develops and no flow can occur. At 14:40, the rising tide recharges the water table at the 0.5 m well and the hydraulic gradient in the edge zone approaches zero.

The Created Port Marsh

By 10:00 on August 27, 2000, the falling tide has exposed the marsh surface but the soil at each well site remains saturated to the surface (Figure 11a). Little subsequent drainage occurs and water tables fall to their maximum depth around 14:40, just prior to surface inundation. At that time, the water table drops below the marsh surface a mere 5.3, 3.1, and 1.2 cm at the 0.5, 4, and 15 m wells, respectively. However, the relative lack of water table fluctuation does not mean that the groundwater here is stagnant. Positive hydraulic gradients develop in both zones of the marsh as soon as the marsh surface drains and they persist at a steady level until the surface floods again, 6 hours later (Figure 11b). This indicates continuous discharge of water to the tidal creek. A one time measurement indicates that salinity of the soil water decreases from 40 parts per thousand (ppt) at marsh edge to 19 ppt at a distance of 25 meters inland. The location of this marsh at the base of an upland dredge island means that the soil water of this marsh is replenished by discharge of fresh water from these uplands.

The water table in this marsh also conforms to the marsh surface topography, which grades gradually into the uplands. While the surface topography creates the hydraulic gradient, the discharge of fresh water contributes to the maintenance of this gradient throughout the time the marsh surface is exposed.

Geomorphology also plays a role in determining the depth of the water table in this marsh. The creek bed is the nearest outlet for subsurface flow but its shallowness means that any drop in the water table below that depth must occur via subsurface flow to another more distant outlet of lower elevation. Negative hydraulic gradients are generally absent in this marsh. Water tables are more likely to be replenished by freshwater flow from upslope and by infiltration of tidal water than from tidal forcing of lateral recharge.

The Created Marine Lab Marsh

There was no tide gage installed at this marsh. Instead, we used NOAA tide tables to help correlate water table levels in the monitoring wells with stages of the tidal cycle. A tidal cycle from December 11 –12 was selected for study since it was typical for the month when water table levels were monitored. As the tide recedes at 20:20, the water table develops a convex shape since the water table at the 1 m well falls more rapidly than that at the 6 m well (Figure 12a). Positive hydraulic gradients develop in both zones but the gradient at the edge is steeper than inland (Figure 12b). Maximum drainage with respect to the soil surface occurs at the 6 m well. Maximum water table depth at both the 1 and 6 m sites occurs at low tide (23:20). The water table at the 21 m site continues to fall even after tides reverse direction. Thus, at 1:20 the water table develops a concave shape since the hydraulic gradient inland is steeper than that of the edge zone. During a brief period prior to high tide the edge zone develops a negative hydraulic gradient indicating lateral recharge. The absence of negative hydraulic gradients inland indicate that no lateral recharge occurs there.

This marsh is also contiguous with the uplands of a spoil island and salinity readings confirm that fresh water enters the marsh at the upland margin. Salinity decreases from 36 ppt at 1 meter from the marsh edge to 28 ppt at 29 meters from marsh edge.

Although the marsh surface is configured similarly to that of the Port Marsh, the intertidal surface offshore from the marsh edge is steeply sloping. When this slope is exposed by the receding tide a zone of discharge becomes available by which drainage of the marsh can occur. By contrast, drainage from the Port Marsh was limited by the shallowness of the creek bed along which the study area was located. Thus, the geomorphology of the marsh itself and that of the adjacent intertidal zone affect the degree to which drainage can occur.

Soil Water Flux

Soil water flux across a marsh is highly affected by the tidal range for a given day as shown in Figure 13. On the day of high tide levels (March 20), flux in the natural marsh is near zero in the first two hours after the tide recedes. Flux across the DOT marsh is generally higher and persists for about two hours longer. This indicates that on this day, the DOT marsh discharges more water than the Natural marsh. On the day of low tide levels (April 12), flux across the DOT marsh is near zero throughout the tidal cycle due to the fact that the inland part of the marsh did not flood on that tidal cycle and the marsh has very little water left to discharge. Flux across the natural marsh, on the other hand, is higher throughout the tidal cycle and persists as long as in the DOT marsh. This indicates that on this day, the Natural marsh discharges more water than the DOT marsh.

On the dates when soil water flux was calculated for the Port and Marine Lab marshes, rates there were about 30% higher than the highest rates observed in the Natural marsh on 4/12/00 (Figure 14). The higher rates in these created marshes relative to the created DOT marsh may be due to the inputs of fresh water from the adjacent uplands which are absent from the intertidal island on which the DOT marsh is located.

Drainage Volume on Selected Tidal Cycles

The water release curves for the soil in the DOT and Natural marshes (Figures A1 and A2) show some important differences between the two sites in both the surface and subsurface layers. The water content in the natural marsh at saturation is considerably higher than that in the DOT marsh, approaching 70% in the inland zone. This is a function of the very high pore volume and finer texture of this soil. In contrast, the water content of the DOT marsh soil at saturation is between 40 and 50%. The moisture release curve for the Natural marsh drops sharply at very low pressures indicating great potential for water discharge in response to small drops in water table level. This is probably a function of the large volume of macropores in the natural marsh which are created by a dense population of burrowing infauna. Animal burrow macropores would also tend to be continuous which would further promote drainage. In contrast, the DOT moisture release curves are relatively flat at low pressures and indicate that much water is retained until pressures of about – 40 cm are reached. Thus, the Natural marsh has greater potential to discharge water at low pressures than does the DOT marsh.

The relationship of water table drop and drainage volume is shown in Table 2. Water table drop is greater at the edge of the natural marsh than at the edge of the created marsh. This is to be expected since the 0.5 and 4 meter positions in the Natural marsh are located at the base and on top of a berm, respectively, while in the Created marsh, these positions are located at the low elevation marsh edge. However, there is also a much greater water table drop at the berm in the Natural marsh (4 m position) relative to the much higher elevation berm in the DOT marsh (15 m position). This is probably related to the topography offshore of the natural marsh which slopes steeply and when exposed provides a site for discharge.

The DOT marsh at low tide is surrounded by an extensive sand flat which provides few sites for discharge. Thus, the inland berm of the DOT marsh is more isolated from points of discharge than is the lower elevation berm of the Natural marsh. Discharge from the different positions in these two marshes reflects the extent of water table drop with higher volumes of discharge occurring from the edge of the Natural marsh relative to any position in the DOT marsh. The 15 m position in the DOT marsh on 4/12 discharges little water despite the 25.2 cm water table depth. This is because discharge for this day was calculated relative to the water table at high tide which was below the marsh surface at a depth of 21 cm.

The calculations in Appendix B indicate that the Port marsh discharges 5.94 liters of water per meter length of creekbank during one tidal cycle. This is only a partial estimate of total drainage volume since it does not account for the volume of water that seeps across the sloping marsh surface as the tide recedes. It is on the same order of magnitude as the 30 liters m^{-1} estimated by Jordan and Correll (1985) to discharge from a natural salt marsh in Chesapeake Bay.

Nutrient Export

The March 20 and April 12 tidal cycles represent either end of a range of export conditions for the DOT and Natural marshes. Therefore, the average export volume from these two tidal cycles was used to represent the volume of water that would typically drain from these marshes per tidal cycle. The export volume from the 0.5 and 4 m positions was averaged due to their close proximity and together presented as the “edge” position while export from the 15 m position was presented as the “inland” condition. These volumes were multiplied by the nutrient concentration in the soil pore water at various seasons. The pore water was sampled by depth and position and results are presented in Tables 3 to 5. The nutrient concentration used in the calculation was the average of the two soil depths sampled minus the nutrient concentration of the nearby estuarine water. These estimates of net nutrient export are shown in Figure 15.

Figure 15 shows that there is great spatial variation within and between the marshes in terms of nutrient export. The contributions from the inland of both the DOT and Natural marshes on a unit area basis are small relative to the edge positions. However, these calculations do not account for transfers of nutrients between the edge and inland positions. Most drainage appears to occur via lateral flow and discharge at marsh edge. Therefore, drainage from the inland part of the marsh must first pass through the marsh edge in order to discharge. This discharge from the inland marsh is believed to replenish the pore water nutrients of the marsh edge (Nuttle and Harvey, 1987).

An estimate of the significance of these quantities may be made by considering them as a proportion of the total N and P contained in the soil and root (MOM) material in the two marshes. These pools are shown in Table 6. The mg N and P exported m^{-2} tidal $cycle^{-1}$ were averaged for the three sampling periods and expressed on an annual basis by multiplying by 706 tidal cycles per year. Relative to the total pools, carbon export is approximately an order of magnitude greater in the DOT marsh relative to the natural marsh. However, with respect to nitrogen and phosphorous, export from the Natural marsh appears somewhat greater.

Calculation of nutrient export from the Port marsh was conducted as demonstrated in Appendix B. These values should be considered a partial estimate of nutrient export since they do not account for seepage across the marsh surface. As a proportion of the total nutrient pool, the Port marsh exports via lateral flow to the creekbank about 0.075% of its carbon, 0.17% of its nitrogen, and 0.10% of its phosphorous on an annual basis.

DISCUSSION

The water table in the Natural marsh resembled that described for most salt marshes in the literature. The marsh edge is hydrologically dynamic and lateral flux oscillates between discharge and recharge. The marsh interior at 15 meters is relatively stagnant. Hydraulic gradients in the marsh interior are generally positive or near zero indicating that lateral flow from the marsh edge does not extend to this distance. Thus recharge of the water table there must occur solely by infiltration. Tidal amplitude influences water table levels and the magnitude of hydraulic gradients that develop across the marsh. In this study, a tidal cycle with relatively high water levels produced gentle hydraulic gradients, particularly in the marsh interior where the gradient was less than 0.01. Hydraulic gradients were steeper during a tidal cycle with relatively low water levels and the inland hydraulic gradients exceeded 0.02 at that time. Approximately the same range of response to tidal variation occurred in mid-summer as had occurred in spring suggesting that the same patterns of discharge and recharge and water table fluctuation occur regardless of the season. This contrasts with conclusions of some studies which found that evapotranspiration is an important process controlling water removal from salt marshes, particularly during low amplitude neap tides. The marsh sites used in those studies occasionally undergo long periods without flooding. However, for all the marshes in this study, twice daily flooding is the norm with the exception of the inland part of the DOT marsh.

During a high water tidal cycle (March 20), both zones of the DOT marsh had hydraulic gradients which alternated between recharge and discharge. This indicates that lateral flow through the soil can recharge the water table of not only the edge zone, but also the inland zone. This is in contrast to the Natural marsh where water table recharge by lateral flow was limited to the edge zone. During a low water tidal cycle (April 12), the DOT marsh has hydraulic gradients in the inland zone that are small and erratic indicating that most drainage from the area has already occurred on previous tidal cycles and that lateral flow is no longer responding to the rise and fall of tides. Instead, local hydrologic sources such as isolated ponds on the surface may drive water flow at that time.

Soil water flux data indicate that during high water tidal cycles, discharge from the DOT marsh is greater than that from the Natural marsh. During low water tidal cycles, flux from the Natural marsh is greater. This appears to be a function of marsh elevation relative to the range of water levels for that tidal cycle. Other factors that affect the extent of drainage are marsh topography and slope of the adjacent offshore zone which create distinct zones for discharge. Landscape scale factors such as proximity of upland areas can affect the extent of drainage. In the case of the Port marsh, which is surrounded by uplands on three sides, discharge of fresh water from those areas may account for the steady hydraulic gradient across the marsh which persists for the entire time the marsh surface is exposed. In contrast, the DOT marsh is on an isolated island without uplands and the hydraulic gradients there tend to peak quickly and diminish as the soil drains to equilibrium.

The soil of the Natural marsh has much greater total porosity than that of the DOT marsh and therefore holds a greater volume of water at saturation. The structure of the natural marsh soil is such that it releases relatively large volumes of water at very low tensions. The abundance of burrowing infauna in the natural marsh probably accounts for this macroporous structure.

Estimates of nutrient flux indicate that in absolute terms the edge of the Natural marsh contributes more nutrients per square meter to the estuary than any of the other sites. The interior of the Natural marsh contributes relatively little since the drop in water table there is small. The interior of the DOT marsh contributes little since its soils yield relatively little water and because low water tidal cycles do not flood that zone. Thus, there is little water available for export. Nutrient export from the edge of the DOT marsh is relatively high since it floods more regularly than the inland zone and because the water yield of these soils at low pressures is higher. As a proportion of their total nitrogen and phosphorous pools, N and P export from the DOT and Natural marshes is on the same order of magnitude. The DOT marsh appears to export approximately one order of magnitude more C than the Natural marsh as a percent of the total C pool. However, since the margins of error on these calculations are unknown, it is difficult to judge whether these differences are actually significant.

The proportion of each marsh represented by the selected positions of this study is another factor to consider in evaluating the nutrient retention capacity of created versus natural marshes. In the Natural marsh, the edge position is a relatively minor zone probably comprising about 10% of the total marsh area. The swell and swale topography of the DOT marsh suggests a more even mix of the two zones. This study demonstrates that there are great spatial differences in nutrient export to the estuary in both natural and created salt marshes. It is probably not possible to generalize about the nutrient export capacity of created and natural salt marshes. The soil water flux recorded in the Port and Marine Lab sites was higher than the highest rates observed in the Natural marsh suggesting that flushing of nutrients could be a factor accounting for the spatial differences in nutrient accumulation in those marshes.

REFERENCES

Carr, A.P. and M.W.L. Blackley. 1986. The effects and implication of tides and rainfall on the circulation of water within salt marsh sediments. Limnol. Oceanogr. 31(2):266-276.

Gardner, L.R. 1973. The effect of hydrologic factors on the pore water chemistry of intertidal marsh sediments. Southeastern Geol. 15:17-28.

Harvey, J.W., P.F. Germann, and W.E. Odum. 1987. Geomorphological control of subsurface hydrology in the creekbank zone of tidal marshes. Estuarine, Coastal, and Shelf Science. 25:677-691.

Hemond, H.F. and J.L. Fifield. 1982. Subsurface flow in a salt marsh peat: A model and field study.

Jordan, T.E. and Correll, D.L. 1985. Nutrient chemistry and hydrology of interstitial water in brackish tidal marshes of Chesapeake Bay. Estuarine, Coastal and Shelf Science 21: 45-55.

Nixon, S.W. 1980. Between coastal waters and coastal waters: A review of 20 years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In: Hamilton, P. and K.B. MacDonald (eds.), Estuarine and wetland processes. Pp. 437-525. Plenum Press, New York.

Nuttle, W.K. and J.W. Harvey. 1987. Geomorphological controls on subsurface transport in two salt marshes. Proceedings of National Wetland Symposium: Wetland Hydrology. September 16-18, Chicago, IL.

Skaggs, R.W. 2000. Course notes, theory of drainage–saturated flow. Dept of Biological and Agricultural Engineering. N.C. State University, Raleigh, NC.

Thompson, S.P. 1995. Seasonal patterns of nitrification and denitrification in a natural and a restored salt marsh. Estuaries 18(2):399-408.

Thurman, H.V. 1997. Introductory Oceanography. 8th ed. Prentice-Hall,Inc. Upper Saddle River, NJ.

Todd, D.K. 1964. Groundwater: basic flow equations. *In* Handbook of Applied Hydrology (Chow, V.T., ed.), Section 13. McGraw-Hill, New York. pp.13-14.

Yelverton, G.F. and C.T. Hackney. 1986. Flux of dissolved organic carbon and pore water through the substrate of a Spartina alterniflora marsh in North Carolina. Estuarine, coastal and shelf science 22:255-267.

TABLES

Table 3-1. Characteristics of selected tidal cycles. Tidal height and amplitude are in meters above MLLW.

Marsh	Date	Time of exposure (hours of day)	High height	time	Low height	time	amplitude
Natural,	3/20/00	11:40 - 19:20	1.25	8:20	0.32	14:40	0.93
DOT	4/12/00	14:00 - 4:00	0.61	14:20	-0.16	21:20	0.77
	6/13/00	6:20 - 17:00	0.63	6:26	0	12:41	0.63
	7/1/00	0:00 - 5:20	1.04	17:50	-0.11	2:35	1.15
Port (both)	8/27/00	7:40 - 17:00	1.08	6:20	-0.09	12:20	1.17
Marine Lab	12/11/01	16:40 - 8:00	0.89	5:16	-0.09	23:18	0.98

Table 3-2. Maximum water table depth (WTD) below marsh surface (cm) and discharge volume (liters m^{-2} tidal $cycle^{-1}$) from three positions within two marshes on two tidal cycles.

marsh	position (m)	20-Mar WTD	Discharge	12-Apr WTD	Discharge
DOT	0.5	1.9	0.10	5.4	0.78
	4	11.3	3.32	23.2	11.37
	15	17.1	2.26	25.2	1.20
Natural	0.5	3	0.26	26.5	11.80
	4	12.4	3.36	37.1	19.90
	15	0.6	0.01	12.1	3.04

Table 3-3. Mean nutrient concentration (mg l^{-1}) in pore water samples taken in April 2001.

Marsh	Nutrient form	Edge mean	SE	Inland mean	SE	Estuary
Natural	NH_4	0.21	0.018	0.23	0.014	0.24
	Total N	1.13	0.096	1.04	0.1	0.95
	DON	0.92	0.092	0.81	0.099	0.71
	PO_4	0.23	0.049	0.18	0.045	0.08
	Total P	0.29	0.051	0.25	0.066	0.16
DOT	NH_4	0.28	0.048	0.36	0.074	
	Total N	1.01	0.091	0.99	0.091	
	DON	0.73	0.079	0.63	0.099	
	PO_4	0.3	0.028	0.28	0.036	
	Total P	0.43	0.043	0.35	0.045	
Port	NH_4	1.47	0.28	0.38	0.12	0.15
	Total N	2.67	0.38	1.28	0.21	1.3
	DON	1.19	0.2	0.89	0.15	1.15
	PO_4	1.12	0.21	0.22	0.032	0.08
	Total P	1.59	0.29	0.34	0.048	0.09

Table 3-4. Mean nutrient concentration (mg l^{-1}) in pore water samples taken in August 2000.

Marsh	Nutrient form	Edge mean	SE	Inland mean	SE	Estuary
Natural	NH_4	0.36	0.056	0.5	0.071	0.16
	Total N	0.73	0.12	0.67	0.075	0.23
	DON	0.37	0.11	0.16	0.038	0.07
	PO_4	0.30	0.052	0.24	0.038	0.1
	Total P	0.38	0.071	0.28	0.038	0.14
	DOC	8.27	0.57	6.58	0.41	4.6
DOT	NH_4	0.71	0.22	0.84	0.22	
	Total N	1.32	0.42	1.22	0.23	
	DON	0.62	0.37	0.38	0.09	
	PO_4	0.72	0.11	0.6	0.10	
	Total P	0.76	0.12	0.65	0.10	
	DOC	18.8	10.31	16	7.15	
Port	NH_4	2.56	0.80	0.35	0.07	0.13
	Total N	3.04	0.89	0.81	0.17	0.14
	DON	0.48	0.11	0.46	0.14	0.01
	PO_4	1.64	0.46	0.27	0.04	0.09
	Total P	1.74	0.48	0.29	0.042	0.13
	DOC	8.08	0.99	9.23	2.06	5.0

Table 3-5. Mean nutrient concentration (mg l^{-1}) in pore water samples taken in November 2000.

Marsh	Nutrient form	Edge mean	Edge SE	Inland mean	Inland SE	Estuary
Natural	NH_4	0.067	0.019	0.24	0.03	<0.1
	Total N	0.35	0.044	0.37	0.03	0.26
	DON	0.28	0.052	0.13	0.013	0.15
	PO_4	0.16	0.019	0.4	0.14	0.1
	Total P	0.25	0.029	0.46	0.15	0.16
DOT	NH_4	0.51	0.18	0.45	0.2	
	Total N	0.69	0.18	0.71	0.21	
	DON	0.18	0.018	0.26	0.071	
	PO_4	0.41	0.057	0.39	0.064	
	Total P	0.46	0.057	0.46	0.062	
Port	NH_4	0.54	0.12	0.42	0.14	<0.1
	Total N	1.28	0.32	1.21	0.6	0.12
	DON	0.74	0.33	0.79	0.61	0.12
	PO_4	0.36	0.17	0.15	0.33	0.09
	Total P	0.61	0.21	0.38	0.18	0.19

Table 3-6. Carbon, Nitrogen and Phosphorous Pools (g m^{-2}) in the 0-30 cm depth of three Marshes.

		Soil pools		MOM pools		Total pools	
Marsh	nutrient	edge	inland	edge	inland	edge	inland
Natural	C	3942	4401	905	1466	4847	5867
	N	291	289	26.8	41.5	317.8	330.5
	P	56.4	46	1.64	2.12	58.04	48.12
DOT	C	994	921	275	473	1269	1394
	N	103	110	4.24	7.22	107.2	117.2
	P	115	117	0.5	0.66	115.5	117.7
Port	C	1854	468	381	403	2235	871
	N	168	89.2	6.36	6.76	174.4	96.0
	P	109	107	0.48	0.44	109.5	107.4

Table 3-7. Total Carbon, Nitrogen and Phosphorous exported from two marshes on an annual basis expressed as a percent of the total C, N, P pools in the marsh soils.

	Carbon		Nitrogen		Phosphorous	
marsh	edge	inland	edge	inland	edge	inland
Natural	0.12	0.079	19.1	0.5	31.3	1.3
DOT	1.0	0.80	24.8	1.1	11.9	0.5

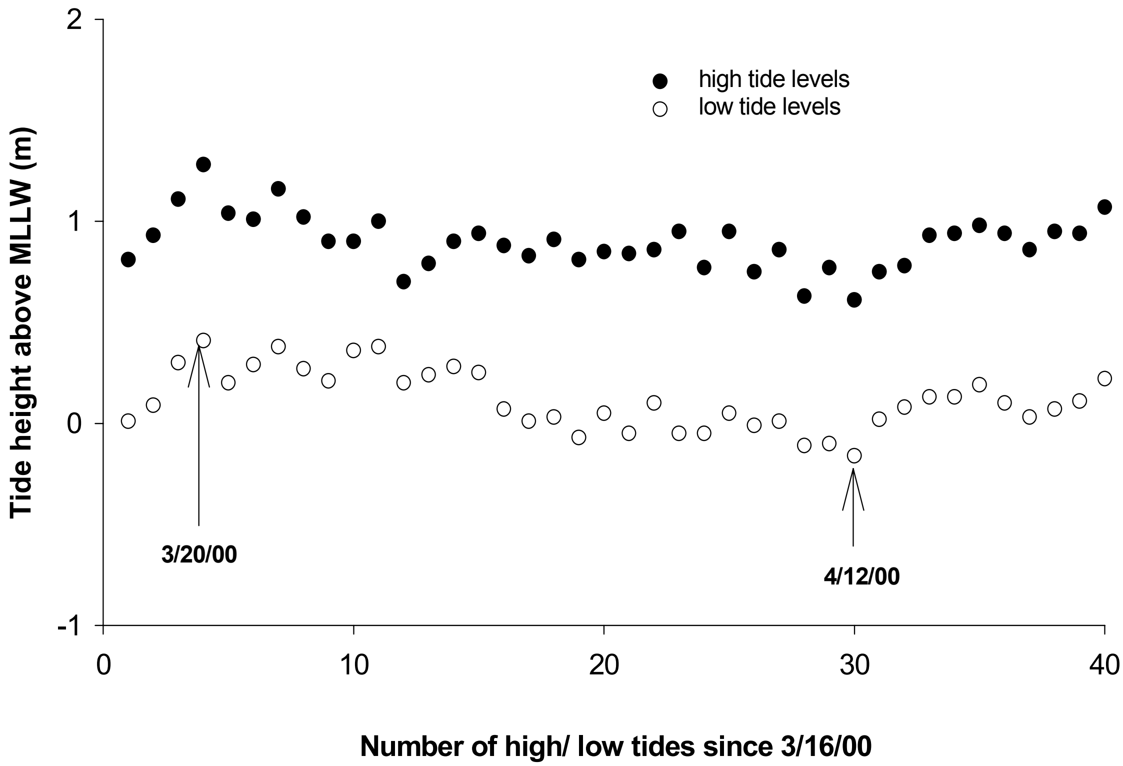


Figure 3-1. High and Low Tide Levels during first Monitoring Period (3/16/00 - 4/18/00)

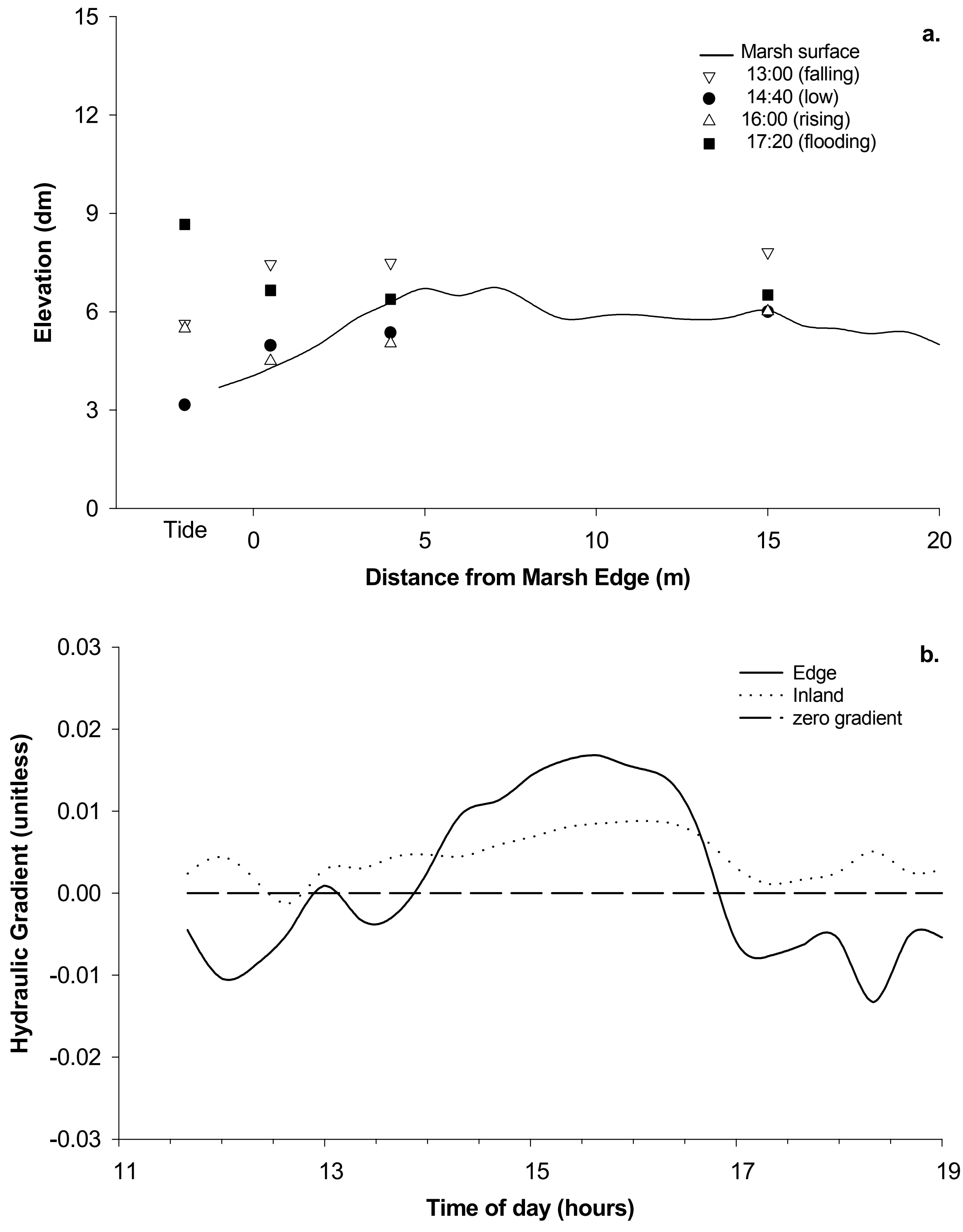


Figure 3-2. Water Levels (a) and Hydraulic Gradients (b) in Natural Marsh on March 20, 2000 Tidal Cyle.

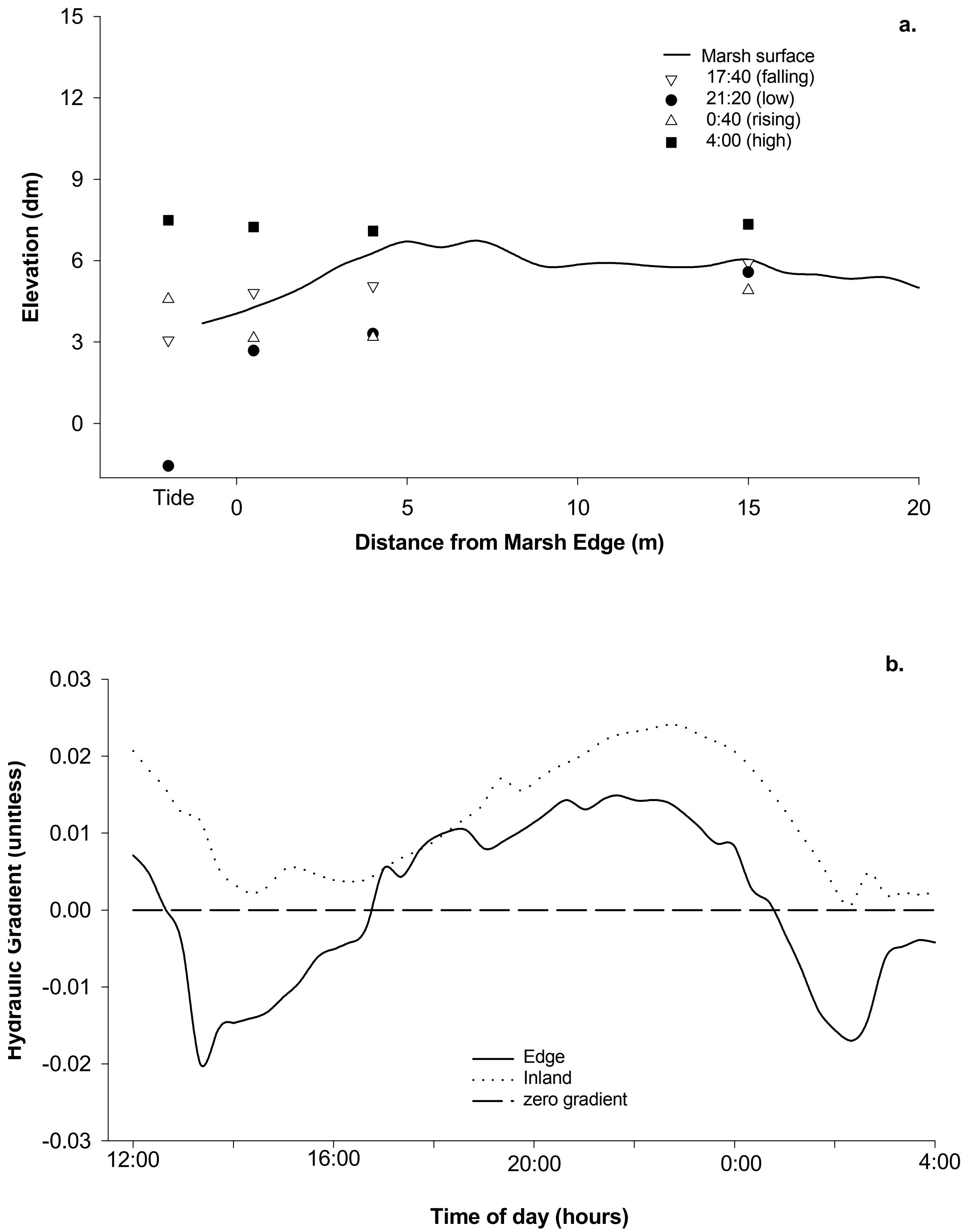
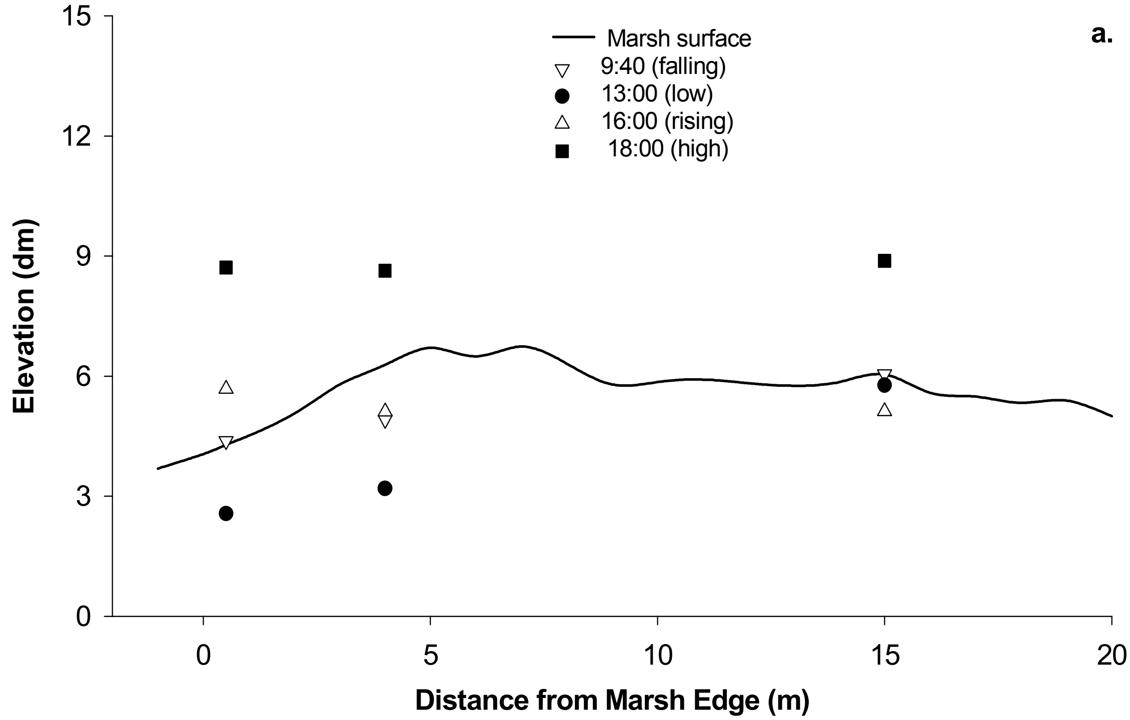


Figure 3-3. Water Levels (a) and Hydraulic Gradients (b) in Natural Marsh on April 12-13 Tidal Cycle.



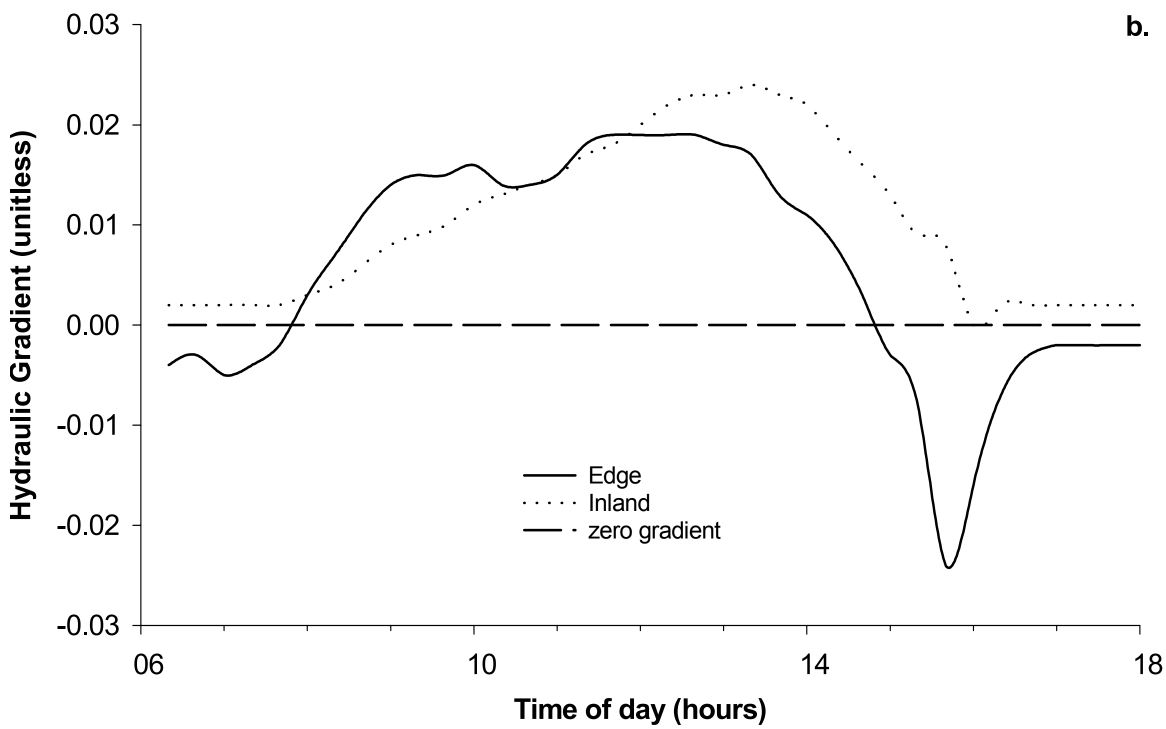


Figure 3-4. Water Levels(a) and Hydraulic Gradients (b) in Natural Marsh on June 13 Tidal Cycle.

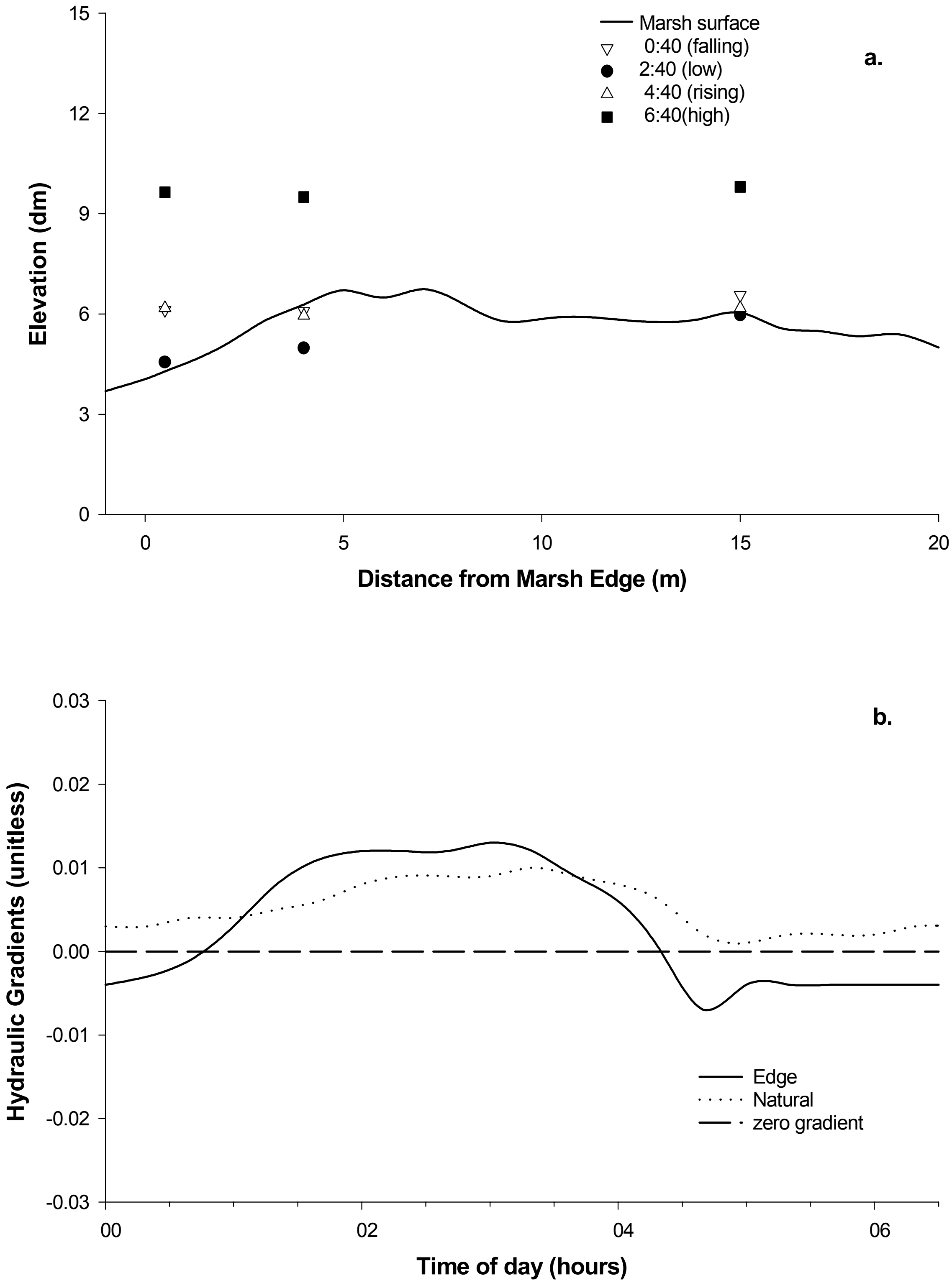


Figure 3-5. Water Levels (a) and Hydraulic Gradients (b) in Natural Marsh on July 1, 2000 Tidal Cycle.

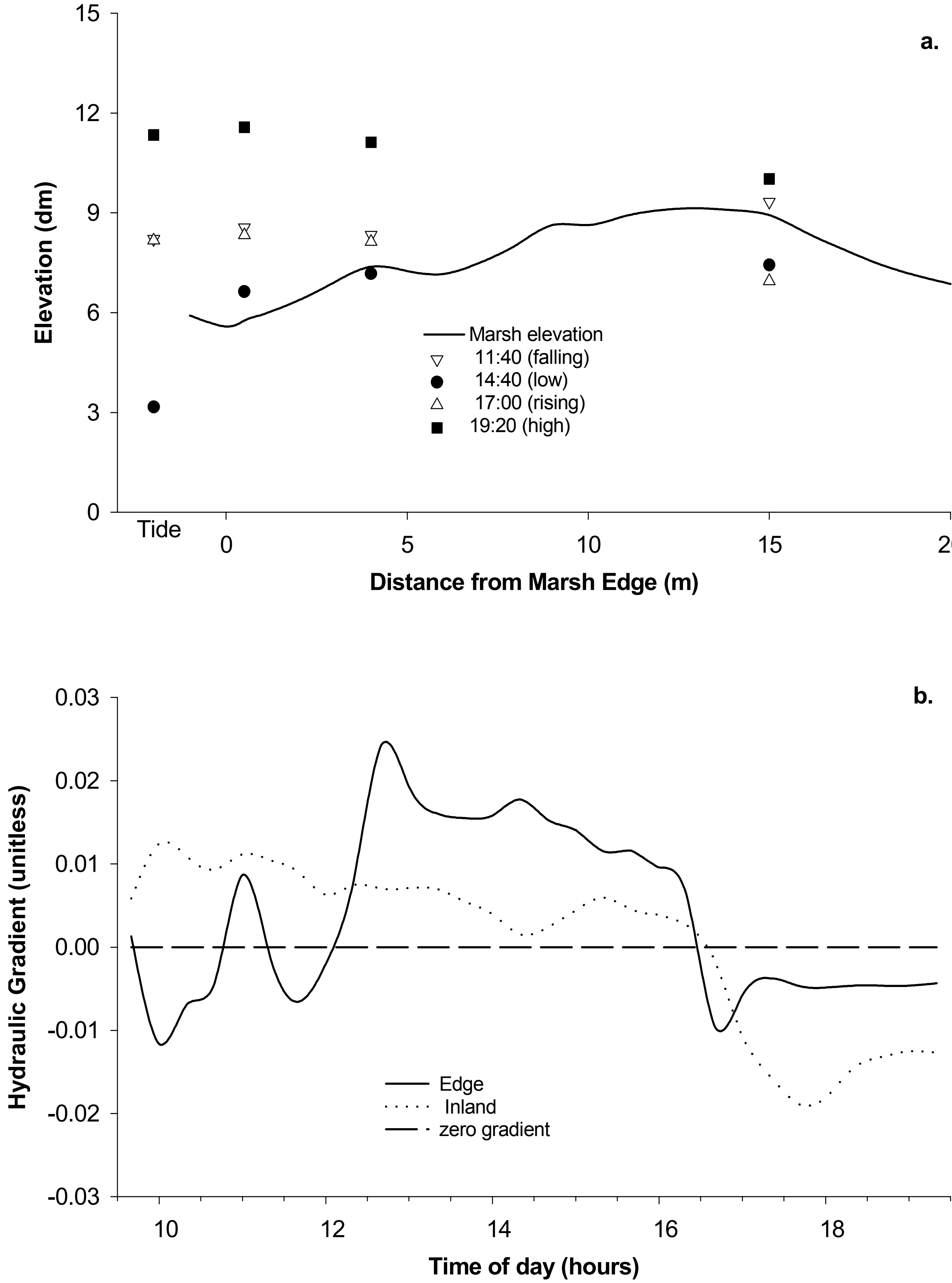
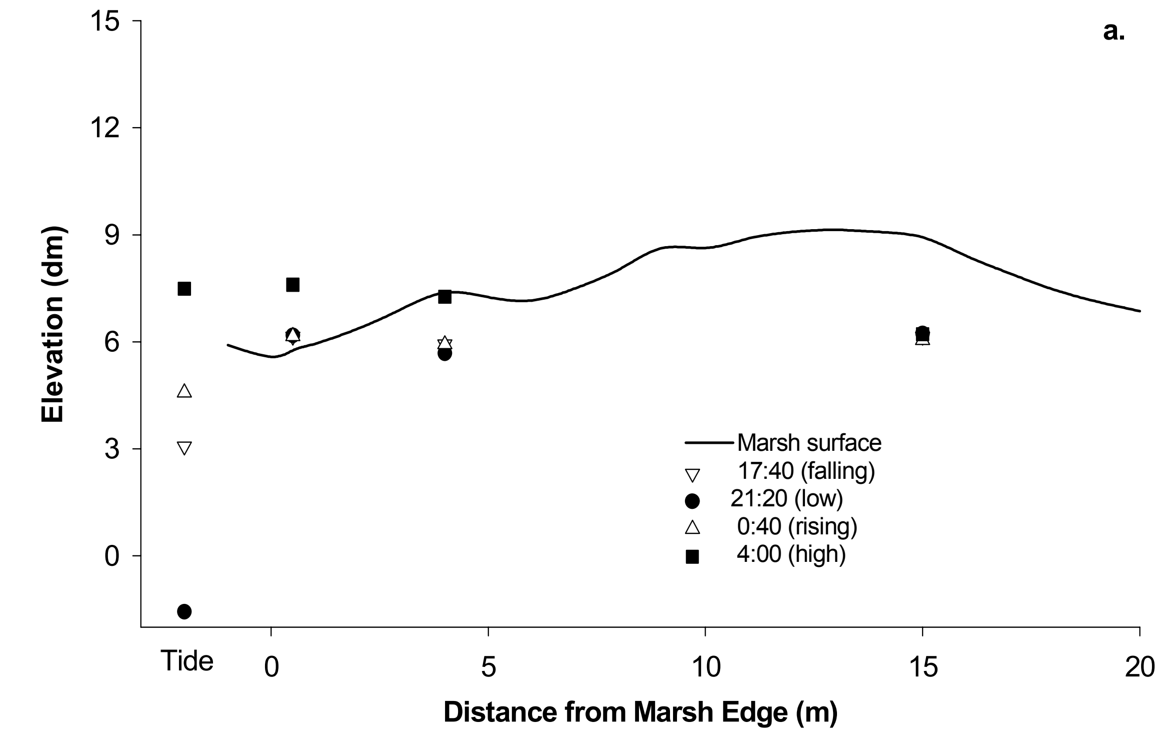


Figure 3-6. Water Levels (a) and Hydraulic Gradients (b) in DOT marsh on March 20, 2000 Tidal Cycle.



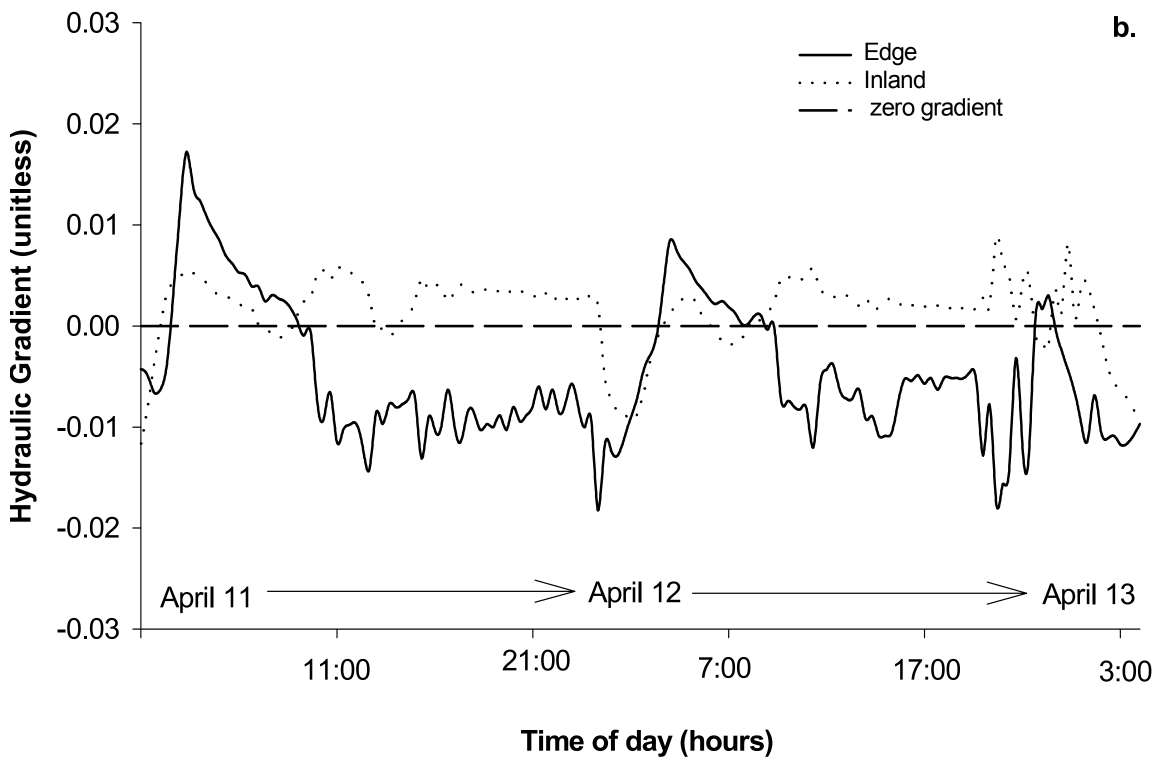


Figure 3-7. Water Levels (a) and Hydraulic Gradients (b) in DOT marsh on April 12 - 13, 2000 Tidal Cycle.

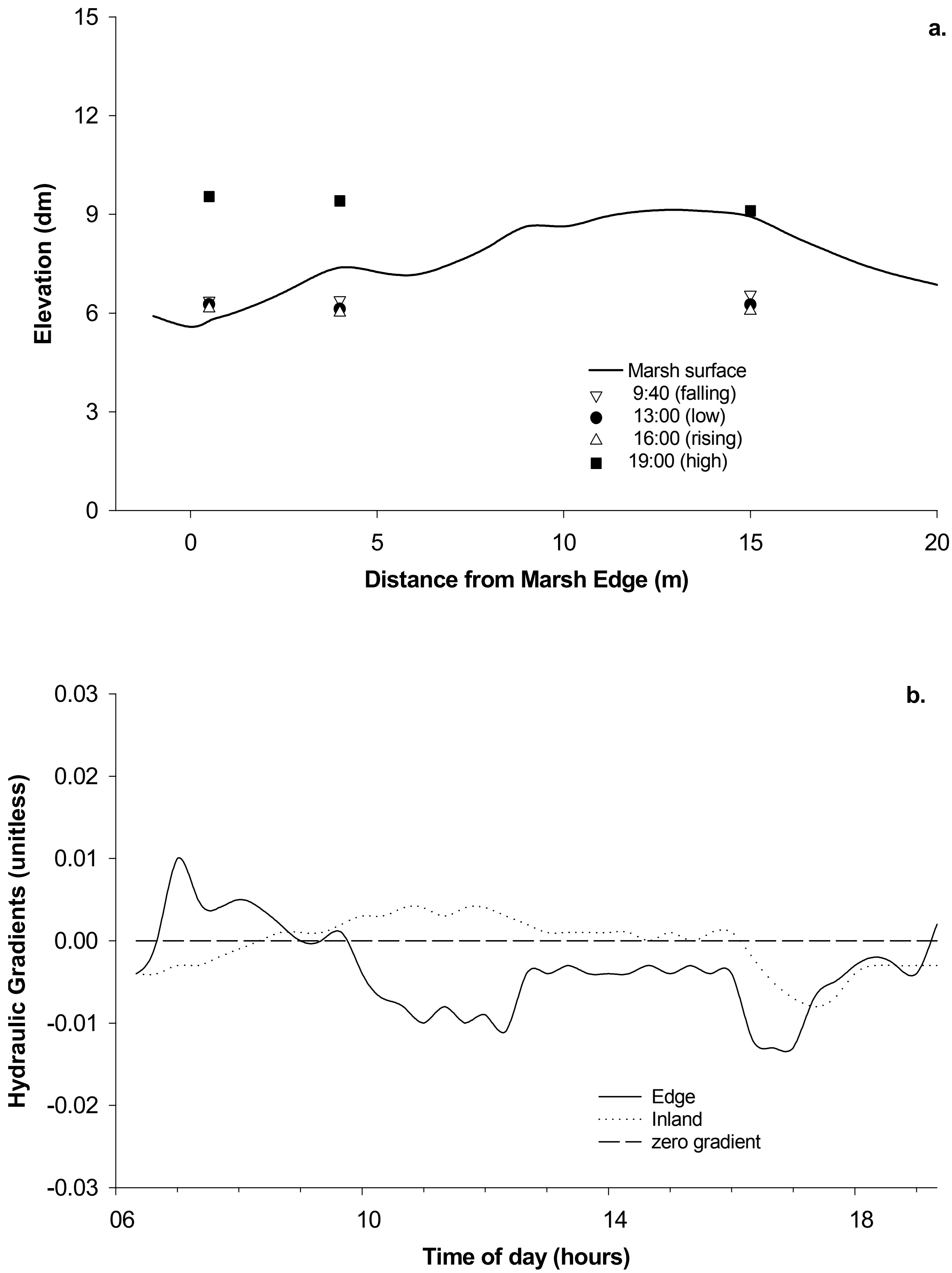
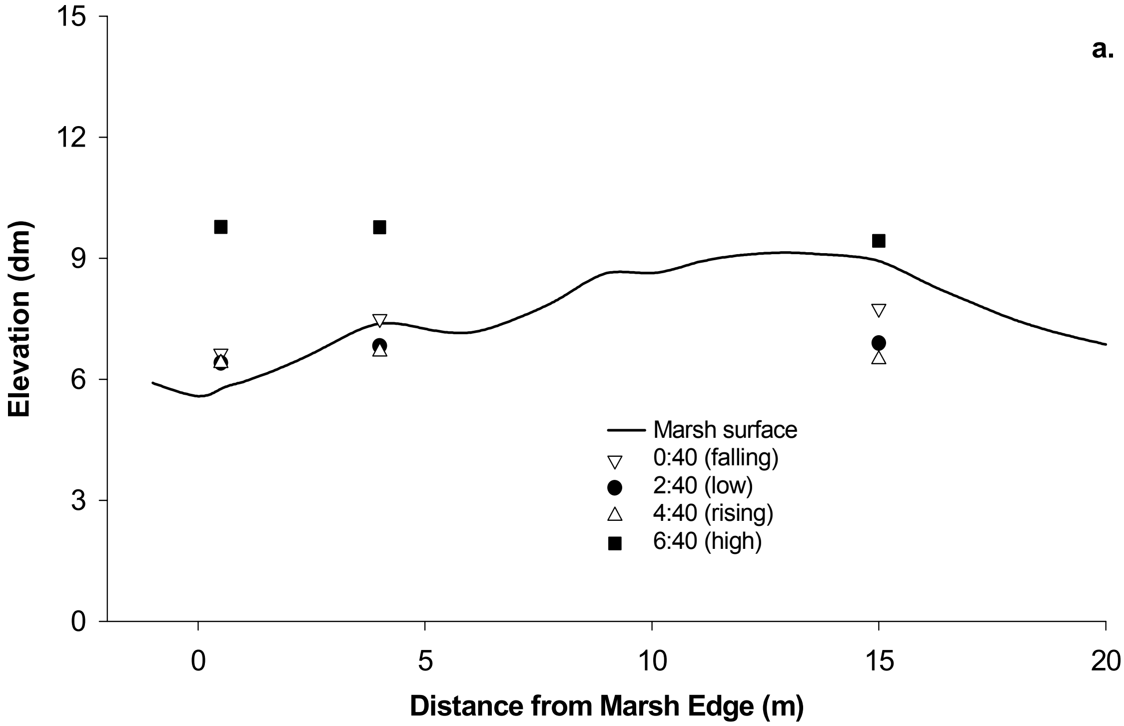


Figure 3-8. Water Levels (a) and Hydraulic Gradients (b) in DOT marsh on June 13, 2000 Tidal Cycle.



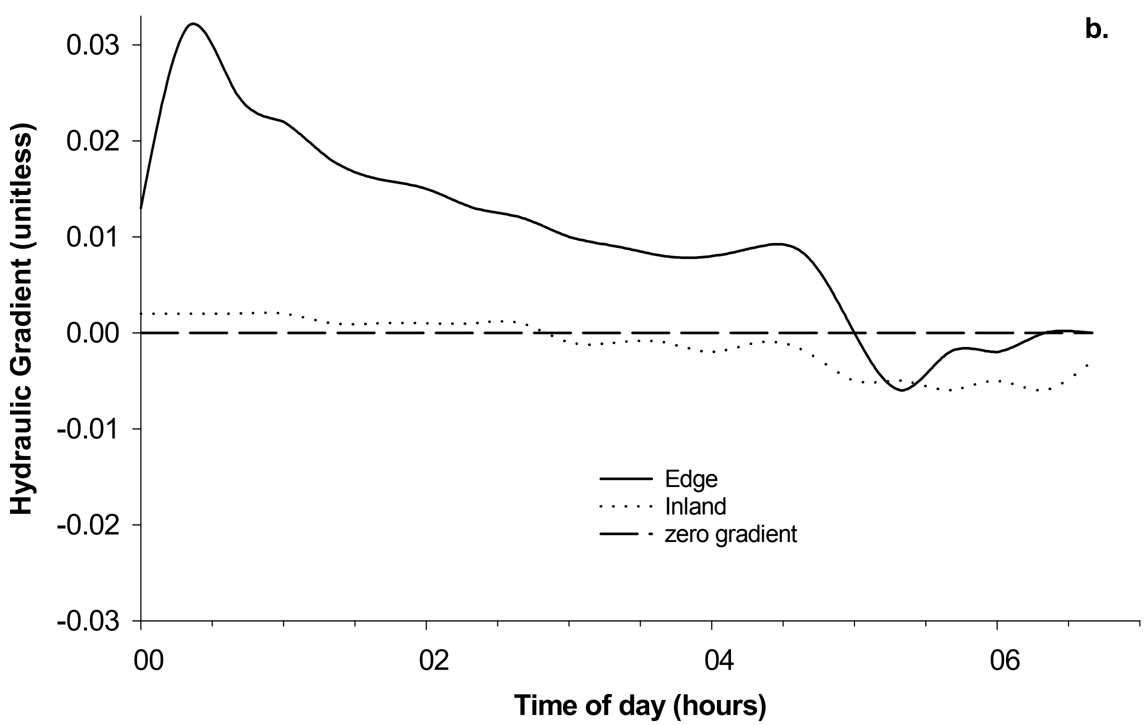


Figure 3-9. Water Levels (a) and Hydraulic Gradients (b) in DOT Marsh on July 1, 2000 Tidal Cycle.

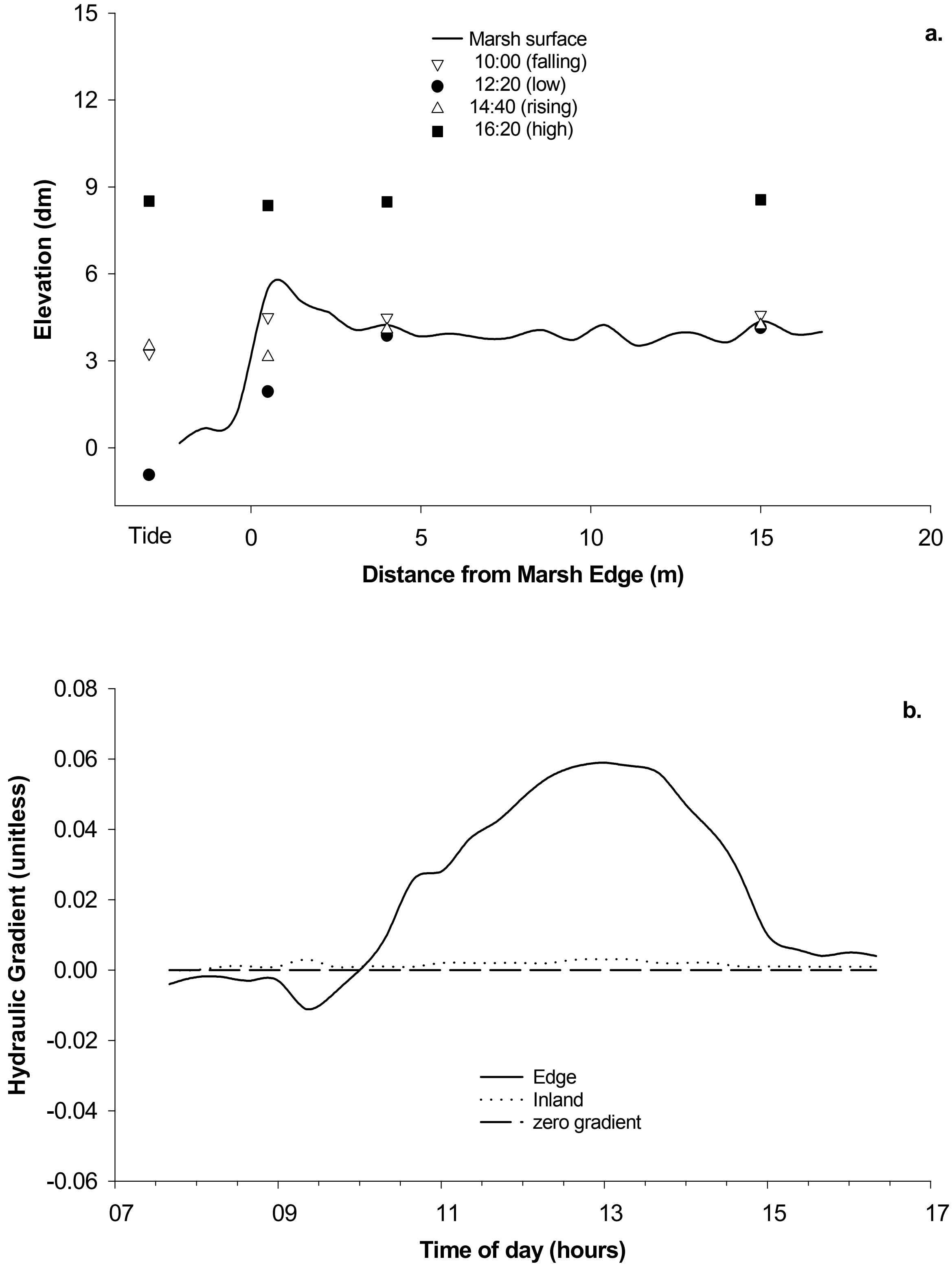


Figure 3-10. Water Levels (a) and Hydraulic Gradients (b) in Natural Port Marsh on August 27, 2000 Tidal Cycle.

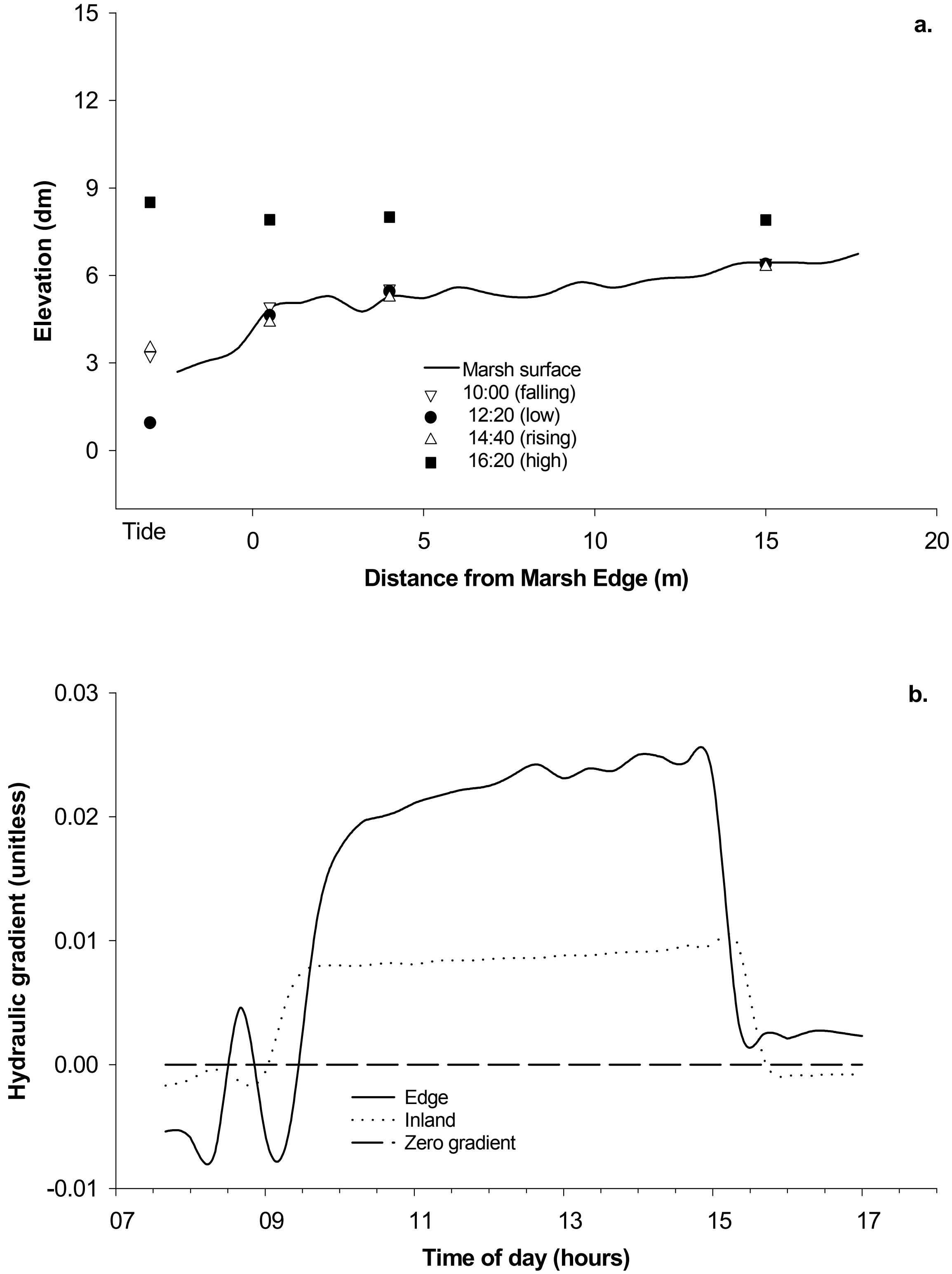


Figure 3-11. Water Levels (a) and Hydraulic Gradients (b) in Created Port Marsh on August 27, 2000 Tidal Cycle.

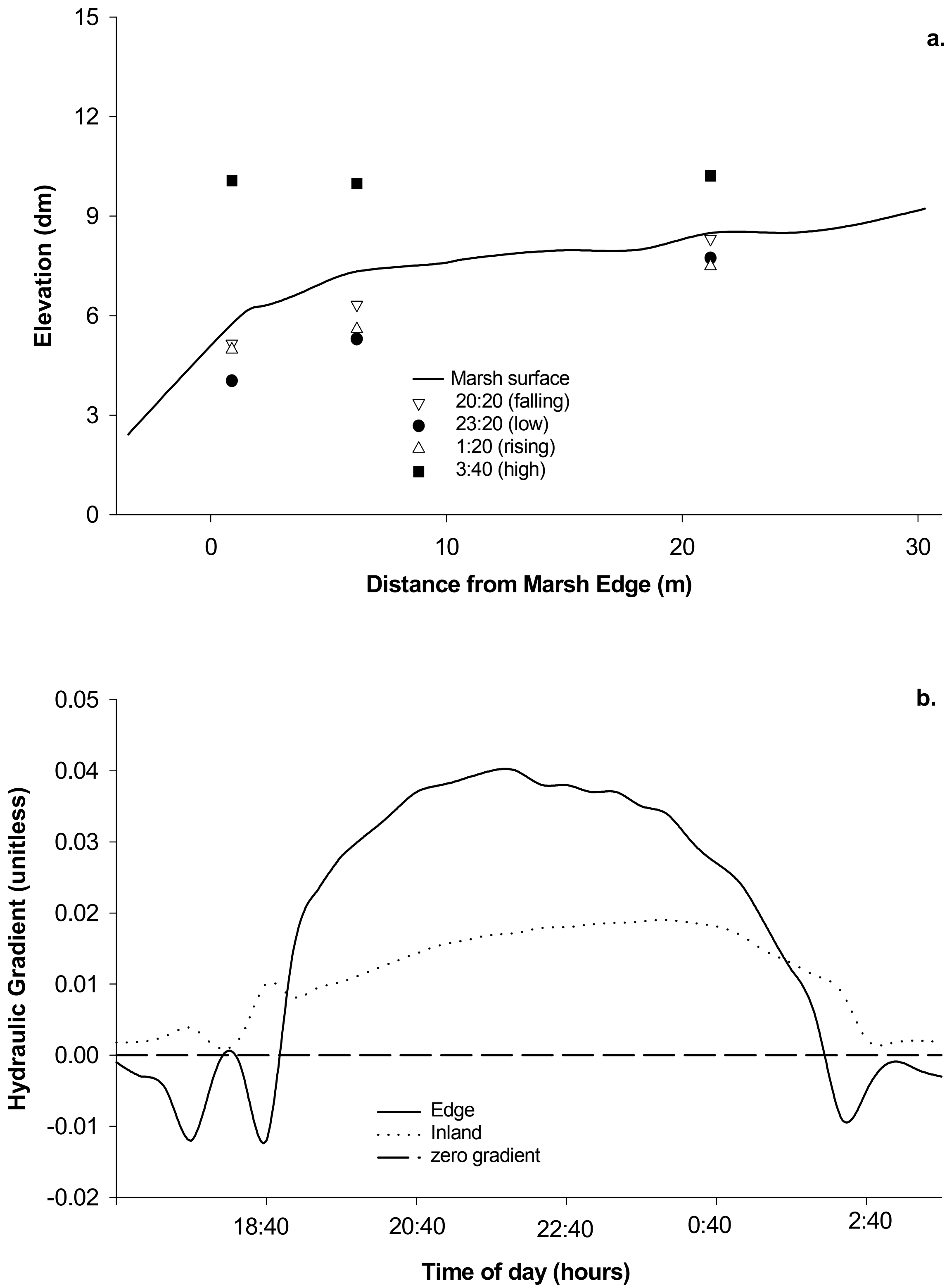


Figure 3-12. Water Levels (a) and Hydraulic Gradients (b)
in Marine Lab Marsh on December 11 - 12, 2001 Tidal Cycle.

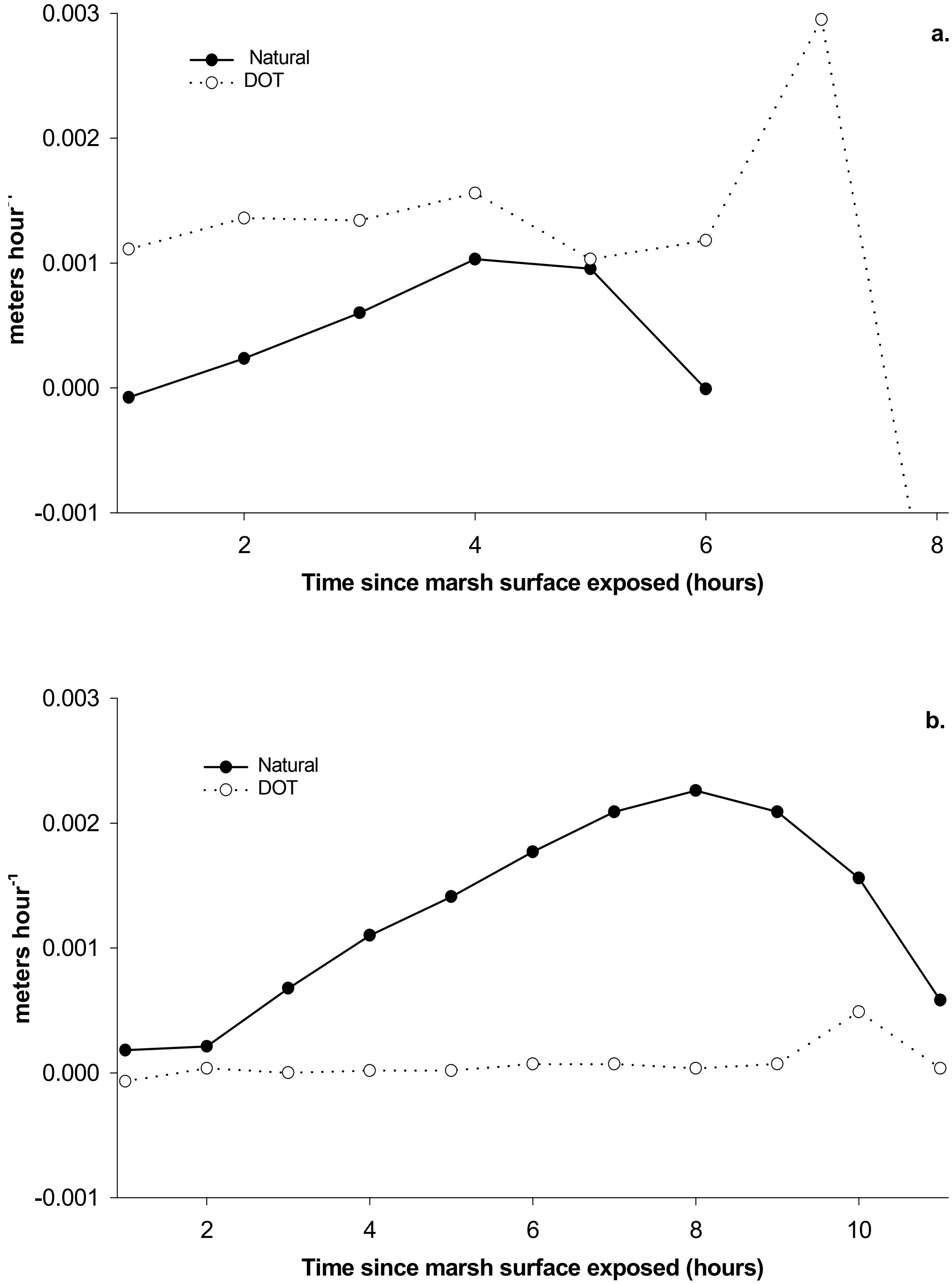


Figure 3-13. Average Hourly Soil Water Flux Between 0.5 and 15 m Wells in Two Marshes on March 20, 2000 (a) and April 12 - 13 (b) Tidal Cycles.

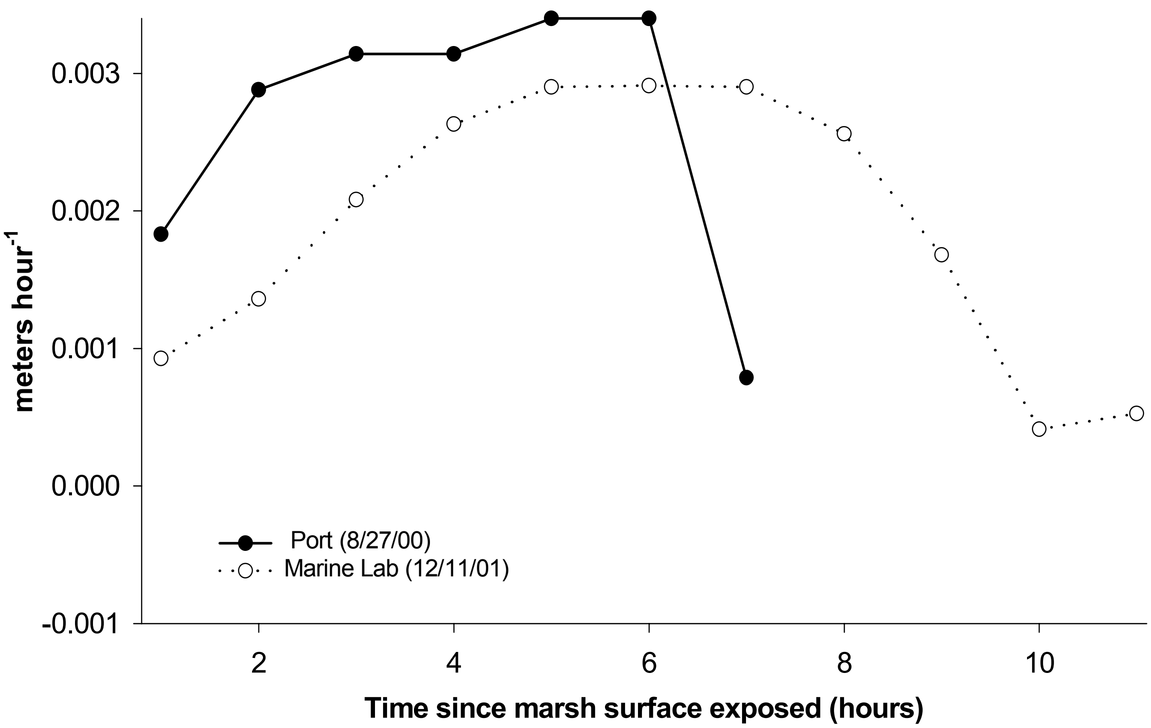


Figure 3-14. Average Hourly Soil Water Flux from two Created Marshes on Separate Dates.

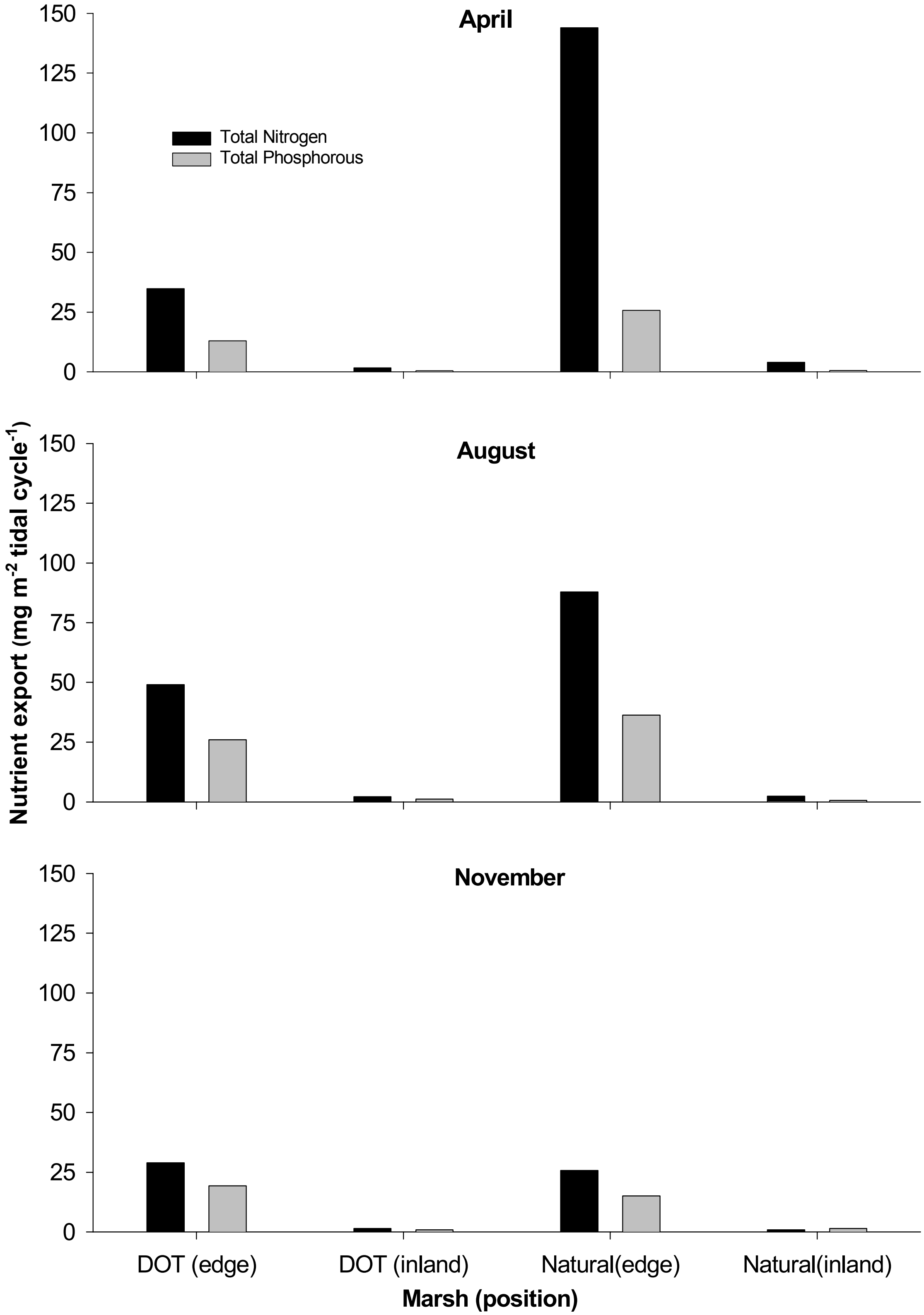


Figure 3-15. Seasonal Variation in Nutrient Export from Edge and Inland Positions within DOT and Natural Marshes.

Appendix A. Procedure for Calculation of Drainage Volume from DOT and Natural Marshes (Skaggs, 2000).

Table A1. Maximum water table drop (cm) below soil surface on selected dates.

Marsh	Well distance	3/20/00	4/12/00	6/13/00	7/1/00
DOT	0.5 m	1.9	5.4	5.4	3.4
	4 m	11.3	23.2	20.3	13.2
	15 m	17.1	25.2	25.9	21.7
Natural	0.5 m	3.0	26.5	22.8	3.0
	4 m	12.4	37.1	32.7	13.9
	15 m	0.6	12.1	9.8	1.0

In a system at equilibrium, hydraulic head (H) is the same everywhere. H has two components that we will consider, pressure head (h) and elevation head (z) such that

$$H = z + h$$

By definition, h = 0 at the surface of the water table, z is calculated relative to an arbitrary datum, set at 100 cm below the marsh surface.

The following is a sample calculation of drainage volume from the Natural marsh, 0.5 meter monitoring well, 4/12/00 date (water table depth = 26.5 cm)

Step 1: Construct the soil water profile in 2.5 cm increments from the soil surface to the top of the water table. Use the relationship between h and θ (volumetric water content) provided by the soil water release curve (Figure A1) to determine the water content at each value of z as a function of h. Use separate water release curves for the 0-20 cm depth (layer "a") and the 20+ cm depth (layer "b").

Table A2. Sample calculation of soil water profile.

z (cm)	h (cm)	H (cm)	θsa	θa(h)	Δθa	θsb	θb(h)	Δθb
100	-26.5	73.5	0.564	0.484	0.080			
97.5	-24.0	73.5	0.564	0.490	0.074			
95	-21.5	73.5	0.564	0.496	0.068			
92.5	-19.0	73.5	0.564	0.502	0.062			
90	-16.5	73.5	0.564	0.508	0.056			
87.5	-14.0	73.5	0.564	0.514	0.051			
85	-11.5	73.5	0.564	0.519	0.045			
82.5	-9.0	73.5	0.564	0.526	0.038			
80	-6.5	73.5	0.564	0.533	0.031	0.555	0.537	0.018
77.5	-4.0	73.5				0.555	0.544	0.011
75	-1.5	73.5				0.555	0.551	0.004
73.5	0	73.5				0.555	0.555	0

θsa = volumetric water content at saturation for 0-20 cm layer
$\theta a(h)$ = volumetric water content at a given z as a function of h (pressure head)
$\Delta\theta a = \theta sa - \theta a(h)$, change in volumetric water content between saturation and the given pressure head.
θsb = volumetric water content at saturation for 20+ cm layer
$\theta b(h)$ = volumetric water content at a given z as a function of h (pressure head)
$\Delta\theta b = \theta sb - \theta b(h)$, change in volumetric water content between saturation and the given pressure head. This is the discharge volume (cm) for each value of z.

Step 2: When $\theta a(h)$ is plotted as a function of z then the soil moisture profile is obtained. If θsa is also plotted as a function of z then the area between the two curves can be integrated to determine total discharge volume. The trapezoidal rule can be used to approximate this quantity.

$$\int_b^a f(z)\,dz \cong T_n = \frac{\Delta z}{2}\left[f(z_0) + 2f(z_1) + 2f(z_2) + \ldots + 2f(z_{n-1}) + f(z_n)\right]$$

where $\Delta z = (b - a)/n$ and $z_i = a + i\Delta z$

For convenience in this calculation, $\Delta z = 2.5$ cm. The integration can be done in three parts, corresponding to the drainage volume from 0-20 cm (Vd_1), drainage volume from the layer below 20 cm (Vd_2), and drainage volume from the small increment of z immediately above the water table (Vd_3).

$Vd_1 = 2.5/2\ [.08 + 2(.074 + .068 + .062 + .056 + .0505 + .045 + .038) + .031] = 1.12$ cm

$Vd_2 = 2.5/2\ [.018 + 2(.011) + .004] = 0.055$ cm

$Vd_3 = 1.5/2\ [.004 + 0] = 0.003$ cm

$Vd_t = Vd_1 + Vd_2 + Vd_3 = 1.18$ cm total drainage volume

This can be expressed as an actual volume by specifying a certain surface area of marsh, such as 1 m^2.

0.0118 m * 1 m^2 = .0118 m^3 = **11.8 liters m^{-2} tidal cycle^{-1}**. This is the volume that drains from a 1 m^2 area of the natural marsh at the site located 0.5 meters from marsh edge for the tidal cycle from April 12, 2000.

Appendix B. Calculation of Volume Discharge from Creekbank in Port Marsh.

The Dupuit-Forchheimer approximations are assumptions that simplify solutions to saturated- unconfined flow problems (Skaggs, 2000). They allow us to assume that streamlines above the lower boundary of flow are horizontal and that equipotential lines are vertical. Through integration of Darcy's law, the following equation for determining outflow per unit length of the marsh edge may be attained (Todd, 1964).

$$Q = \frac{K}{2L}(H_1^2 - H_2^2)$$

where: Q = flowrate per unit length of marsh edge ($m^3\ hr^{-1}\ m^{-1}$)
H_1 = hydraulic head at inflow point, relative to confining layer
H_2 = hydraulic head at discharge point, relative to confining layer
L = lateral distance between H_1 and H_2 (14.5 m at Port marsh)
K = average hydraulic conductivity (0.212 m h^{-1} for Port marsh)

In the Port marsh, H_1 = hydraulic head at the 15 meter well, H_2 = hydraulic head at 0.5 meter well. The hydraulic conductivity used in this calculation (0.212 m h^{-1}) is an average of all positions and depths.

Table B1. Hourly averages of hydraulic head used to calculate lateral discharge from a one meter length of creekbank in the Port Marsh on 8/27/00.

Time of day	H_1^2	H_2^2	$H_1^2 - H_2^2$	Discharge ($m^3\ hr^{-1}\ m^{-1}$ length of creek)
9:00 – 10:00	0.24	0.19	0.04	0.00033
10:00 – 11:00	0.23	0.11	0.13	0.00092
11:00 – 12:00	0.23	0.10	0.13	0.00097
12:00 – 13:00	0.23	0.09	0.14	0.00101
13:00 – 14:00	0.23	0.09	0.14	0.00102
14:00 – 15:00	0.22	0.08	0.14	0.00104
15:00 – 16:00	0.22	0.13	0.09	0.00066

The sum of the discharges from a one meter length of creekbank during the 7 hours the marsh surface is exposed is 0.00594 m^3 or **5.94 liters**.

Calculation of Nutrient Export

Since the 5.94 liter discharge represents discharge from the whole marsh through the creekbank edge, separate calculations of nutrient loss for edge and inland positions are not possible. Instead, pore water concentrations of C,N,P are averaged for the two positions and depths. In order to compare this export to the total C,N,P pool (g m^{-1}) shown in Figure 6, it is necessary to express nutrient export from an area of the marsh rather than from length of the creekbank. As shown in Table 1 of the previous chapter, the average width of this marsh is 31 meters and thus the average meter length of creek edge may be expected to drain about 31 m^2. The following calculation demonstrates how N export from this marsh may be estimated as a proportion of the total N pool.

5.94 liters $H_2O\ m^{-1}$ * 1.72 mg N $liter^{-1}$ = 10.2 mg N m^{-1}
10.2 mg N m^{-1} * 706 tidal cycles $year^{-1}$ * 0.001g mg^{-1} = 7.21 g N m-^{1} yr^{-1}
7.21/ 4191 = .00172 or **0.17%** export of the total soil N pool on a yearly basis.

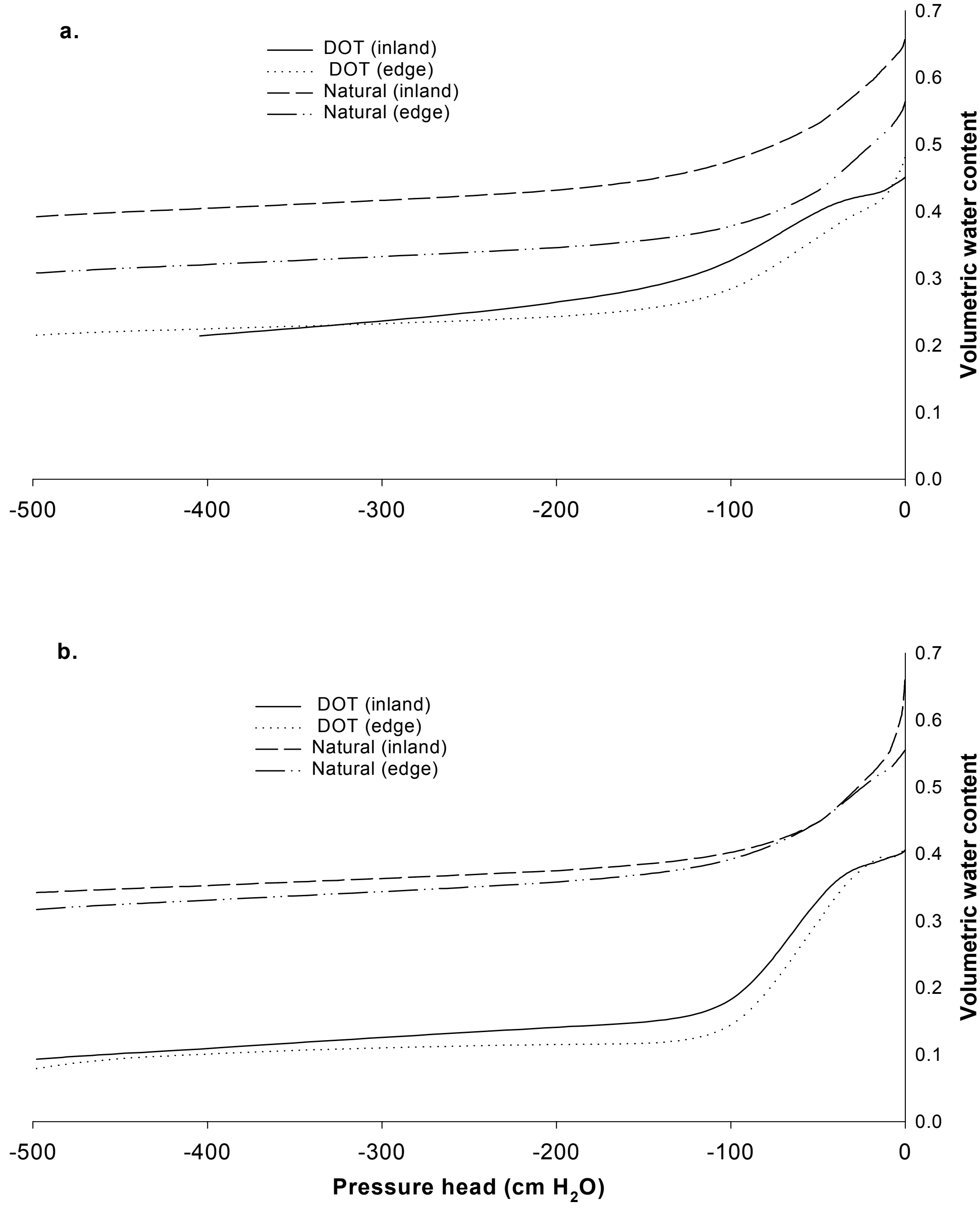


Figure A. Soil Water Release Curves for 0-20 cm layer (a), and 20+ cm Layer (b).