LANDSCAPE-LEVEL ASSESSMENT OF SUBAQUEOUS SOILS AND WATER QUALITY IN SHALLOW EMBAYMENTS IN SOUTHERN NEW ENGLAND

BY

MARGOT KIDD PAYNE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

ENVIRONMENTAL SCIENCES

UNIVERSITY OF RHODE ISLAND

2007

MASTER OF SCIENCE THESIS

OF

MARGOT KIDD PAYNE

APPROVED:

Thesis Committee:

Major Professor_____

_____

_____

_____
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

2007

ABSTRACT

Recent soil survey efforts along the Atlantic and Gulf Coasts have begun to include the mapping of subtidal environments in shallow water bodies. The mapping of these "subaqueous soils" is being driven by a recognized need for an inventory of the shallow subtidal resources. An account of these soils would be an important resource for eelgrass, fish, and shellfish habitat mapping and would also provide valuable information to coastal regulators as to areas of sedimentation, shoreline change, and potential dredge sites. The primary objectives of my research were: i) to evaluate how well the soil-landscape approach works for mapping subaqueous soils in shallow coastal embayments; ii) to determine if indicators of water quality follow landscape level boundaries; and iii) to document sulfide distribution within subaqueous landscapes. Three shallow coastal embayments in Connecticut and Rhode Island, 160 to 1200 ha and having a range of human impact, were investigated. Twenty-one landscape units were delineated based on slope, depth, parent material, aerial photo interpretation, and sidescan sonar data. Fifteen of the landscape units were found in at least two of the three bays, whereas eight were found in all three of the bays. Within seven of these shared landscape units, six units contained soils that were dominated by a single subgroup, suggesting that subaqueous soils in embayments can be related to landscape unit. A total of 54 soils were described, sampled, and analyzed. The majority of soils classified as Sulfiwassents (63%) and Psammowassents (30%). Carbon pools of landscape units dominated by Sulfiwassents were equivalent to poorly drained subaerial soils (mean = 181 Mg ha^{-1}).

Landscape units with a majority of Psammowassents contained carbon pools equivalent to excessively drained subaerial soils (mean = 57 Mg ha^{-1}).

Low energy landscape units (Bayfloor, Cove, Drowned Channel, and Fluviomarine Bottom), dominated by fine-grained soils, had significantly lower water quality indices than higher energy landscape units such as Washover Fan, Mainland Shoreface, Spit, and Shoal. Hypoxic and severely hypoxic dissolved oxygen (DO) readings (<5 mg L^{-1}) occurred most frequently in low energy landscape units, whereas in the high-energy units hypoxia was observed on only one occasion. Chlorophyll *a* levels were highest in the low energy landscape units in all seasons, and areas with high chlorophyll levels had lower soil redox potential (R^2=0.59). Redox potential was significantly different among landscape units; with the lowest potentials on landscape units where deposition of fine-grained soil particles occur, and more positive redox potentials on high-energy landscape units where sandy soils are dominant. Thickness of the oxidized surface changed over the monitoring season and followed redox potential trends. A multimetric indicator based on salinity, redox potential, chlorophyll *a* in the early summer, and dissolved oxygen content in the late summer revealed significant differences in water quality between high and low energy landscape units. These results suggest that stratifying embayments by landscape unit may be a useful tool in identifying locations with a high risk of water quality problems such as hypoxia.

Fifty-two soil samples from three shallow estuaries in Rhode Island were analyzed for sulfide content using the diffusion method, incubation pH, and salt content after oxidation with peroxide. Total sulfide measurements ranged from 20 –

11592 μg/g with an average of 2965 μg/g. Nearly half of all samples measured (47%) had incubation pH readings ≤4.0. Soils that reached an incubation pH ≤4 showed no significant difference in carbon content from those that had an incubation pH >4, and samples with higher incubation pH values had significantly higher levels of calcium carbonate than those with low incubation pH. Carbon content and particle size appear to be the two factors that were the most strongly related to the distribution of sulfides. Total dry weight of salts after oxidation with hydrogen peroxide showed a stronger relationship with total sulfides (R^2=0.70) than incubation pH (R^2=0.19), suggesting that measuring salts generated from oxidation may provide a surrogate for sulfide measures. Sulfide content and incubation pH showed similar trends among landscape units with high sulfide levels, low incubation pH, and high carbon and calcium carbonate contents on low energy, silty landscape units. Thus, sulfide content appears to be highly dependent on landscape unit and is just one of many potential interpretations for estuary management that could be made based on subaqueous soil maps of these shallow coastal areas.

ACKNOWLEDGEMENTS

I would like to thank my major professor Dr. Mark Stolt for giving me the opportunity to pursue this research and for his guidance and support through the last three years. I would also like to thank my committee members, Dr. Jon Boothroyd, Dr. Peter August, and Dr. John King, as well as the entire MapCoast group for sharing their knowledge and equipment to support this study. I would especially like to thank Mike Bradley and Jim Turenne. I cannot thank these two enough for helping to jumpstart the study of subaqueous soils in Rhode Island and for all of the assistance and training that they provided (and continue to provide).

There are many people who assisted in this study through the years who deserve my thanks: Justin Tuthill, Joel Schmidt, John Richard, and all of the folks at Rhode Island NRCS for use and training of the RTK and tide gauges; the soils staff of Connecticut NRCS for their assistance in Little Narragansett Bay; Linda Green and Elizabeth Herron for the use of Watershed Watch equipment; Bryan Oakley for expert boat advice and Sidescan data; and Emily Shumchenia for SPI camera data. Multiple Coastal Fellows and assistants including Sarah Lincoln, Emily Blair, and Michelle Marasco provided valuable help in the field and lab. Of course, thank you to all those in the URI pedology lab, past and present: Tim Twohig, Matt Richardson, Sean Donohue, Kim Devlin, Dave Millar, and Alex Salisbury.

Finally, I would like to thank my family for their support and enthusiasm. Last and certainly not least, I would like to thank my husband, Justin, for his support and for sacrificing nights and weekends to provide technical, field, financial, and emotional assistance.

PREFACE

This thesis was written and formatted following the guidelines presented by the University of Rhode Island Graduate School. There are three chapters: Subaqueous Soil-Landscape Relationships in Shallow Estuaries (Chapter 1), Stratifying Embayments by Landscape Unit to Evaluate Subaqueous Soil-Water Quality Relationships (Chapter 2), and Sulfide Distribution in Subaqueous Soil Systems (Chapter 3).

TABLE OF CONTENTS

ABSTRACT……... ii

ACKNOWLEDGEMENTS……... v

PREFACE……..... vi

TABLE OF CONTENTS……. vii

LIST OF TABLES…….ix

LIST OF FIGURES……x

CHAPTER 1: SUBAQUEOUS SOIL-LANDSCAPE RELATIONSHIPS IN SHALLOW ESTUARIES

ABSTRACT……1

INTRODUCTION……..2

MATERIALS AND METHODS……5

STUDY SITES……5

MAPPING AND SOIL ANALYSIS……..6

RESULTS AND DISCUSSION……...10

SUBAQUEOUS SOIL CARBON POOLS……. 16

SUMMARY AND CONCLUSIONS…….. 18

CHAPTER 2: STRATIFYING EMBAYMENTS BY LANDSCAPE UNIT TO EVALUATE SUBAQUEOUS SOIL-WATER QUALITY RELATIONSHIPS

ABSTRACT……. 43

INTRODUCTION……44

MATERIALS AND METHODS……. 48

STUDY AREAS…….. 48

MONITORING…… 50

RESULTS AND DISCUSSION……. 53

WATER QUALITY ASSESSMENT……. 53

REDOX POTENTIAL…… 58

PROFILE DARKNESS INDEX……. 62

SEDIMENT PROFILE IMAGING……. 63

SUMMARY AND CONCLUSIONS…….. 64

CHAPTER 3: SULFIDE DISTRIBUTION IN SUBAQUEOUS SOIL SYSTEMS

ABSTRACT……. 92

INTRODUCTION……... 93

MATERIALS AND METHODS…… 96

RESULTS AND DISCUSSION……. 99

IMPLICATIONS……105

APPENDIX 1: PEDON FIELD DESCRIPTIONS AND LAB DATA……. 119

APPENDIX 2: PROPOSED AMENMENTS TO SOIL TAXONOMY..... 169

APPENDIX 3: WATER QUALITY MEASUREMENTS BY SEASON……..175

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES……..177

APPENDIX 5: SULFIDE ANALYSIS DATA……..188

BIBLIOGRAPHY……...192

LIST OF TABLES

Table		Page
1.1	Number of pedons collected in landscape units investigated for each study site	20
1.2	Landscape unit definitions	21
1.3	Total area of each landscape unit mapped and percent of total bay area that the landscape unit comprises	26
1.4	Total numbers of subgroups identified and landscape units on which each soil was found	27
1.5	Taxonomic purity of landscape units investigated	28
1.6	Profile descriptions from vibracore samples typical of the four great groups most commonly encountered	29
1.7	Particle size analysis for vibracore samples typical of the great groups most commonly encountered	33
1.8	Laboratory analysis for vibracore samples typical of the great groups most commonly encountered	34
2.1	Water quality measurements by landscape unit in each bay measured in four monitoring seasons	68
2.2	Percent of hypoxic and severely hypoxic DO readings (<5 mg/l) in each monitored landscape unit	69
2.3	Bottom type predicted by the five most significant water quality parameters	70
3.1	Variance-covariance matrix of sulfide contents and factors related to sulfide content	107
3.2	Principal components and rotated factor loading for physical variables related to sulfide content	108

LIST OF FIGURES

Figure		Page
1.1	Study sites in Rhode Island and Connecticut	35
1.2	Orthophotograph of Greenwich Bay, a 1200 ha subestuary of Narragansett Bay	...36
1.3	Orthophotograph of Wickford Harbor, a 160 ha bay within Narragansett Bay	..37
1.4	Orthophotograph of Little Narragansett Bay, a 1000 ha bay at the mouth of the Pawcatuck River	..38
1.5	Landscape units identified in Greenwich Bay	.....insert 1
1.6	Landscape units identified in Wickford Harbor	..insert 2
1.7	Landscape units mapped in Little Narragansett Bay	...insert 3
1.8	Delineations and sampling locations of the landscape units investigated within Greenwich Bay	..39
1.9	Delineations and sampling locations of the landscape units investigated within Wickford Harbor	...40
1.10	Delineations and sampling locations of landscape units investigated in Little Narragansett Bay	.41
1.11	Carbon pools within the upper meter of soils within seven landscape units	..42
2.1	Monitoring locations in Greenwich Bay	...71
2.2	Monitoring locations in Wickford Harbor	72
2.3	Monitoring locations in Little Narragansett Bay	..73
2.4	Average DO levels for the four sampling periods	74
2.5	Sites in Greenwich Bay that reached hypoxic DO levels	.75

Figure Page

2.6 Lowest DO measurements recorded in Greenwich Bay stratified by soil texture class……...76

2.7 Lowest DO measurements recorded in Wickford Harbor stratified by soil texture class……...77

2.8 Lowest DO measurements recorded in Little Narragansett Bay stratified by soil texture class……78

2.9 Chlorophyll *a* levels in the four sampling periods……79

2.10 Average chl *a* levels in each landscape unit……. 80

2.11 Mean TSS during each sampling period……...81

2.12 A typical redox curve for the top 15 cm of subaqueous soil in Little Narragansett Bay Cove landscape unit……82

2.13 Redox potential measurements at the 1 cm and 5 cm depths in each sampling period for soft-bottom landscape units……..82

2.14 Seasonal averages of redox potential at 5 cm for each sampling site in Greenwich Bay…….……..83

2.15 Seasonal averages of redox potential at 5 cm for each sampling site in Little Narragansett Bay…….…….84

2.16 Seasonal averages of redox potential at 5 cm for each sampling site in Wickford Harbor…….……...85

2.17 Average redox potential trends for each bay……86

2.18 Redox potential (Eh) at the 5 cm depth for each landscape unit……..86

2.19 Percent organic carbon (OC) and silt + clay percent……87

2.20 Redox potential (Eh) at 1 cm and chl *a* in low energy, depositional landscape units……..87

2.21 Distribution of PDI values among landscape units……...88

2.22 The relationship of PDI values and percent carbon……..88

2.23 The relationship between PDI and spring Eh at the 5 cm depth……...89

Figure Page

2.24 Redox potential profiles for Greenwich Bay site GR03 and corresponding aRPD depths measured with a SPI camera…….. 90

2.25 Redox potential profiles for Greenwich Bay site GR08 and corresponding aRPD depths measured with a SPI camera…….. 90

2.26 Sediment profile image of site GR03 with corresponding redox profile measured on May 29 and 30…… 91

3.1 Distribution of incubation pH measurements for all horizons analyzed…….….109

3.2 Initial and incubation pH with depth in a Cove landscape unit in Little Narragansett Bay……...109

3.3 Initial and incubation pH with depth in a Depositional Beach landscape unit in Greenwich Bay……110

3.4 Mean total sulfides by landscape unit in all horizons…….111

3.5 Total sulfide and sand contents……...111

3.6 Mean incubation pH by landscape unit for all horizons…….112

3.7 Incubation pH and total sulfide concentration……113

3.8 The rate of change in pH values over the 8-week incubation period……..114

3.9 Percent organic carbon and calcium carbonate ($CaCO_3$) and incubation pH……..115

3.10 Initial salinity, salinity after peroxide treatment, and salinity after moist incubation……..116

3.11 Total sulfides, salt content, and change in salinity with peroxide oxidation……. 117

3.12 Total sulfides and soil organic carbon content……118

3.13 Total sulfides and soil physical properties principal component……118

CHAPTER 1:

SUBAQUEOUS SOIL-LANDSCAPE RELATIONSHIPS IN SHALLOW ESTUARIES

ABSTRACT

Soil-landscape relationships such as those developed for mapping subaerial soils have been shown to be an effective subaqueous soil mapping technique for coastal lagoons. Developing similar soil-landscape relationships for open embayments will help extend the mapping of coastal subaqueous soils to these important shallow subtidal habitats. Bathymetry maps of three bays in Rhode Island (Little Narragansett Bay, Greenwich Bay, and Wickford Harbor) were created and landscape units were delineated on these maps based on slope, depth, parent material, aerial photo interpretation, and sidescan sonar data. Twenty-one landscape units were identified in the three bays. Over 90% of the area mapped in Greenwich Bay and Wickford Harbor consisted of landscape units that were found in more than one of the study bays. Approximately half of Little Narragansett Bay was composed of landscape units more commonly seen in coastal ponds, and not found in either of the other bays. Fifteen of the landscape units identified were found in at least two of the three bays, while eight were found in all three of the bays. Soils within seven landscape units commonly encountered in the three bays were compared to determine the variability of the soil type within landscape unit and among bays. Sulfiwassents

were the dominant soil type found within Bayfloor, Cove, Fluviomarine Bottom, and Drowned Channel landscape units in all bays. Soils on Spit, Shoal, and Mainland Shoreface landscape units consisted largely of Psammowassents. Within six of the eight landscape units, soils were dominantly classified within a single subgroup. Cove, Bayfloor, and Drowned Channel landscapes contained the largest carbon pools of all landscapes (mean = 181 Mg ha^{-1}). Higher carbon contents were seen in Little Narragansett Bay soils than in soils on equivalent landscapes in other bays. Sandy, high-energy landscapes (Spit, Shoal, and Mainland Shoreface) had much lower carbon pools (mean = 57 Mg ha^{-1}). These carbon pools are similar to poorly drained and excessively drained subaerial soils, respectively, suggesting that subaqueous soils are an important sink for carbon.

INTRODUCTION

Recent soil survey efforts along the Atlantic and Gulf Coasts (US states of Delaware, Florida, Texas, Maine, Maryland, and Rhode Island) have begun to include the mapping of subtidal environments in shallow water bodies (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003; Flannagan and Osher, 2003; Coppock and Rabenhorst, 2003; Fischler et al., 2005). The definition of soils has recently been extended to include subaqueous soils, or those soils that are permanently submerged under less than 2.5 meters of salt or freshwater (Soil Survey Staff, 2006). The soils in shallow areas along the coast were not previously considered and mapped as part of the soil survey and have often been overlooked in studies of marine sediments, which focus on deep-water habitats.

The factors that affect the development of subaerial soils include climate, organisms that interact with the soil, topography of the land, parent material from which the soil developed, and the age of the soil or the amount of time the soil has been undergoing pedogenesis (Jenny, 1941). The soil-landscape paradigm used in mapping is based on the concept that discontinuities in soil type can be identified by location on a landform. Soil-landscape units are recognized as forms and shapes on the earth's surface that are created due to one or more of the soil forming factors (Hudson, 1992). These soil-landscape units are repeated across the terrain and similar soils are consistently found within a particular landscape unit because the soil forming factors act in a distinctive way in each area (Hudson, 1990). As with subaerial soils, subaqueous soil characteristics have been shown to adhere to the soil-landscape paradigm (McMaster, 1960; Demas and Rabenhorst, 1999; Bradley and Stolt, 2003). In addition to the five factors of soil formation defined by Jenny (1941), soils that form underwater have additional factors that control soil development including flow regime, water column attributes, catastrophic events, and bathymetry (Demas and Rabenhorst, 2001).

In order to apply the soil-landscape concept to subaqueous soils, scientists need detailed bathymetric maps to determine underwater topography and landform. Most shallow estuaries do not have accurate or detailed bathymetric maps available and these maps need to be created using precise manual depth measurements and transects with a fathometer (Demas, 1998; Bradley and Stolt, 2002). In a subaqueous environment, landscape units can be determined based on these detailed bathymetry maps by considering water depth, slope, topography, geographic location, and

depositional environment. Bradley and Stolt (2003) identified 13 different landscape units within a Rhode Island coastal pond and determined that soil landscape units developed in this manner were very effective at predicting soil types. Other studies have also found a relationship between soil and landscape unit in shallow lagoons on the east coast (Demas and Rabenhorst, 1999).

Shallow-water habitats along the coast including coastal lagoons, shallow bays, and estuarine areas are highly valued and heavily used resources. An account of the soils in these areas would provide valuable information to coastal regulators as to areas important for eelgrass or shellfish habitat, as well as areas of sedimentation, shoreline change, or potential dredge sites (MapCoast, 2007). Most of the recent research on subaqueous soils has taken place within shallow coastal lagoons (Demas, 1998; Bradley and Stolt, 2003). Minimal subaqueous soils information is available for shallow bays. In Rhode Island, these areas differ in parent material and have larger tidal and wave influence than more protected lagoons (McMaster, 1984; Boothroyd et al., 1985). Thus, establishing soil-landscape relationships for shallow embayments is the first step in creating a subaqueous soil map for these estuaries.

The objectives of this portion of my thesis are: i) to identify subtidal landscape units within three shallow open embayments, ii) to assess the soil-landscape unit model in these bays by determining soil variability within landscape units and among estuaries, and iii) to assess interpretive abilities of these landscape unit maps by comparing carbon pools among soil landscape units.

MATERIALS AND METHODS

Study Sites

Three shallow estuaries in Rhode Island were investigated: Greenwich Bay (1200 ha), Wickford Harbor (160 ha), and Little Narragansett Bay (1000 ha) (Figure 1.1). These estuaries were chosen because they have similar landscape units and parent materials and cover a range of human impact within their watersheds (see Chapter 2 for further discussion). Greenwich Bay and Wickford Harbor are embayments within the larger Narragansett Bay. Narragansett Bay began as a bedrock valley in the Tertiary period. The present day surficial geology of all of Rhode Island is determined by the advance and retreat of the most recent Laurentide Ice Sheet (Gustavson and Boothroyd, 1987). As the glaciers retreated, glacial melt-water formed a variety of depositional environments and streams carved out channels that ran into Narragansett Bay. As glaciers melted, sea level rose, and the low land around these streams became flooded, forming the shallow bays of today including Greenwich Bay and Wickford Harbor (McMaster, 1984; Fitzgerald et al., 2002). Most of the shallow coves within these bays were created in a similar manner as glaciers melted, due to a process known as spring sapping (FitzGerald et al., 2002; Oakley and Boothroyd, 2006).

Greenwich Bay consists of ice-marginal alluvial and lacustrine fans on the western shore and submerged delta plain deposits to the north (Oakley and Boothroyd, 2006). This bay consists of the main bay section and five shallow coves (Warwick, Apponaug, Greenwich, Buttonwoods, and Brushneck Coves; Figure 1.2). At mean low water the average depth of the central basin is 2.7 meters and 1-2 meters in the

coves (Erikson, 1998) with a tidal fluctuation of between 0.9 and 1.2 meters (Kennedy and Lee, 2003).

Wickford Harbor is smaller and less urbanized than Greenwich Bay (Figure 1.3). Located on an outwash plain, soils surrounding this bay are predominantly sandy outwash materials. The largest freshwater input into Wickford Harbor is Mill Creek, which flows into Mill Cove in the northwest corner of the bay. The average water depth in the bay at mean low tide is 1.5 meters and the tidal fluctuation is approximately one meter.

Little Narragansett Bay is a semi-enclosed estuary on the southern shore of Rhode Island and Connecticut. Most of the freshwater entering the bay is from the Pawcatuck River (Figure 1.4). Located at the western end of the Charlestown moraine, parent materials surrounding this bay are a mixture of outwash and ablation till. Napatree Point, a barrier that once spanned most of the opening of Little Narragansett Bay, was breached during the hurricane of 1938 and now provides two passages from the bay into Fisher's Island Sound (Brown, 1939). The average depth of the bay is two meters with a tidal range of 80 centimeters. The bay is well-flushed, with an approximate flushing time of three days (Fulweiler and Nixon, 2005).

Mapping and Soil Analysis

Detailed bathymetric maps of each estuary were created using a Garmin® GPSMap 178 chartplotter and depth-finder with WAAS (Wide Area Augmentation System) differential correction. Points were taken at 10 second intervals traveling at a speed of 4-10 kph in track lines 50-100 meters apart. Approximately 8,300 depth readings were taken in Greenwich Bay (6.9 points/ha) with higher concentrations in

shallow (<3 m) areas, 3,000 points were measured in Wickford Harbor (18.8 points/ha), and 14,500 depth points were measured in Little Narragansett Bay (12.1 points/ha). All depth readings were corrected for tide using pressure-sensor tide gauges recording water level at six minute intervals at locations near the area being mapped. Tide gauge locations and the precise elevation of the sensors were measured using RTK GPS. Using this elevation and the polynomial equation for the tide elevation on each day, depth readings were corrected to feet below zero NAVD88. This datum was used in order to measure elevations in the area between mean low water and mean sea level: an area that is often left out as a gap in data between subaerial mapping and bathymetric mapping. In addition, this approach allows for the merging of elevation and bathymetric data into a single, seamless dataset. Manually measured depths were taken periodically in order to assure accuracy of fathometer readings. Contour lines were created through Kriging using Golden Software Surfer modeling program. Rhode Island elevation data was used for shoreline elevations (RIGIS, 2005).

Landscape units were mapped based on slope, water depth, land-surface shape, aerial photo interpretation (Bradley and Stolt, 2002), and side-scan data (Oakley and Boothroyd, 2006; Figures 1.5, 1.6, and 1.7). Side-scan sonar data were gathered by University of Rhode Island Department of Geosciences for Greenwich Bay and Wickford Harbor, providing images of the reflectance of the substrate for the entire subaqueous environment in the bays. I used the maps created from these images to assist in delineating landscape units (Germano et al., 1989; Oakley and Boothroyd, 2006). Seven landscape units that were commonly encountered among the three

estuaries were chosen for study (Table 1.1). Two sites in each landscape unit were randomly selected for water quality and redox monitoring (see Chapter 2 for further discussion). Fifty-five descriptions were made within these selected landscape units from samples collected with an auger, Macauley peat sampler, or vibracore. Twenty-eight cores were collected with a vibracore or peat sampler for description and laboratory analysis (Figures 1.8, 1.9, 1.10; Appendix 1). Vibracores were kept in coring tubes in a walk-in refrigerator until they were cut open lengthwise, described, and sampled. Soils collected with the peat sampler were divided by horizon in the field and kept on ice in plastic sample bags. Descriptions were made according the Soil Survey Manual (Soil Survey Staff, 1993) to include horizon depth, soil texture, soil color, shell and coarse fragments, redoximorphic features, and n-value. All samples collected after description were stored in a -15 °C freezer until analysis of each horizon for incubated pH, bulk density, particle size distribution, salinity, salinity after oxidization, organic matter, calcium carbonate, organic carbon, and total nitrogen contents. Acid volatile sulfides (AVS) and chromium reducible sulfur (CRS) were also measured for select horizons.

Bulk density was determined from samples collected with the Macauley peat sampler or vibracore. These tools were used because they produce relatively undisturbed samples that can be used to determine volume. Oven-dry soil weight divided by the volume of the soil sample was used to calculate bulk density for each soil horizon.

Soil pH was measured using an Accumet® pH ATC combination electrode with silver/silver chloride reference. Samples were mixed with equal parts soil and

water to make a paste for the measurements. The initial pH was measured immediately after thawing. Samples were incubated in moist conditions for eight weeks. The pH was recorded daily for the first two weeks, then weekly after that to determine potential acidity and identify the presence of sulfidic materials (Soil Survey Laboratory Staff, 2004).

Salinity measurements were carried out using an Oakton WD-35607 hand held conductivity meter on saturated paste extracts (Soil Survey Laboratory Staff, 2004). Immediately after removal from the freezer, water was added to samples to make a saturated paste. After overnight refrigeration, samples were vacuumed through a glass-fiber filter and the salinity of the extracted water was measured. The residual samples were treated with 30% H_2O_2 and heated to 70 ˚C overnight in order to oxidize and remove organic matter (Soil Survey Laboratory Staff, 2004). Salinity was measured again after this treatment. Residual soil samples were rinsed with additional deionized water to insure removal of salts.

Particle size distribution was carried out on the residual salinity samples described above after salts and organic matter were removed. Samples were wet-sieved to separate sand from finer particles. Clay content was determined by pipette (Soil Survey Laboratory Staff, 2004). Sands were dry-sieved to separate into the various fractions.

Total organic carbon and calcium carbonate were determined sequentially by percent weight loss on ignition (LOI) assuming organic matter combustion at 550 °C and a soil organic carbon-organic matter ratio of 0.5 (Nelson and Sommers, 1996). Calcium carbonate was determined by loss on ignition at 1000 ˚C calculated as:

$$CaCO_3 = (DW_{550}\text{-}DW_{1000})/0.5995$$

where $CaCO_3$ is the weight of the calcium carbonate in the original sample, DW_{550} is the dry weight after LOI at 550 ˚C, DW_{1000} is the dry weight after combustion at 1000 ˚C, and 0.5995 represents the percent of $CaCO_3$ that is lost as carbon dioxide through combustion (Heiri et al., 2001).

Total nitrogen and organic carbon contents were measured using a Carlo Erba NA 1500 Series 2, Nitrogen/Carbon Analyzer (Carlo Erba Instruments, Milan, Italy). Approximately one gram of air-dry sample was treated with 0.1 M HCl to remove calcium carbonate (Midwood and Boutton, 1998). Samples were rinsed three times with DI water, dried, and ground to be passed through a 60-mesh (0.25 mm) sieve. Ten to 50 mg of sample was packed in tin foil and passed through the elemental analyzer to determine nitrogen and organic carbon levels through combustion (Soil Survey Laboratory Staff, 2004).

Carbon pools in soils were calculated in Mg ha^{-1} for the upper meter of soil based on the bulk density and carbon content of the soils (Compton et al., 1998). For cores that were less than one meter in length (n=20), I assumed that the deepest horizon continued to a depth of one meter. Statistical comparisons of carbon contents among landscape units were carried out using ANOVA and Tukey's HSD test using JMP IN software (SAS, 2003).

RESULTS AND DISCUSSION

Twenty-one different soil landscape units were mapped in Greenwich Bay, Little Narragansett Bay, and Wickford Harbor (Table 1.2; Figures 1.5, 1.6, and 1.7).

Although the three study areas are all considered embayments, only 40% of the landscape units identified occurred in all three bays (Table 1.3). Differences in geology, geomorphology, geography, and wind and tidal patterns among the bays account for much of the variation in landscape unit distribution. Greenwich Bay and Wickford Harbor are similar in geographic and geomorphologic characteristics, but differ in size and depth, which influence water movement within the bays. Greenwich Bay is the largest and deepest of the three bays, with a mean depth of 2.07 m (NAVD88) and a fetch of >4 km, creating high wind and wave energy in areas. Wickford Harbor is the smallest and most protected bay. The mean depth is 1.52 m (NAVD88) and the bay does not contain areas of fetch greater than one km, protecting the shoreline from most wave-induced erosion. Little Narragansett Bay has a mean depth of 1.81 m (NAVD88), is almost as large as Greenwich Bay, but has much greater marine flushing and wind influence as it opens into the ocean. Long-shore transport of marine sands is an important influence on Little Narragansett Bay and the barrier island system that does not affect either Greenwich Bay or Wickford Harbor. Little Narragansett Bay also has a much larger riverine influence than the other two bays with the Pawcatuck River continuously bringing large amounts of freshwater into the bay.

Despite the differences in bay characteristics, over 70% of landscape units identified were seen in two or more bays in this study. These shared landscape units compose over 90% of the bay area of Greenwich Bay and Wickford Harbor, but only 50% of the mapped area in Little Narragansett Bay. Eight landscape units are common to all three bays including Bayfloor, Cove, Drowned Channel, Fluviomarine

Bottom, Bouldery Submerged Mainland Beach, and Submerged Mainland Beach units. The Mainland Shoreface unit covers almost a quarter of the area of Greenwich Bay, is common in Wickford Harbor, but absent in Little Narragansett Bay. This unit develops as a result of wind and wave activity causing the erosion of sandy glacial outwash materials from the adjacent upland soils (Oakley and Boothroyd, 2006). The upland soils surrounding Little Narragansett Bay have less sandy material and more bouldery till soils, making the Mainland Shoreface unit less common. Little Narragansett Bay contains units such as the Sandy Bayfloor, Barrier Shoreface, and Washover Fan that were not seen in the other bays. These units are more consistent with landscapes seen in coastal lagoons that have barriers between the estuary and the open ocean (Demas and Rabenhorst, 1999; Bradley and Stolt, 2002).

All soils described and sampled classified as Wassents according to the proposed subaqueous soil amendments to Soil Taxonomy (Table 1.4; Stolt, 2007). Wassents are the first suborder to classify out under Entisols and are defined as soils that have a positive water potential at the surface for at least 21 hours of each day (Appendix 2). A total of 15 different family-level taxonomic classes were found in these bays including five great groups and nine subgroups. Great groups and subgroups are differentiated based on texture (Psammowassents), n-value (Hydrowassents), presence of sulfidic material (Sulfiwassents), and irregular decreases in organic carbon with depth (Fluviwassents and Fluvic Sulfiwassents). Particle size families ranged from sandy to fine-silty.

Sulfiwassents were the most common great group found in these bays (63%). These soils have sulfidic materials within 50 cm of the soil surface (Soil Survey Staff,

2006). Previous studies found sulfidic materials much less frequently than in my research. In Rhode Island coastal lagoons, sulfidic soils were only identified in Barrier Cove and Washover Fan Flat landscape units (Bradley and Stolt, 2002). Demas and Rabenhorst (1999) identified sulfidic materials in Shoal and Deep Mainland Cove landscape units in a Maryland lagoon. The predominantly sulfidic soils found in the present study suggest that strongly reducing conditions are present in many areas of all of these bays allowing for the accumulation of sulfides.

Sulfiwassents were found to dominate low energy, soft-bottom landscapes including Fluviomarine Bottom, Bayfloor, Drowned Channel, and Cove units in all bays. Of soils sampled on Fluviomarine Bottom landscape units in the three bays, 83% classified as Fluvic Sulfiwassents (Table 1.5). The remaining soils were Haplic Sulfiwassents. Sulfidic materials, high organic carbon content, and fine particle size define Sulfiwassents. Fluviomarine bottom landscapes are low energy areas where organic matter and low dissolved oxygen levels in the water create ideal conditions for sulfides to form. These units are influenced by both riverine and estuarine inputs, which bring organic matter and sediment into these areas. Buried horizons and high amounts of organic carbon at depth were observed in most of these soils indicating periodic deposition (Tables 1.6, 1.7, and 1.8).

All three bays contained approximately equal numbers of Fluvic and Haplic subgroups on Bayfloor, Drowned Channel, and Cove landscape units. Haplic soils have n-values ≤ 0.7 (non-fluid) at a depth < 0.5 m. The Fluvic subgroup indicates soils with high amounts of organic carbon at depth. In these relatively low energy environments, the deposition of fine mineral and organic material is common, creating

a highly fluid soil surface. The depth at which glacial deposits were encountered was often the factor that determined if a soil fell into a Haplic or Fluvic subgroup. Glacial materials in these study areas are non-fluid and generally have lower organic carbon contents than marine deposits. Due to the high rate of organic matter deposition, sulfides are also common at these sites.

The second most common soil great group was Psammowassents (30%). These soils have a sandy particle size throughout the upper meter and are found in higher energy areas of the bays such as the Mainland Shoreface unit. Half of all Mainland Shoreface soils classified as Typic Psammowassents, the remaining soils were either Fluventic or Sulfic Psammowassents. These deep sands result from the active erosion of the upland and deposition in these adjacent subaqueous settings (Tables 1.6, 1.7, and 1.8). Soils in the Fluventic suborder contain an irregular decrease in SOC with depth indicating old soil surfaces that were buried. Greenwich Bay and Wickford Harbor contained a similar distribution of these subgroups. Little Narragansett Bay did not have any Mainland Shoreface units, though Washover Fan landscape units have similarly active deposition, with buried surface horizons and soils that classify as Fluventic Psammowassents.

Typic Psammowassents were the dominant soil type on the Spit landscape unit. This landscape is adjacent to the shore and forms relatively long, narrow embankment with one end attached to the mainland and the other terminating in open water. These units are created through marine deposition of sands and consist of more than one meter of unconsolidated sand. The remaining soils found on Spits were Sulfic Psammowassents and Typic Haplowassents.

Submerged Mainland Beach units contained the greatest variety of soil types. The Submerged Mainland Beach soils generally have less than one meter of marine material over a submerged upland soil and are influenced by the adjacent terrestrial landscapes more so than other subaqueous landscape units that have a considerable amount of marine-deposited materials. Therefore, relating certain taxonomic groups with this landscape unit is not possible, and other parameters such as geographic location will need to be considered when mapping these landscapes in bays.

Sulfiwassents and Psammowassents made up 92% of all the soils classified in this study. The remaining great groups were Hydrowassents, Fluviwassents, and Haplowassents. These soil great groups do not contain sulfidic materials, have low n-value horizons, are not exclusively sand, and contain very little organic carbon. In most cases these soils are found on Shoal and Spit landscape units in association with Psammowassents (Table 1.6, 1.7, and 1.8).

The distribution of soil taxa that I observed is different than that reported by Bradley and Stolt (2003). In their study, Hydrowassents were the most common great group, dominating the low energy Lagoon Bottom and Mainland Cove landscape units. Because of the large quantity of soils containing sulfidic materials in the bays studied here, I only found one of the 19 soils sampled in equivalent Bayfloor and Cove landscape units to classify as a Hydrowassent. Demas and Rabenhorst (1999) found a distribution of Sulfiwassents more similar to results that I found. Their study (in a coastal lagoon in Maryland) found Sulfiwassents in Deep Cove and Shoal landscape units. Both of these prior studies found the distribution of Psammowassents to be comparable to that found in my research, with Psammowassents dominating high-

energy landscapes including Washover Fan Flat and Flood-tidal Delta (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003).

Taxonomic purities at the subgroup level within landscape units were ≥50% for five of the seven landscape units investigated in this study when compared across all bays. These taxonomic purity values are similar to those reported by Bradley and Stolt (2003), in which 11 of the 12 landscape units had purity values ≥50%. Bradley and Stolt (2003) reported that six landscape units only had one subgroup classification (100% taxonomic purity). I did not find this strong of a soil-landscape relationship, however, my evaluations were across a much larger area and included three geographically independent bays (Bradley and Stolt (2003) focused on a 160 ha section of a single coastal lagoon). The mapping scale used in this study also consisted of larger minimum mapping units (3 ha) than Bradley and Stolt (2003) (0.5 ha), perhaps accounting for the greater variability in this study. Additionally, Bradley and Stolt (2003) classified the soils under the Aquents suborder, which does not distinguish between as many characteristics as does the proposed Wassents suborder used in my research. Although purity values were slightly lower than those found in an individual lagoon, most of the landscape units contained a majority of a single taxonomic subgroup classification. This is a strong indication that landscape unit can be used as an initial delineation of soil type within geographically diverse estuaries.

Subaqueous Soil Carbon Pools

Soil survey maps are important in their own right just based on the resource descriptions and distributions they provide. More importantly, however, are the use and management interpretations that can be made based on these maps. Some

important interpretations include eelgrass restoration potential, mooring and dock location, and suitability of dredging operations (Bradley and Stolt, 2003). In his study, I tested whether soil mapping units could be useful predictors of carbon pools in subaqueous environments. Recent studies suggest that subaqueous soils may potentially be important carbon sinks that had previously been unaccounted for in the global carbon budget (Jespersen and Osher, 2007). I found that Cove, Drowned Channel, Fluviomarine Bottom, and Bayfloor landscape units had the highest amount of carbon stored in the upper meter of soil, averaging 181 Mg ha^{-1} ($p<0.05$; Figure 1.11). Sandier landscapes including Shoal, Spit, and Mainland Shoreface had much lower carbon pools with an average of only 57 Mg ha^{-1}. On landscape units in which multiple samples were analyzed for a single bay, very little standard error was seen within most landscape units. Despite having the lowest average bulk density in soil horizons, Little Narragansett Bay had the highest carbon pools of the bays in the four soft-bottom landscape units. The higher carbon content in Little Narragansett Bay could be due to the large amount of organic matter brought in from the Pawcatuck River that accumulates in the soils in calm parts of the bay.

Carbon pools in these subaqueous soils are very similar to those reported for forested mineral subaerial soils in Rhode Island (Davis et al., 2004; Richardson, 2006). Soil organic carbon concentrations ranged from 20-87 g kg^{-1} for marine-deposited soils in low energy landscape units. This falls within the range of A horizons of subaerial soils in Rhode Island. The soil organic carbon content for high-energy sites was more equivalent to terrestrial B horizons and ranged from 0.9-10 g kg^{-1} (Davis et al., 2004). The rapid rate of deposition in subaqueous environments

suggests that greater amounts of carbon are sequestered yearly in these subaqueous soils than in subaerial soils with similar carbon contents.

SUMMARY AND CONCLUSIONS

Identifying landscape units and developing an understanding of the soils that systematically form in these units is a common approach to mapping soils. In this study, I investigated the soil-landscape paradigm for subaqueous soils and landscapes in three shallow subtidal embayments. Twenty-one subtidal landscape units were identified within the three bays studied. The landscape units most commonly shared among the bays were Bayfloor, Cove, Fluviomarine Bottom, and Drowned Channel.

Soils generally fell into one of two categories: either sandy (Psammowassents) without sulfidic materials near the surface, or soils that contained sulfidic horizons (Sulfiwassents) and were very fluid and silty with high amounts of organic carbon. These two soils were found almost exclusively on landscapes separate from one another. Haplic and Fluvic Sulfiwassents were the predominant soils found in low energy, silty settings. Typic and Fluventic Psammowassents were the dominant soils on more open high-energy landscape units. Although no landscape units classified to the subgroup level had 100% taxonomic purity, dominant subgroups comprised 50% or more of the pedons described within most landscape units among the three bays. Fluvic Sulfiwassents were predominant on Bayfloor, Drowned Channel, and Fluviomarine Bottom landscape units. Typic Psammowassents were the most common soil subgroup on Mainland Shoreface, Spit, and Shoal landscape units. The variability in soft-bottom soils was largely due to the depth of the highly fluid surface

horizons. Variability within landscape units containing mostly Psammowassents was due to the presence of buried surface horizons or sulfidic materials in some soils but not in others. Submerged Mainland Beach landscape units were the most variable because this unit is adjacent to the shoreline and consists of submerged subaerial soils overlain by a thin layer of marine deposited material. Refinement of landscape unit definitions in the future to more accurately take into account wind and water movement may enable landscape-unit mapping to reduce the variability in soil subgroup classification that was seen on Submerged Mainland Beach landscape units.

My research suggests that the soil-landscape paradigm holds true for most subaqueous soils and that landscape units that contain similar soils may be delineated within a variety of coastal embayments. These soil maps can be used for multiple interpretations including assessment of carbon pools and distributions in subaqueous environments. My carbon inventories found that Bayfloor, Cove, and Drowned Channel landscape units contained greater amounts of carbon than high-energy Spit and Shoal units. The carbon contained in these high n-value sites is equivalent to the carbon sequestered in poorly drained subaerial soils in Rhode Island and represents a significant part of the carbon budget not previously considered.

Table 1.1. Number of pedons collected in landscape units investigated for each study site.

Landscape Unit (mapping symbol)	WH*	GB*	LNB*
Bayfloor (By)	2	1	2
Cove (Cv)	1	2	4
Drowned Channel (Dc)	1	1	2
Fluviomarine Bottom (Fb)	1	1	2
Spit (Pt)	1	1	-
Shoal (Sg)	1	-	1
Mainland Shoreface (Dp)	1	3	-

* WH = Wickford Harbor, GB = Greenwich Bay, LNB = Little Narragansett Bay

Table 1.2. Landscape unit definitions.

Landscape Unit Name (map unit symbol)	Soil-Landscape Unit Description
Bayfloor (By1, By2, By3)	Moderately shallow to deep water (1-4 m), low energy areas in central locations in a bay where fines have accumulated. Landscapes are flat or gently sloping. Soils consist of highly fluid silt loam and fine sandy loam over coarse sand and gravel. Surface horizons contain relatively high SOC (2-8%) and clay (5-19%). Sulfidic materials are common throughout. Soils classify as Fluvic and Haplic Sulfiwassents.
Bayfloor Sandy (Bd1, Bd3)	Moderately shallow to deep (1.5–4 m), flat or gently sloping central area in a bay that is dominated by sandy material deposited from higher energy water movement or large storm events. Organic carbon contents are low (<1%) in all horizons. Sulfides may be present in these soils, but not enough to constitute sulfidic materials. Soils classify as Typic Psammowassents.
Bayfloor Slope (Bp2)	Moderately shallow to moderately deep water (1-3 m), sloping unit adjacent to high-energy channel units. Soils are coarse and medium sand with low organic carbon and clay contents (McMaster, 1984). Not sampled.
Channel (Cn3*)	Deep water (2-8 m), elongate, steeply sloping units that occur in channels generally central to the bay that have been carved out by water movement. Soils are dominated by sands and sandy loams (Oakley and Boothroyd, 2006). Not sampled.
Cove (Cv0, Cv1, Cv2)	Small, shallow to moderately deep (0-2 m) sheltered bays or recesses in the mainland or an island. Soils contain >50 cm of highly fluid silt loam with relatively high SOC (3-8%) and clay (10-29%) contents and contain sulfidic materials. Soils classify as Fluvic and Haplic Sulfiwassents.

Table 1.2. Continued

Landscape Unit Name (map unit symbol)	Soil-Landscape Unit Description
Mainland Shoreface (Dp0, Dp1, Dp2)	Shallow to moderately deep (1-3 m), gently sloping unit along shorelines dominated by sandy soils. Soils are fine-sands derived from wave erosion and deposition of sand from terrestrial soils (Oakley and Boothroyd, 2006). Soils have low SOC (<0.5%) and may contain buried surface horizons. Sulfidic materials are found in some horizons in these soils, but sulfides are generally absent or minimal. Soils classify as Typic, Fluventic, and Sulfic Psammowassents.
Dredged/ Anthropogenic (Dr2, Dr3*)	Deep (>3 m), level to steeply sloping areas that have been altered by humans through dredging typically for navigation channels or marina construction. Soil characteristics vary by location.
Drowned Channel (Dc0, Dc2)	Shallow to moderately deep (0-2 m), level to gently sloping areas in elongate, sheltered recesses. In outwash areas many of these units were created due to spring sapping that occurred while glaciers receded (Fitzgerald et al., 2002). Soils consist of highly fluid deep silts over glaciofluvial material and often contain buried surface horizons or buried marshes. Surface horizons have relatively high SOC (2-8%) and clay (8-26%) contents. Sulfidic horizons and irregular decreases in organic carbon are common with depth. Soils classify as Fluvic, Haplic, and Thapto-Histic Sulfiwassents.
Flood-Tidal Delta (Ft0*)	Shallow (0-1 m), flat or slightly sloping unit found adjacent to a channel. Soils are sands with low clay and organic carbon contents. Buried horizons and stratification are common. Not sampled.
Fluvial (Fv0)	Shallow (0-1 m) flat or convex and gently sloping units adjacent to small rivers that enter the bay. Soils are sandy and organic carbon and clay contents are low. Buried horizons and stratification are common. Not sampled.

Table 1.2. Continued

Landscape Unit Name (map unit symbol)	Soil-Landscape Unit Description
Fluviomarine Bottom (Fb0, Fb1)	Shallow water (0-2 m) nearly level to slightly undulating, low energy, depositional environment in areas with influence from both river and marine environments. Surface horizons are highly fluid, sulfidic, and silty over glacial material. Surface horizons have moderate SOC (2-3%) and relatively high clay (14-20%) contents. Soils classify as Fluvic and Haplic Sulfiwassents.
Fluviomarine Terrace (Fc0)	Shallow (0-1 m), flat or convex and gently sloping units generally adjacent to the shore in a fluvial or fluviomarine environment. Soils are sandy with relatively low SOC and clay contents. Not sampled.
Fringing Flat (Ff0)	Shallow water (0-1.5 m) flat or gently sloping unit that borders salt marsh. Soils consist of shallow marine silts or loams over glacial material. Soils classify as Haplic Sulfiwassents.
Spit (Pt0, Pt1)	Shallow to moderately deep (0-3 m) gently sloping point or narrow ridge extending from the shoreline and consists of coarse, marine deposited material. Soils are sandy with relatively low SOC contents (<0.5%). Sulfides are present in some horizons. Soils classify as Typic and Sulfic Psammowassents, and Typic Haplowassents.
Submerged Mainland Beach (Mf0*)	Shallow water (0-1.5 m) moderately or steeply sloping unit along the shoreline of a bay that is composed of shallow marine deposits over glaciofluvial material. Soils are loamy to sandy and vary with shoreline type and underlying glacial material.
Bouldery Submerged Mainland Beach (Mb0, Mb1*)	Shallow water (0-1.5 m) moderately or steeply sloping unit along the shoreline of a bay that is composed of shallow marine deposits over glaciofluvial material. Boulders (some emergent) do not exceed 15% cover. Soil types vary with diverse shoreline types and can include Fluvic Sulfiwassents, Typic Haplowassents, and Typic Psammowassents.

Table 1.2. Continued

Landscape Unit Name (map unit symbol)	Soil-Landscape Unit Description
Very Bouldery Submerged Mainland Beach (Mx0*)	Shallow water (0-1.5 m) moderately or steeply sloping unit along the shoreline of a bay that is composed of shallow marine deposits over glaciofluvial material. Boulders (some emergent) cover between 15-35% of the area. Soils are loamy to sandy and vary with shoreline type and underlying glacial material. Not sampled.
Shoal (Sg1)	Moderately shallow (1-2 m) gently sloping convex ridge or bar generally in a central location of a bay and rising above the surrounding bay bottom. Soils are generally sandy, with relatively low levels of SOC (<1%). Some horizons may contain sulfidic material. Soils classify as Typic Psammowassents, Haplic Sulfiwassents, and Typic Fluviwassents.
Barrier Shoreface (Sa0, Sa1)	Shallow to moderately shallow (0-1.5 m) nearly level or gently sloping unit seaward of a barrier island. Soils consist of sands. Organic carbon and clay contents are low. This unit is highly dynamic and changes with yearly cycles of erosion and deposition on the barrier island. Drastic changes can occur from severe storm events. Not sampled.
Washover Fan Flat (Wf0, Wf2*)	Shallow to moderately deep (0-2 m) level to gently sloping unit formed from sand washed over a barrier island or spit during a storm and deposited on the landward side. Soils are sandy with low organic carbon and clay contents. Buried surface horizons are often present. Not sampled.

Table 1.2. Continued

Map Unit Class Symbol	Water Depth (m)	Class
0	0-1	Shallow
1	1-2	Moderately shallow
2	2-3	Moderately deep
3	3 +	Deep

* indicate landscape units mapped in by Bradley, (2001).

Table 1.3. Total area of each landscape unit mapped and percent of total bay area that the landscape unit comprises.

Landscape Unit (mapping symbol)	Total area (ha)			% of total area		
	Wickford	Greenwich	Little Narragansett	Wickford	Greenwich	Little Narragansett
Barrier Shoreface (Sa)	0	0	93	-	-	10
Bayfloor (By)*	53	377	20	32	32	2
Bayfloor Slope (Bp)	6	85	25	4	7	3
Bayfloor Sand (Bd)	0	0	267	-	-	29
Bouldery Mainland Beach (Mb)*	6	22	77	4	2	8
Channel (Cn)	10	132	93	6	11	10
Cove (Cv)*	20	43	78	12	4	8
Delta (Dt)	0	8	0	-	1	-
Dredged/Anthropogenic (Dr)	7	80	0	4	7	-
Drowned Channel (Dc)*	14	55	29	9	5	3
Flood Tidal Delta (Ft)	0	7	0	-	1	-
Fluviomarine Bottom (Fb)*	10	44	88	6	4	9
Fluviomarine Terrace (Fc)	2	0	40	1	-	4
Fringing Flat (Ff)	4	0	3	2	-	-
Mainland Shoreface (Dp)*	13	297	0	8	25	-
Shoal (Sg)*	2	0	7	2	-	1
Spit (Pt)*	8	32	0	5	3	-
Submerged Mainland Beach (Mf)	7	12	4	5	1	-
Very Bouldery Mainland Beach (Mx)	0	1	0	-	-	-
Washover Fan (Wf)	0	0	112	-	-	12
Total hectares mapped	**164**	**1197**	**935**			

*Landscape units compared among estuaries in this study.

Table 1.4. Total numbers of subgroups identified and landscape units on which each soil was found.

Subgroup Classification (total # of classification)	Particle Size Class (# of classifications in subgroup)	Landscape Units (# of classifications)
Typic Haplowassents		
(1)	Coarse-loamy (1)	Bouldery Submerged Mainland Beach (1)
	Coarse-loamy (1)	Spit (1)
Typic Hydrowassents		
(1)	Coarse-silty (1)	Cove (1)
Typic Fluviwassents		
(2)	Sandy (1)	Shoal (1)
Fluventic Psammowassents		
(4)		Mainland Shoreface (3)
		Washover Fan (1)
Sulfic Psammowassents		
(2)		Spit (1)
		Mainland Shoreface (1)
Typic Psammowassents		
(10)		Mainland Shoreface (5)
		Shoal (2)
		Spit (2)
		Bouldery Submerged Mainland Beach (1)
Fluvic Sulfiwassents		
(19)	Coarse-loamy (11)	Mainland Cove (6)
	Fine-silty (4)	Drowned Channel (4)
	Coarse-silty (4)	Fluviomarine Bottom (5)
		Bayfloor (3)
		Bouldery Submerged Mainland Beach (1)
Haplic Sulfiwassents		
(14)	Coarse-loamy (10)	Cove (6)
	Fine-silty (2)	Bouldery Submerged Mainland Beach (1)
	Coarse-silty over sandy (1)	Bayfloor (3)
	Sandy (1)	Shoal (1)
		Mainland Shoreface (1)
		Fringing Flat (1)
		Fluviomarine Bottom (1)
Thapto-histic Sulfiwassents		
(1)	Coarse-loamy (1)	Drowned Channel (1)

Table 1.5. Taxonomic purity of landscape units investigated. Taxonomic purity determined as the percent of pedons on a landscape unit that classify to the same subgroup.

Landscape Unit	Classification (# of occurrences)	GB	LNB	WH	Taxonomic Purity (%)
		# of occurrences			
Bayfloor					
	Fluvic Sulfiwassents (3)	1		2	50
	Haplic Sulfiwassents (3)	1	2		
Bouldery Submerged Mainland Beach					
	Haplic Sulfiwassents (1)			1	25
	Fluvic Sulfiwassents (1)		1		
	Typic Haplowassents (1)		1		
	Typic Psammowassents (1)		1		
Mainland Shoreface					
	Typic Psammowassents (5)	3		2	50
	Fluventic Psammowassents (3)	2		1	
	Haplic Sulfiwassents (1)			1	
	Sulfic Psammowassents (1)	1		1	
Drowned Channel					
	Fluvic Sulfiwassents (3)	1	1	2	60
	Thapto-histic Sulfiwassents (1)		1		
Fluviomarine Bottom					
	Fluvic Sulfiwassents (5)	1	1	3	83
	Haplic Sulfiwassents (1)		1		
Cove					
	Fluvic Sulfiwassents (6)		4	2	46
	Haplic Sulfiwassents (6)	2	2	2	
	Typic Hydrowassents (1)	1			
Spit					
	Typic Psammowassents (2)	1		1	50
	Sulfic Psammowassents (1)			1	
	Typic Haplowassents (1)	1			
Shoal					
	Typic Psammowassents (2)		1	1	50
	Haplic Sulfiwassents (1)			1	
	Typic Fluviwassents (1)	1			

Table 1.6. Profile descriptions from vibracore samples typical of the four great groups most commonly encountered.

Sulfiwassents (RI009-2006-006-WH)	A--0 to 5 centimeters black (5Y 2.5/1) interior, sandy loam; 1 percent very fine plant fragments; abrupt smooth boundary; very fluid; n-value = 2. AC--5 to 14 centimeters very dark gray (5Y 3/1) interior; loam; 1 percent shell fragments; abrupt smooth boundary; very fluid; n-value = 2. C1--14 to 33 centimeters; very dark gray (5Y 3/1) interior; loam; slightly fluid; n-value = 0.7; clear smooth boundary. C2--33 to 53 centimeters very dark gray (5Y 3/1) interior, loam; slightly fluid; n-value = 0.7; clear smooth boundary. C3--53 to 64 centimeters very dark gray (5Y 3/1) interior, fine sandy loam; few fine plant fragments; nonfluid; very abrupt smooth boundary. 2C4--64 to 74 centimeters dark gray (N 4/0) interior, loamy sand; nonfluid; abrupt smooth boundary. 2C5--74 to 95 centimeters; dark grayish brown (2.5Y 4/2) interior, loamy coarse sand; 3 percent fine prominent irregular iron concentrations with sharp boundaries in matrix and 1 percent fine prominent irregular iron concentrations with clear boundaries in matrix; nonfluid; abrupt smooth boundary. 2C6--95 to 96 centimeters olive brown (2.5Y 4/3) interior, sandy loam; 15 percent nonflat well rounded mixed rock fragments; rock fragments are 2 cm at largest; nonfluid.

Table 1.6. Continued

Psammowassents (RI003-2006-007-GR)	Cg--0 to 17 centimeters; greenish gray (10Y 6/1) interior, sand; single grain; loose, nonfluid; clear smooth boundary. C/A--17 to 31 centimeters; 50 percent greenish gray (10Y 6/1) and 50 percent dark greenish gray (10Y 3/1) interior, sandy; loose; nonfluid; clear smooth boundary. Ab--31 to 36 centimeters; dark greenish gray (10Y 3/1) interior, loamy sand; massive; very friable; nonfluid; abrupt smooth boundary. C'g--36 to 41 centimeters; olive gray (5Y 5/2) interior, sand; single grain; loose; nonfluid; abrupt smooth boundary. CA--41 to 64 centimeters; 90 percent dark gray (5Y 4/1) interior and 10 percent very dark gray (5Y 3/1) interior, sand; massive; very friable; nonfluid; 2 percent nonflat subangular shell fragments; few fine plant fragments and clamshell pieces; gradual smooth boundary. C''g--64 to 96 centimeters; gray (5Y 5/1) interior, loamy sand; massive; very friable; nonfluid; 2 percent nonflat subangular shell fragments and 1 percent nonflat well rounded mixed rock fragments; clamshell pieces small gravel at the bottom.

Table 1.6. Continued

Hydrowassents (RI003-2006-008-GR)	A1--0 to 1 centimeters; dark olive gray (5Y 3/2) interior, silt loam; massive; very friable; very fluid; n-value = 2; abrupt smooth boundary. A2--1 to 13 centimeters; black (2.5Y 2.5/1) interior, silt loam; massive; very friable; very fluid; n-value = 2; 1 percent nonflat subrounded shell fragments; Periwinkle; clear smooth boundary. AC--13 to 26 centimeters; black (2.5Y 2.5/1) interior, silt loam; massive; very friable; very fluid; n-value = 2; 3 percent nonflat subrounded shell fragments; Periwinkle and clam fragments; clear smooth boundary. C1--26 to 50 centimeters; black (5Y 2.5/1) interior, silt loam; massive; very friable; slightly fluid; n-value = 1; 1 percent nonflat subrounded shell fragments (periwinkle and clam fragments); clear smooth boundary. C2--50 to 91 centimeters; very dark gray (5Y 3/1) interior, sandy loam; massive; very friable; slightly fluid; n-value = 0.7; 10 percent shell fragments (razor clams, periwinkle, scallop fragments, whole scallops and whole oyster) and 5 percent nonflat angular mixed rock fragments.

Table 1.6. Continued

Haplowassents (RI003-2006-004-GR)	Cg--0 to 9 centimeters; olive gray (5Y 5/2) interior, sand; single grain; loose; nonfluid; 1 percent nonflat angular shell fragments; abrupt smooth boundary. A--9 to 17 centimeters; very dark gray (5Y 3/1) interior, loamy sand; single grain; loose; nonfluid; clear wavy boundary. 2C/A--17 to 30 centimeters; 70 percent dark greenish gray (5GY 3/1) interior, fine sandy loam and 30 percent dark greenish gray (5GY 3/1) loamy sand in tongues from A horizon; massive; friable; nonfluid; clear wavy boundary. 2Cg1--30 to 55 centimeters; dark greenish gray (5GY 4/1) interior, fine sandy loam; massive; friable; nonfluid; clear smooth boundary. 2Cg2--55 to 64 centimeters; dark greenish gray (5GY 4/1) interior, fine sandy loam; massive; friable; nonfluid; 20 percent coarse prominent irregular iron concentrations (10YR 4/4) with clear boundaries in matrix; concentrations surrounding sandy material 1mm in width; clear smooth boundary. 3Cg3--64 to 82 centimeters; 70 percent olive gray (5Y 5/2) interior and 30 percent dark greenish gray (5GY 4/1) interior, loamy sand and fine sandy loam; massive; friable; nonfluid; 5 percent coarse prominent irregular iron concentrations (10YR 4/4) with sharp boundaries in matrix surrounding redox depletions.

Table 1.7. Particle size analysis for vibracore samples typical of the great groups most commonly encountered.

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)
Sulfiwassents (RI009-2006-006-WH)									
AC	1	2	7	14	14	40	43	17	6
C1	0	2	5	12	8	27	47	26	3
C2	1	3	7	18	10	39	48	13	1
C3	6	6	12	27	11	62	30	8	1
2C1	6	8	14	32	21	81	19	0	3
2C2	24	16	16	18	6	80	17	3	22
Psammowassents (RI003-2006-007-GR)									
Cg'	0	0	8	79	11	98	2	0	0
C/A	0	1	13	69	14	97	3	0	0
Ab	0	2	15	62	15	94	5	1	1
Cg'	3	7	29	54	5	98	2	0	2
CA	1	1	17	69	8	96	3	1	0
Cg''	2	5	28	59	3	97	2	1	2
Hydrowassents (RI003-2006-008-GR)									
A2	0	1	1	2	12	16	63	21	0
AC	0	1	1	2	20	24	66	10	0
C1	0	0	1	2	6	9	70	21	0
C2	2	2	4	9	18	35	60	5	0
Haplowassents (RI003-2006-004-GR)									
Cg	2	10	49	37	1	99	1	0	0
A	3	9	28	42	6	88	11	1	3
2C/A	0	2	7	19	18	46	52	2	0
2Cg1	0	0	1	9	23	33	65	2	0
2Cg2	0	0	1	13	22	36	62	2	0
2Cg3	0	0	0	51	32	83	16	1	0

Table 1.8. Laboratory analysis for vibracore samples typical of the great group most commonly encountered.

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salinity ($dS\ m^{-1}$)	Peroxide oxidized salinity ($dS\ m^{-1}$)	Incubation pH (8 week)	pH change
Sulfiwassents (RI009-2006-006-WH)								
A	0.25	0.30	2.90	3.09	50		3.5	-3.3
AC	0.40	0.28	2.80	3.03	48	220	3.3	-4.1
C1	0.42	0.33	3.31	3.77	53	98	4.2	-3.8
C2	0.50	0.20	2.59	2.16	17	77	3.7	-3.5
C3	1.16	0.18	2.02	1.54	15	63	3.3	-4.0
2C4	1.65	0	1.39	0.36	7	6	6.1	-0.4
2C5	0.92	0.03	0.53	0.17	17	20	4.0	-3.3
Psammowassents (RI003-2006-007-GR)								
Cg	1.41	0	0.16	0.16	19	12	6.1	-0.5
C/A	1.70	0	0.15	0.22	26	14	7.0	-0.4
Ab	2.18	0	0.16	0.21	26	20	7.8	0.1
C'g	2.02	0	0.14	0.17	26	15	6.8	-0.8
CA	1.59	0	0.14	0.19	32	18	5.8	-1.8
C''g	1.28	0	0.14	0.33	29	19	7.9	0.3
Hydrowassents (RI003-2006-008-GR)								
A2	0.33	0.48	4.44	3.50	40	45	5.6	-1.8
AC	0.65	0.36	4.28	3.09	36	37	7.7	-0.5
C1	0.46	0.34	4.12	3.13	36	50	7.8	-0.2
C2	1.08	0.15	1.60	1.59	18	23	5.0	-2.8
Haplowassents (RI003-2006-004-GR)								
Cg	1.93	0	0.26	0.22	23	15	5.4	-1.1
A	1.72	0	0.36	0.32	28	29	6.1	-1.5
2C/A	1.84	0	0.27	0.37	27	22	4.4	-3.5
2Cg1	1.96	0	0.33	0.44	27	13	7.3	0.2
2Cg2	1.70	0	0.266	0.44	26	13	7.0	0.1
2Cg3	1.32	0	0.18	0.28	21	12	7.6	0.3

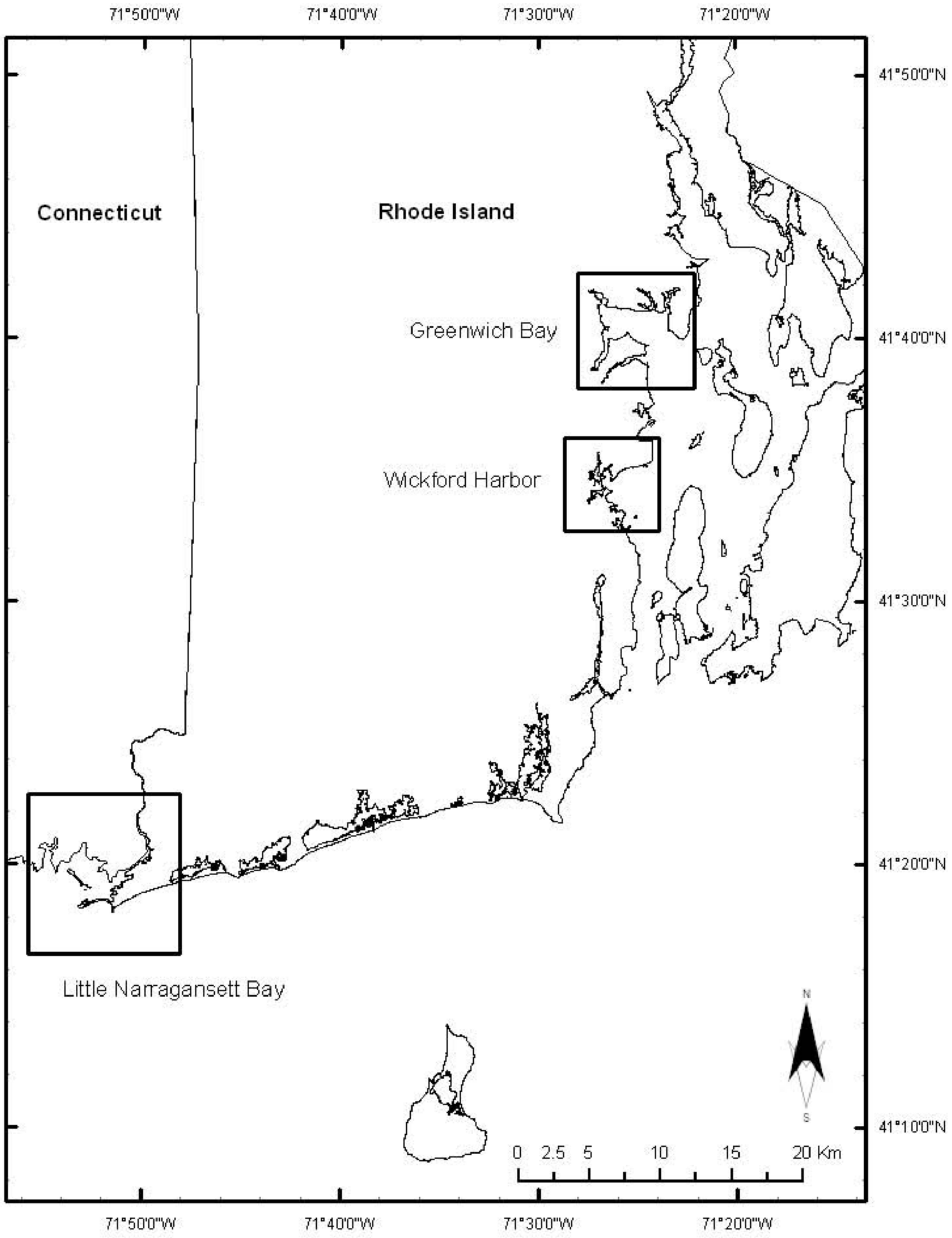

Figure 1.1: Study sites in Rhode Island and Connecticut

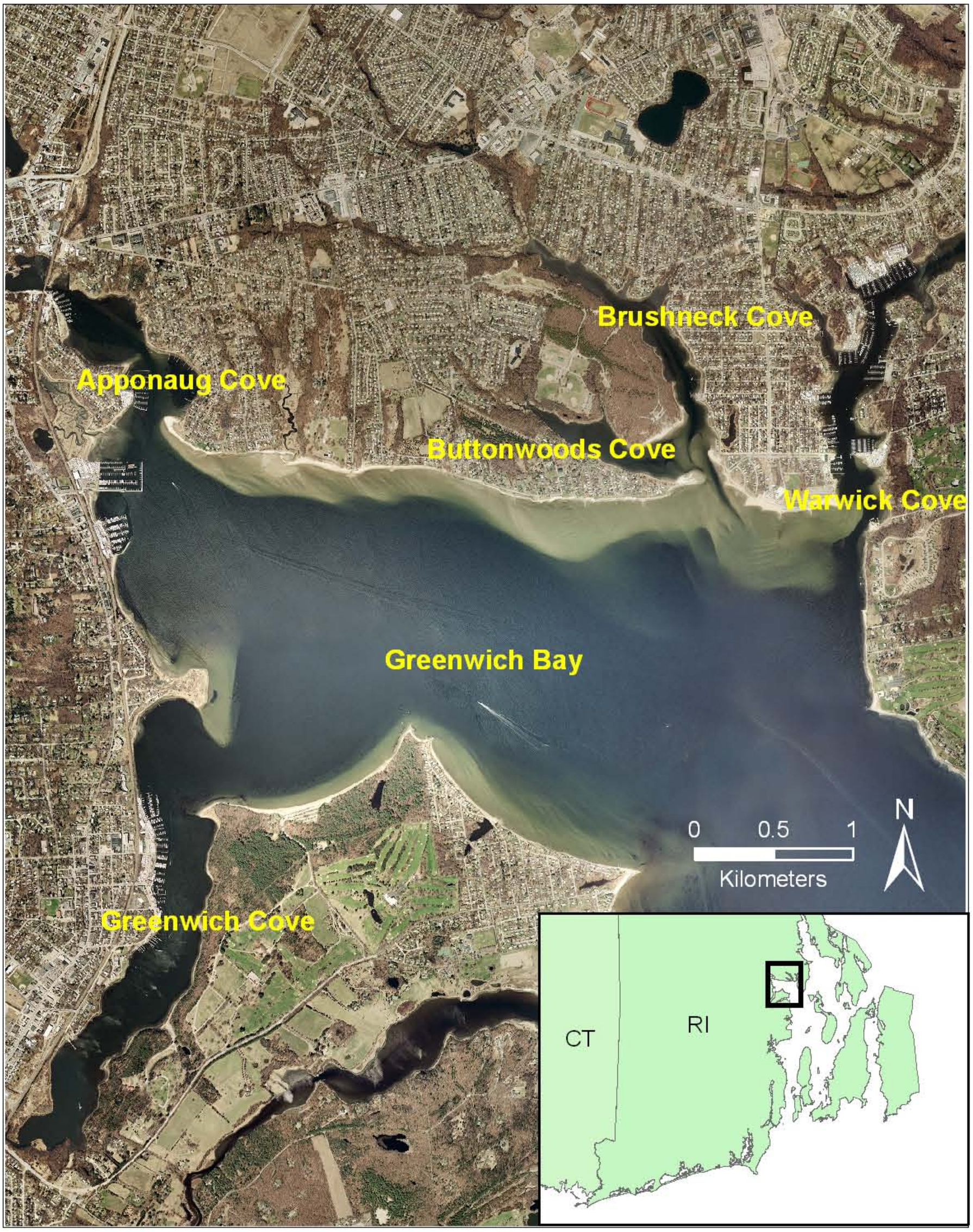

Figure 1.2: Orthophotograph of Greenwich Bay, a 1200 ha subestuary of Narragansett Bay.

Figure 1.3: Orthophotograph of Wickford Harbor, a 160 ha bay within Narragansett Bay.

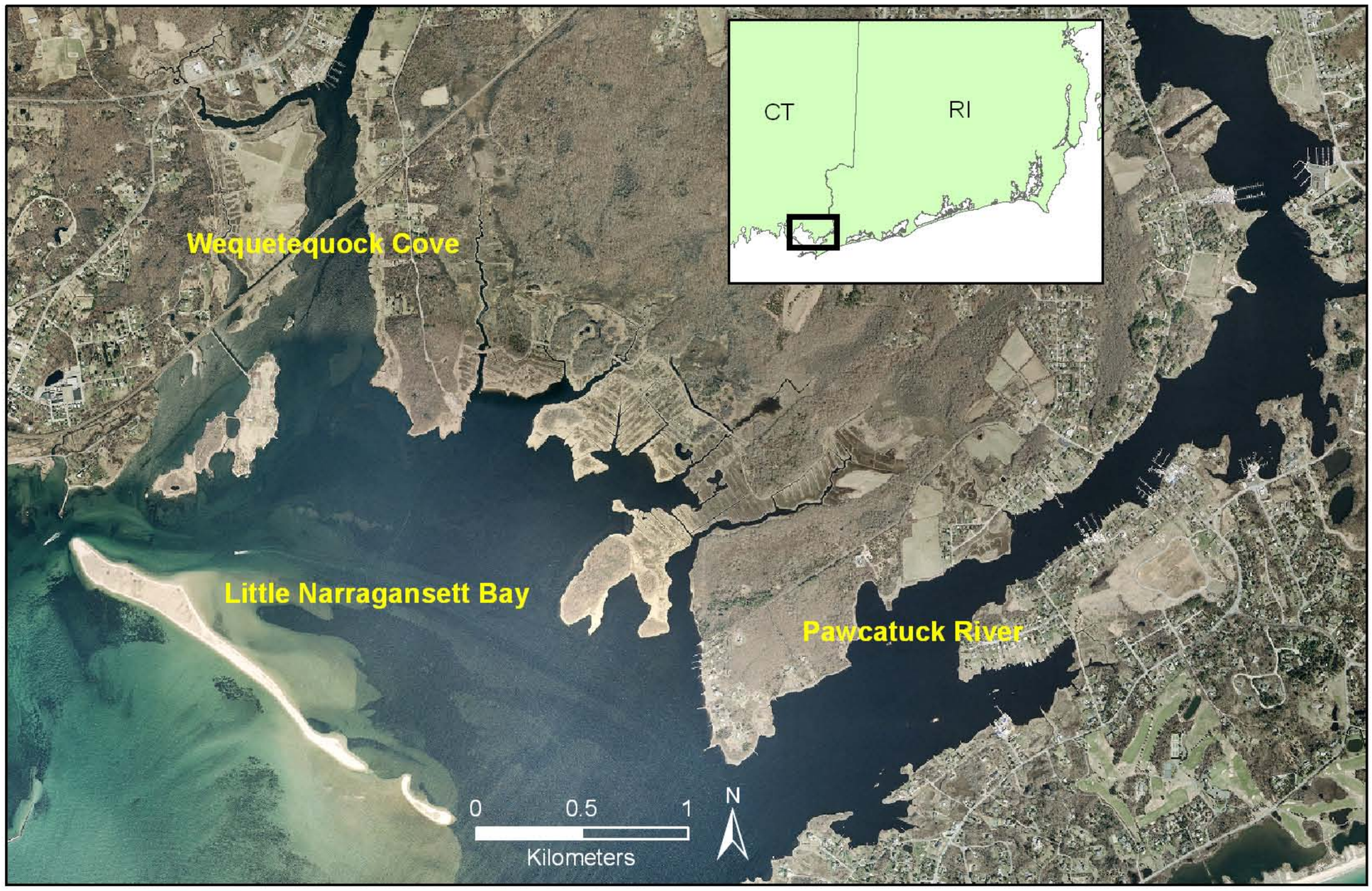

Figure 1.4: Orthophotograph of Little Narragansett Bay, a 1000 ha bay at the mouth of the Pawcatuck River.

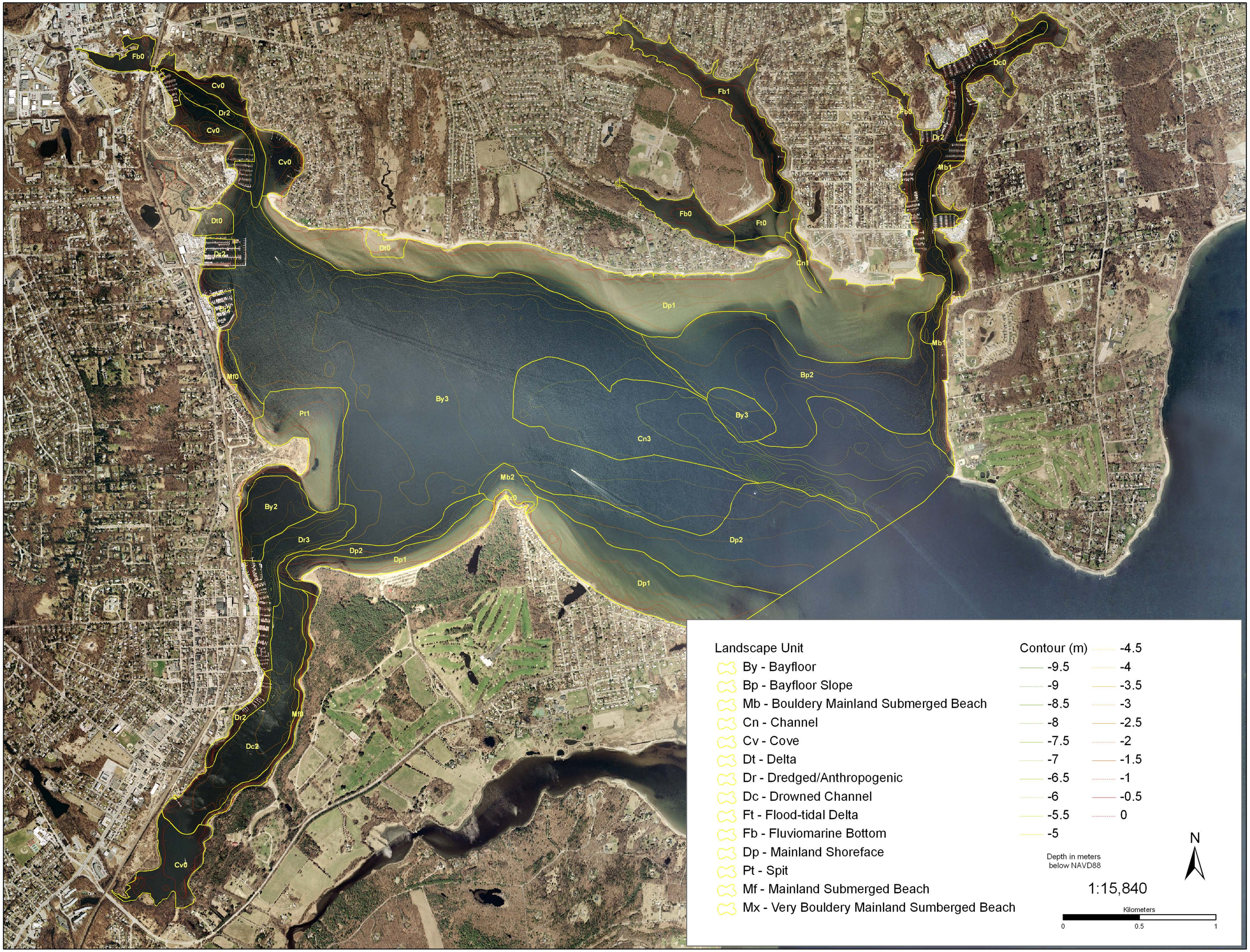

Figure 1.5: Landscape units identified in Greenwich Bay.

Figure 1.6: Landscape units identified in Wickford Harbor.

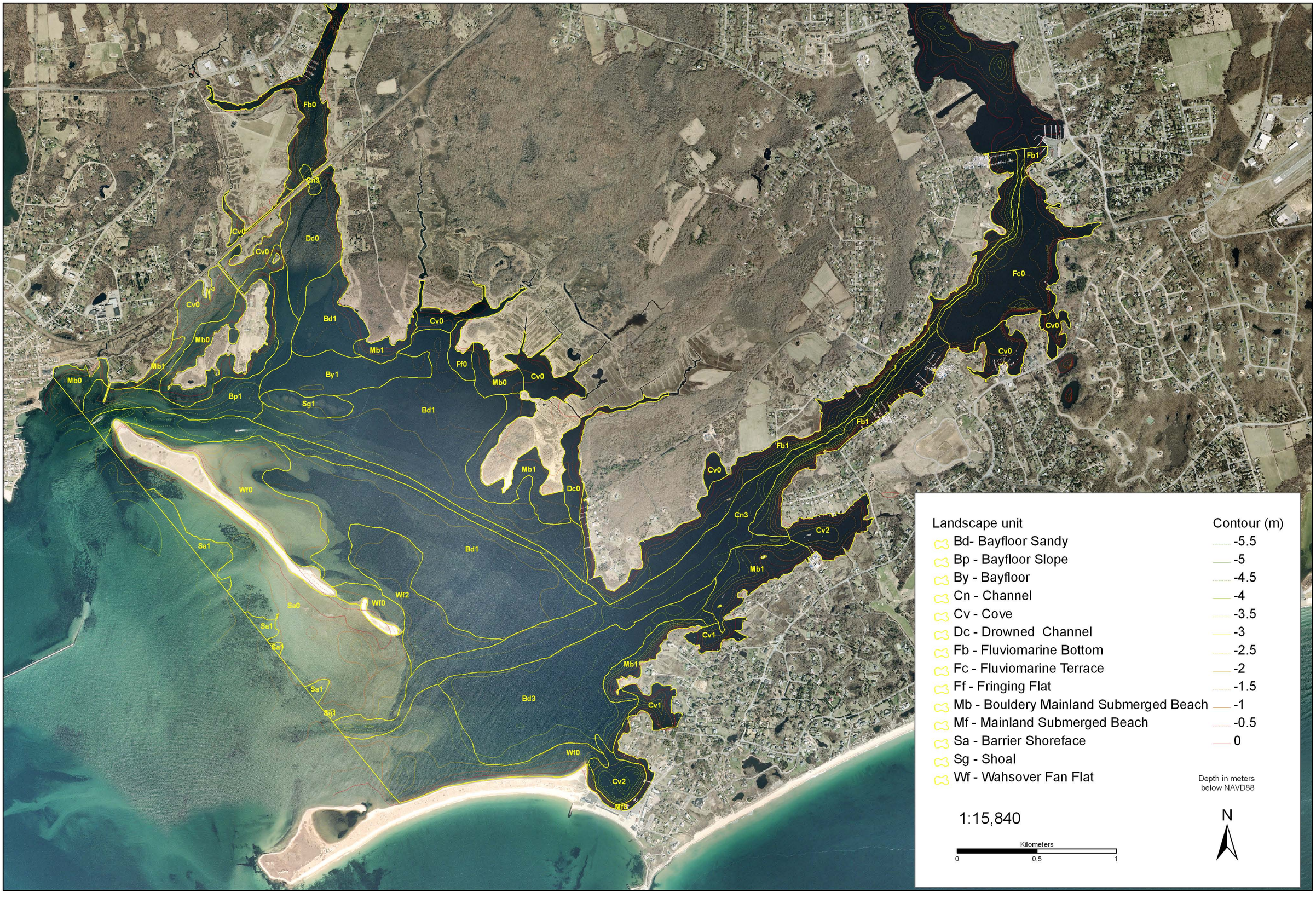

Figure 1.7: Landscape units identified in Little Narragansett Bay.

Figure 1.8: Delineations and sampling locations of the landscape units investigated within Greenwich Bay. Landscape units include Bayfloor (By), Mainland Shoreface (Dp), Drowned Channel (Dc), Spit (Pt), Cove (Cv), and Fluviomarine Bottom (Fb). Pedon locations indicate where cores were sampled for laboratory analysis.

Figure 1.9: Delineations and sampling locations of the landscape units investigated within Wickford Harbor. Landscape units include Bayfloor (By), Shoal (Sg), Spit (Pt), Mainland Shoreface (Dp), Cove (Cv), Fluviomarine Bottom (Fb), and Drowned Channel (Dc) landscapes. Locations where pedons were collected for laboratory analysis are indicated.

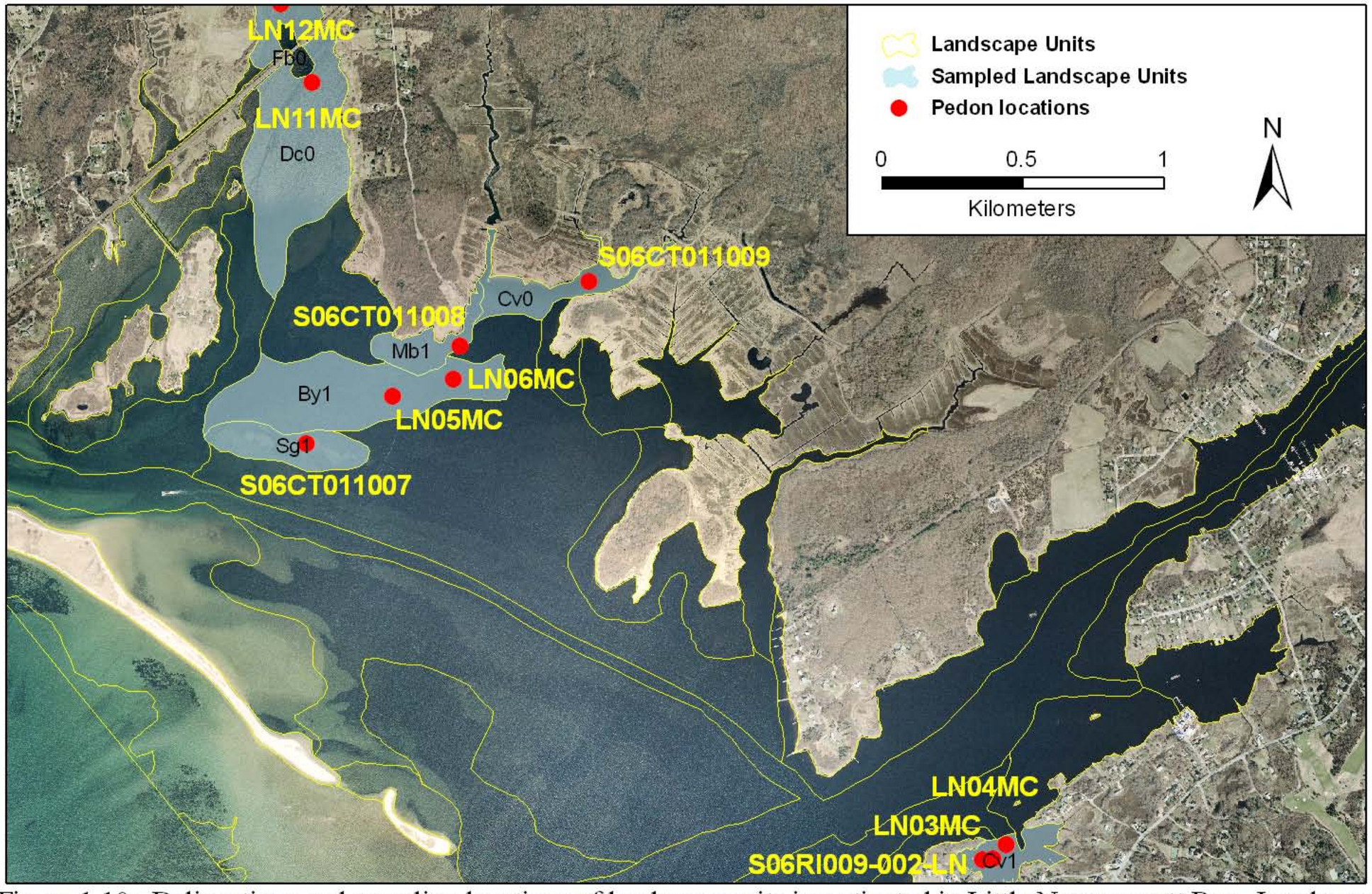

Figure 1.10: Delineations and sampling locations of landscape units investigated in Little Narragansett Bay. Landscape units include Drowned Channel (Dc), Cove (Cv), Bouldery Mainland Submerged Beach (Mb), Bayfloor (By), and Shoal (Sg) units. Pedon locations indicate where cores were collected for laboratory analysis.

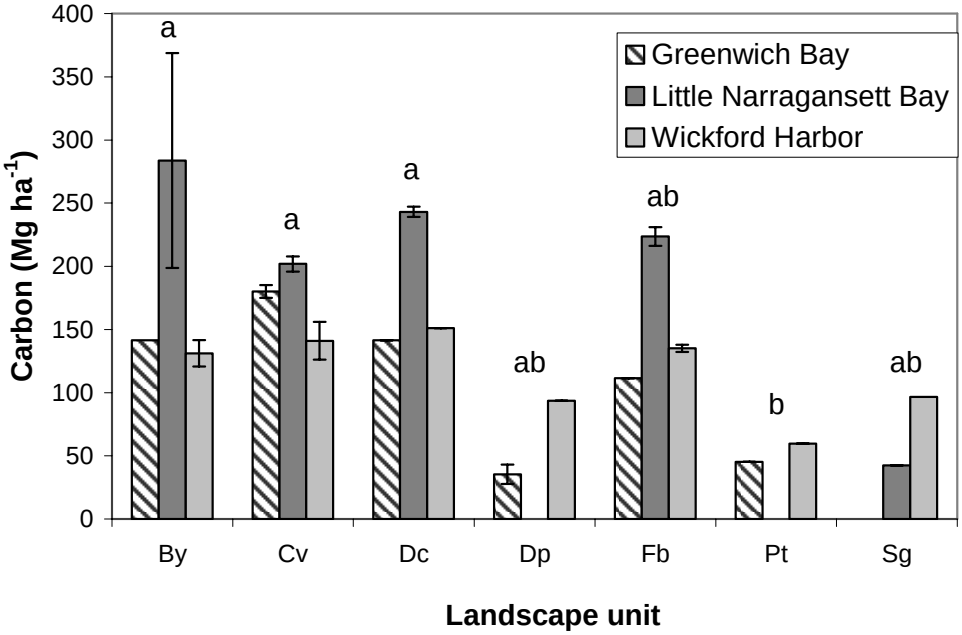

Figure 1.11. Carbon pools within the upper meter of soils within seven landscape units. Letters indicate landscape unit means of all bays that are significantly different according to Tukey's HSD test at the p=0.05 level. Bars represent standard error (n is between 1 and 4 for each bar).

CHAPTER 2:

STRATIFYING EMBAYMENTS BY LANDSCAPE UNIT TO EVALUATE SUBAQUEOUS SOIL-WATER QUALITY RELATIONSHIPS

ABSTRACT

Recent studies have shown that substrates within shallow subtidal estuaries can be mapped as subaqueous soils by following landscape boundaries. In this study, dissolved oxygen, total suspended solids, and chlorophyll *a* (chl *a*) were measured within 21 landscape units in three shallow embayments in Rhode Island (Greenwich Bay, Wickford Harbor, and Little Narragansett Bay) to determine if these water quality attributes also follow landscape-level boundaries. In addition, I compared water quality attributes with three soil properties: oxidation-reduction (redox) potential, Profile Darkness Index (PDI), and depth to the apparent redox potential discontinuity (aRPD). I found that hypoxic and severely hypoxic DO readings (<5 mg L^{-1}) occurred most frequently in low energy Drowned Channel, Cove, Bayfloor, Spit, and Fluviomarine Bottom landscape units. In the high-energy Mainland Shoreface, Shoal, and Washover Fan units hypoxia was observed on only one occasion during monitoring. Chlorophyll *a* levels were highest in Greenwich Bay ($p<0.05$), highest in the low energy landscape units in all seasons, and negatively related with soil redox potential. Redox potential was significantly different among landscape units; with the lowest levels on landscape units where deposition of fine-grained soil particles occur

(Bayfloor, Drowned Channel, Fluviomarine Bottom, and Cove) and more positive on high energy landscape units where sandy soils are dominant (Mainland Shoreface, Spit, Shoal, and Washover Fan). The PDI had a positive relationship with percent organic carbon in the surface horizons (R^2=0.34). Thickness of the oxidized surface changed over the monitoring season and followed redox potential trends. A multimetric model based on salinity, redox potential, chlorophyll *a* in the early summer, and dissolved oxygen content in the late summer revealed significant differences in water quality between high and low energy landscape units. The relationships between redox potential, PDI, and water quality measurements suggest that soil-based methods have the potential to serve as indicators of long-term water quality degradation that can be difficult to conclude based solely on water quality monitoring. Results also suggest that shallow subtidal estuaries should be stratified by landscape unit when documenting water quality.

INTRODUCTION

Estuaries are semi-enclosed coastal bodies of water with a free connection to the open ocean and within which marine water is diluted with fresh water derived from land drainage (Pritchard, 1967). Estuaries and shallow coastal waters are some of the most productive habitats in the world, making up only 1-2% of the ocean area, yet supporting approximately 20% of oceanic primary production (Smith, 1981). This production feeds as much as half of the marine fish population (Ryther, 1969). Estuaries are often the centers of human populations and are used as a means of food, production, transportation, and recreation (Odum, 1970; Dryer, 1979).

Almost two-thirds of the worldwide population currently lives in coastal areas (Trenhaile, 1997). Recent demographic studies suggest that in the next 25 years 75% of the US population will be living near the coast (Bush, 2004). Continued development of coastal areas will result in increased runoff and nutrient inputs into estuaries, causing environmental problems such as eutrophication, algal blooms, hypoxia, and the degradation of resources such as finfish and shellfish (Dryer, 1979; Frithsen, 1989). Water quality has traditionally been used in coastal areas as an indicator of the overall health of an estuary (Stevensen et al., 1993; Glasgow and Burkholder, 2000; Granger et al., 2000). Nutrient enrichment in the water and sediments can lead to eutrophication and can cause a significant drop in dissolved oxygen levels (D'Avanzo and Kremer, 1994). Low dissolved oxygen (hypoxia) or lack of dissolved oxygen (anoxia) in the water column has been blamed for major fish kills and can make water unsuitable for collecting shellfish or undesirable for recreation (Frithsen, 1989; RIDEM, 2003).

Because water quality can fluctuate with tidal cycles and seasonal and yearly weather changes, water quality trends are difficult to predict or to use as a reliable indicator of long term changes in the health of an estuarine system (D'Avanzo and Kremer, 1994; Bortone, 2005; Cicchetti et al., 2006). In order to address this problem, many other indicators have been suggested to measure the health of estuaries ranging from the type of bacterial communities to the number of wading birds present. There is no consensus among scientists, however, as to the best way to accurately assess trends within and among estuarine systems. The development of a standard group of

easily measurable indices that could be compared among estuaries and over time would be beneficial in the study of estuary health.

Soil physical, chemical, and morphological properties and characteristics develop in response to the environment. Terrestrial soil morphology has long been used as an indicator of certain properties of a landscape. For example, soil morphology is often used to determine wetland boundaries or to identify the depth of the seasonal high water table for making decisions regarding building or waste disposal (USDA-NRCS, 2006). In a similar manner, subaqueous soils could potentially be used as an indicator of the degree that shallow estuarine ecosystems have become degraded. Because subaqueous soil morphology follows landscape level boundaries (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003), soil morphological characteristics indicative of water quality such as depth of an oxidized surface and accumulations of sulfides may also be systematically stratified based on landscape unit (Germano and Rhoads, 1988; Valente et al., 1992).

Oxidation-reduction (redox) potentials of sediments have been investigated as a rapid means of assessing the amount of enrichment that a water body is receiving and the impacts on benthic communities present (Pearson and Stanley, 1979). Previous studies have suggested redox potential measurements as a possible indicator of relative levels of organic matter loading into an aquatic system (Pearson and Stanley, 1979). The decomposition of organic matter by microbes fuels the redox reactions in soil and sediment. Oxygen is the strongest oxidizing agent in aqueous systems and acts as an electron acceptor during microbial decomposition. In subaqueous systems, oxygen can quickly become depleted and other electron

acceptors including nitrate, manganese, iron, sulfate, and carbon are used by the microbes. Each species, respectively, is reduced at a lower range of redox potentials depending on the pH (Bohn, 1971).

Reduction of redox species in a subaqueous setting produces a vertical profile of decreasing redox potential with depth as each oxidizing agent is reduced until all organic matter has been decomposed (Teasdale et al., 1998). A redox potential gradient found in sediments often includes the oxidized surface layer where oxygen is still present in the interstitial water, a zone of transition where other species are being reduced, and a sulfidic zone that is totally anaerobic, H_2S is prevalent, and redox potentials are generally below -150 mV (Bohn, 1971; Knox, 1986). Because redox potentials respond to long-term impacts on an estuary such as continued organic loading, this measurement has been suggested as a potential indicator of estuary health (Pearson and Stanley, 1979).

Sediment profile imaging (SPI) is another way to evaluate the health of an estuary based on the depth of the apparent redox potential discontinuity (aRPD) or the oxidized surface of the soil. In marine systems, a deeper aRPD indicates a system with more benthic infauna and higher oxygen levels in the near-bottom waters (Germano and Rhoads, 1988; Valente et al., 1992; Cicchetti et al., 2006).

Stratifying embayments by landscape unit has the potential to provide a systematic method to understand variability in water quality within an estuary and identify areas that are more prone to water quality problems. In addition, the determination of a reproducible and widespread correlation between subaqueous soil properties and water quality would support the use of these soils as an indicator of

estuary health. Such indicators would allow management teams to target particular areas for conservation, protection, and restoration of resources based on a subaqueous landscape level map. The focus of this portion of my study was to determine if water quality parameters follow landscape-level boundaries in order to be able to more accurately predict areas within an estuary in danger of becoming impacted by poor water quality. Redox potential and subaqueous soil morphology were also investigated in order to attempt to make correlations between water quality and certain soil parameters that could potentially be used as indicators of estuary health.

MATERIALS AND METHODS

Study Areas

Greenwich Bay, Wickford Harbor, and Little Narragansett Bay were selected for study. These bays were chosen because they contain similar landscape units, but cover a range of human impact. The Greenwich Bay watershed includes approximately 4.5% of the state's population with only 2% of the land area, representing the most human-impacted site in this study (RICRMC, 2005). Greenwich Bay contains some of the most fertile shell fishing on the east coast, but impaired water quality due to increased runoff, nitrogen discharge from septic systems, and historical discharges of manufacturing waste and sewage has forced the closure of shell fishing in recent years in parts or all of the bay (Kennedy and Lee, 2003). With an estimated 135-234 metric tons of nitrogen and 35-63 metric tons of phosphorous discharged into the bay per year, there are sufficient nutrients to stimulate excess organic matter production that lowers dissolved oxygen levels in the summer months

(Granger et al., 2000). Greenwich Cove and Apponaug Cove are the two areas within Greenwich Bay that have been most impacted by low dissolved oxygen levels in the past (Germano and Rhoads, 1988; Granger et al., 2000).

Wickford Harbor is also an important area for fish and shellfish as well as boating and swimming. Although this bay is high in nutrients, some of the few eelgrass beds that remain in Narragansett Bay are found in Wickford Harbor (Joubert and Lucht, 2000). These eelgrass beds represent an important part of the estuarine system that is rapidly declining in Rhode Island waters. Eelgrass and other valued resources are at risk from pollution because a large amount (27%) of Wickford Harbor's 4500-acre watershed consists of impervious cover (Joubert and Lucht, 2000).

Little Narragansett Bay has an extensive watershed covering about 780 square kilometers of rural Rhode Island and Connecticut (Dillingham et al., 1993). Unlike the other two study area watersheds, the Little Narragansett Bay watershed is not heavily developed or industrialized. The watershed is >60% forest cover and has a population density of approximately 80 people/km^2 as compared to 426 people/km^2 in the Narragansett Bay watershed (Fulweiler and Nixon, 2005). The water quality of Little Narragansett Bay has been shown to meet state water quality standards and seldom suffers from low dissolved oxygen levels. High bacteria levels have resulted in the closure of shell fishing for human health concerns (Dillingham et al., 1993; Desbonnet, 1999).

Monitoring

A total of 21 landscape units, representative of those found within shallow embayments, were selected for water quality and redox potential monitoring. Two locations within each landscape unit were randomly selected as replicate sampling points and marked with a Garmin® GPSmap in order to assure ability to return to the same site for each monitoring period (Figures 2.1, 2.2, and 2.3). Each site was visited once in each of four sampling periods: spring (May-June), early summer (July), late summer (August) and fall (September-November), 2006. At each monitoring location measurements included dissolved oxygen (DO) and temperature at the soil-water interface, salinity, chlorophyll *a* (chl *a*), total suspended solids (TSS), and secchi disk readings. Dissolved oxygen and temperature were measured using a YSI-55 dissolved oxygen meter or with the Winkler titration method for samples brought back to the lab (Winkler, 1888). Salinity was measured using a hand refractometer from water sampled 0.5 m below the water surface.

Chlorophyll *a* water samples were collected at a 0.5 meter depth in two 150 ml tinted glass bottles. From these samples, 50 ml of water was filtered through glass-fiber filters either on board the sampling vessel or immediately after returning to the laboratory. Two replicates were performed from each sample collected, representing four replicates for each sampling station on each monitoring date. Filters were wrapped in foil and kept in a -15 °C freezer until processing. Determination of chl *a* collected on the filters was made using spectrophotometric determination of the acetone-extracted chlorophyll (Clesceri et al., 1998).

Total suspended solids were measured from water samples collected from 0.5 m below the water surface and kept on ice until they could be transferred to a refrigerator. The samples were refrigerated in the lab and filtered through pre-weighed glass-fiber filters within 48 hours of sampling. Two replicate 200-ml samples were filtered for each monitoring site in each sampling period. Filters were rinsed, dried, and reweighed to calculate TSS (Clesceri et al., 1998). Secchi depth was also used in order to estimate the clarity of the water at each sample site (Preisendorfer, 1986).

A redox profile of the top 15 cm of soil was recorded during monitoring for each sample site. Soil samples were collected using an aluminum core tube with a 30-cm long removable polycarbonate end. This tube was vibrated or pushed into the soil to a depth of approximately 20 cm. Water was added to fill the tube and the tube was sealed on top with an airtight plug to retain the soil as the tube was lifted from the bay bottom. The soil and the interstitial water were kept in the core tube by sealing the bottom of the core with a rubber stopper before removal from the water. Once removed from the water, the polycarbonate sampler was disconnected, and redox potentials were measured at 2 cm intervals beginning at a depth of 1 cm from the soil surface. An Accumet® calomel reference electrode, volt meter, and platinum-tipped redox probes (constructed according to Wafer et al., 2004) were inserted from the surface to measure redox potential. Redox probes were tested before use and periodically during the sampling season against Light solution (Light, 1973). Probes that strayed more than three mV from the standard were cleaned and retested or discarded. Field measurements were recorded when the millivolt reading did not drift

more than one millivolt in 10 seconds, or after the probe had been inserted in the soil for two minutes. Millivolt readings measured in the field were corrected to the standard hydrogen electrode by adding 244 mV to all readings (Vepraskas and Faulkner, 2001).

A modified profile darkness index (PDI) was calculated for all profiles described in order to test if soil morphology could be an indicator of water quality (Thompson et al., 1997; Reuter and Bell, 2003). The PDI was calculated by

$$PDI = \sum \text{horizon thickness}_i / ((V_i C_i)+1)$$

for all horizons to a depth of 25 cm, where V_i is the Munsell color value and C_i is the Munsell color chroma for the specified horizon. A depth of 25 cm was used instead of simply the depth of the A horizon because some subaqueous soils do not have an A horizon described.

Sediment profile imaging (SPI) data for selected monitoring sites in Drowned Channel and Bayfloor landscape units in Greenwich Bay were collected by the University of Rhode Island Graduate School of Oceanography Paleomagnetics Laboratory. These data consist of images of the top 15-20 cm of the soil, and are used to visually measure the depth of the apparent redox potential discontinuity (aRPD) in the soils (Cicchetti et al., 2006).

One-way analyses of variance (ANOVA) and Tukey's honestly significant difference test were used to determine the significance of differences in water quality parameters as well as redox potentials among bays, seasons, and landscape units. Water quality parameters were assessed using a stepwise fit model applied to soil-water relationships by using indicator values (water quality parameter) to discriminate

between two mutually exclusive soil-landscape types (dominant soil texture). The five most significant water quality variables were used to create a multimetric model that could predict dominant soil texture based on water quality parameters. Coefficients of determination were determined for selected parameters. All statistics were carried out using JMP IN and Excel software (SAS, 2003; Microsoft, 2003). A significance level of 0.05 was used in all analyses.

RESULTS AND DISCUSSION

Water Quality Assessment

I examined DO, chl *a*, and TSS as indicators of water quality in the study areas (Appendix 3). Average DO levels varied among seasons and bays (Figure 2.4). No single bay consistently had the lowest DO levels. Greenwich Bay had significantly lower DO levels than Little Narragansett Bay in the early summer sampling period, while in the fall, Wickford Harbor had the lowest oxygen levels. All of the bays showed significant differences in DO among seasons with highest levels in the spring. The largest differences in seasonal average DO levels were observed in Greenwich Bay. Lowest DO in Greenwich Bay was seen in the early summer (mean = 4.9 mg L^{-1}, SD = 2.33), with low DO continuing through the late summer and increasing again in the fall monitoring period. Little Narragansett Bay reached the lowest average DO in the late summer monitoring period (mean = 6.2 mg L^{-1}, SD = 0.89) with similar values in the early summer and fall monitoring periods (mean = 7.9, SD = 0.94 and 8.2 mg L^{-1}, SD = 0.52, respectively). Wickford Harbor also had lowest average DO in the

late summer (mean = 5.6 mg L^{-1}, SD = 0.74), but levels did not vary significantly from early summer through the fall.

Lowest DO levels occurred in the early or late summer monitoring periods, typical of most water bodies in which low DO corresponds with warmest temperatures and stratified water conditions. In the past, Greenwich Bay, especially Apponaug Cove and Greenwich Cove in the western part of the bay, has experienced hypoxia in the summer months due to high levels of nitrogen input causing excess algae production as well as temperature stratification (Germano and Rhoads, 1988; Granger et al., 2000; Kennedy and Lee, 2003). The frequent observation of low DO levels in particular areas of a bay can be a warning sign that a fish kill is possible, though it is difficult to determine when these conditions will occur (RIDEM, 2003).

Average DO levels within landscape units varied among seasons and bays (Table 2.1). When DO levels are between 2.0 and 5.0 mg L^{-1} the water is considered hypoxic, while levels below 2.0 mg L^{-1} are severely hypoxic. Anoxia occurs when there is a total lack of oxygen in the water. Eight sites monitored in western Greenwich Bay reached DO levels of 5.0 mg L^{-1} or less in the early summer and six sites reached these levels in the late summer (Figure 2.5). Severely hypoxic conditions were seen only in Greenwich Bay at the Greenwich Cove (Drowned Channel; GR04 and GR03) and Apponaug Cove (Cove; GR10 and GR09) locations in the July and August monitoring periods with DO levels reaching as low as 0.77 mg L^{-1} and 0.38 mg L^{-1} at sites in Apponaug Cove (Figure 2.6). These Greenwich Bay observations are comparable to more frequent DO monitoring conducted by Prell et al. (2006) over the same period in which Apponaug Cove remained hypoxic or severely

hypoxic at the sediment water interface from June through August, and Greenwich Cove reached hypoxic oxygen levels two out of three monitoring dates in the month of August. Prell et al. (2006) found severely hypoxic conditions were reached at the bottom of the entire bay in early August of 2006.

Wickford Harbor had only two recorded occurrence of hypoxia in early summer and three in late summer, with DO reaching 3.06 mg L^{-1} in a Cove site (WK72) in the early summer (Figure 2.7; Table 2.1). Dissolved oxygen levels in Little Narragansett Bay remained high throughout the year, with the lowest recorded level at 5.02 mg L^{-1} in the late summer (Figure 2.8).

Cove, Spit, and Drowned Channel were the only three landscape units to experience severe hypoxia during monitoring. Hypoxic and severely hypoxic DO readings (<5 mg L^{-1}) occurred most frequently in the Drowned Channel landscape. Cove, Bayfloor, Spit, and Fluviomarine Bottom landscapes also experienced hypoxic DO levels, while Mainland Shoreface, Shoal, and Washover Fan units did not experience hypoxia during monitoring (Table 2.2).

Chlorophyll *a* is a measurement used to estimate the amount of algae or phytoplankton in the water column (Addy and Green, 1996). Greenwich Bay sites contained the highest chl *a* content in all four sampling periods ($p<0.05$), with Wickford Harbor and Little Narragansett Bay having similar average levels of phytoplankton present (Figure 2.9). In all bays, chl *a* levels were found to drop in the fall to be much lower than in the other three sampling periods. Levels did not vary significantly from spring through late summer. A significant difference in chl *a* levels was noted on different landscape units (Figure 2.10). Lowest chl *a* levels were seen in

high-energy, sandy landscape units such as Shoal and Mainland Shoreface units. The highest average phytoplankton levels were measured in lower energy units dominated by finer soils including Drowned Channel. This difference in chl *a* can be attributed to slower flushing time and greater nutrient input in these sheltered areas providing more fuel and time for phytoplankton to grow.

Narragansett Bay typically has a winter/spring phytoplankton bloom as well as high chlorophyll levels in the summer. This cycle varies from year to year and is impacted by the temperature of the water and the amount of sunlight available (Oviatt et al., 2002). Although phytoplankton are present in all healthy water bodies, excess algae can cause decreased light attenuation and low DO levels, which have been linked to decreases in submerged aquatic vegetation (Dennison et al., 1993; Addy and Green, 1996). Phytoplankton in the water column also can have a great impact on the organic carbon found in subaqueous soils, as 30-80% of the carbon produced by phytoplankton falls to the estuary floor via sedimentation depending on the amount of predation that occurs from zooplankton or mussels (Keller et al., 1999).

In addition to phytoplankton, other suspended solids can impact water clarity and affect the quality of water in an estuary. Total suspended solids were significantly greater in Little Narragansett Bay in the late summer, but were similar among bays in all other sample periods. Season influenced TSS levels with significantly higher levels in the fall sampling period for all three bays ($p<0.001$; Figure 2.11). No significant difference in TSS was observed between landscape units. Secchi depth is another measurement often used as an indication of the clarity of the water. Although secchi measurements were made in this study, the disk could be seen all the way to the

bottom at most sample sites in all sampling periods, so the data was not useful for water quality comparisons.

Soils in these bays generally fell into two groups: highly fluid, fine-grained, Sulfiwassents and sandy Psammowassents (see Chapter 1 for further discussion). Psammowassents are found on high-energy landscape units including Mainland Shoreface, Shoal, Spit, and Washover Fan. Sulfiwassents are found on sheltered low energy landscapes such as Cove, Bayfloor, Drowned Channel, and Fluviomarine Bottom landscapes. When landscape units were grouped into these two categories, I found that salinity (χ^2=3.81, p=0.05), chl *a* content in the early summer (χ^2=1.87, p=0.17), DO level in the late summer (χ^2=2.64, p=0.1), redox potential at 5 cm in the fall (χ^2=3.27, p=0.07), and redox potential at 1 cm in the late summer (χ^2=3.06, p=0.08), were the parameters most highly related with soil type based on a stepwise fit model. Lower salinity levels were most likely found in low energy landscape units because these landscapes occupy coves or other protected areas that receive less flushing from ocean water than more open high-energy landscape units. Another possibility is that these low energy, protected areas receive groundwater inputs containing nutrients that lead to algal blooms. Consequently, chl *a* levels are higher and DO levels lower in low energy landscape units dominated by Sulfiwassents than in high-energy landscape units. These five parameters can be combined to create a model that is highly predictive of texture class (χ^2=42.42, p<0.001; Table 2.3). Considering this, a landscape unit map could be used to identify areas that would reach low DO levels and have high chl *a* contents in the summer months. Salinity and redox potential could also be estimated based on landscape unit.

Redox potential

Redox potentials were generally higher at the soil surface and decreased over the first three to five cm before leveling off or continuing to decrease very slightly (Figure 2.12). Values ranged from +267 to -182 mV (Appendix 4). Redox profiles were recorded in order to determine if this measurement could be indicative of the degree of organic loading or the quality of the overlying water. For comparative purposes, I examined redox potential at the 1 cm and 5 cm depths. I chose these depths because redox at the 1 cm depth should be representative of soil materials that are directly impacted by transient environmental changes at the sediment-water interface. At 5 cm and below, soils are impacted by longer-term organic loading and soil development processes (Moshiri and Crumpton, 1978; Pearson and Stanley, 1979).

Redox potential is a quantitative measure of the availability of electrons in an environment and is often used as a measure of the capacity of a system to reduce or oxidize particular elements (Hinchey and Schaffner, 2005). Over the course of the six months that redox profiles were recorded, seasonal trends were seen at the 1 cm soil depth in fine particle depositional landscape units (Bayfloor, Drowned Channel, Fluviomarine Bottom, and Cove; Figure 2.13). Lowest values were measured in the early summer and highest values in the fall ($p<0.05$). Redox potential near the soil surface likely reflects the short term changes that occur seasonally in the amount of respiration taking place at the sediment surface and the dissolved oxygen content of the overlying water.

This seasonal trend was not seen in redox potentials at the 5 cm depth (Figure 2.13). Redox potentials at 5 cm were overwhelmingly negative for Greenwich Bay sites with only 26% of readings greater than zero (Figure 2.14). Little Narragansett Bay and Wickford Harbor sites had higher overall Eh readings, with 55% and 51% of all readings, giving positive results at a 5 cm depth respectively (Figures 2.15 and 2.16). Greenwich Bay had the lowest average redox curve followed by Wickford Harbor. Little Narragansett Bay had the highest overall redox (Figure 2.17).

Landscape units dominated by highly fluid silty soils (Bayfloor, Drowned Channel, Fluviomarine Bottom, and Cove) had lower redox potential readings at a 5 cm depth than higher energy landscape units where water movement prevents the deposition of fine particles, and sandy soils are dominant (Washover Fan; $p<0.001$; Figure 2.18). Soils on these silty landscape units had negative Eh readings at the 5 cm depth a majority (66%) of the time (Appendix 4).

Soils on sandy, high-energy landscape units (Mainland Shoreface, Spit, Shoal, and Washover Fan) had negative Eh readings at 5 cm only 27% of the time. There were significant differences in Eh among landscape units within Greenwich Bay and Little Narragansett Bay. Wickford Harbor had more uniform Eh measurements throughout the landscape units and had no significant difference in redox potential with landscape ($p=0.7$), perhaps due to the small size and sheltered nature of this bay. The higher redox potential on the sandy landscape units may be due to a number of influences. The coarse particle size of the soils on these landscape units allows oxygen from the overlying water to penetrate deeper into the soil. The depth that oxygen penetrates into the soil has been shown to reflect redox profiles, with deeper

penetration of oxygen corresponding with higher Eh values at depth (Meijer and Avnimelech, 1999). These sandy landscape units are generally found in open areas of the bays that receive greater wind and wave influence. Water movement and flushing occur much more rapidly on these areas, allowing oxygenated water to move across the soil surface leading to higher soil redox values.

The significantly lower amounts of organic matter in these sandy soils can also have an influence on redox potential, because soil organic matter fuels the microbes that require electron acceptors such as oxygen. In an oxygen-limited environment, the decomposition of organic carbon by microorganisms is the driving force behind the creation of a redox potential gradient in soils and sediments (Biggs, 1967). Most organic carbon is generally found in low energy areas with very fine particle size (Knox, 1986; Hennessee et al., 1986). A positive relationship was seen between percent fine particles (silt and clay) and the percent organic carbon found in soil samples (R^2=0.63; Figure 2.19).

Impacts from continued organic loading coming from deposition and decay of organic material cause a decrease in redox potential below the four cm depth in a soil profile (Pearson and Stanley, 1979). At fine-particle depositional sites, the average chl *a* content in the overlying water over the period of this study had a negative relationship with the redox potential at the 1 cm (R^2=0.59) depth in the spring sampling period (Figure 2.20). This relationship occurred to a lesser degree in the early summer and did not occur in the late summer or fall sampling periods. The organic carbon in these silt and clay dominated depositional areas comes in part from decomposition of macrophytes and microalgae as well as high sedimentation rates.

An increase in the growth of phytoplankton as a result of eutrophication or excess nutrients in a system will increase the amount of organic carbon added to the sediment surface (Cooper and Brush, 1993). More organic matter in the sediment fuels reduction by microbial decomposition. Continued high levels of phytoplankton in the water overlying the depositional landscapes, indicated by high chl *a* measurements, should have an impact on the organic carbon and thus, the redox potential in the underlying soil.

The time between a loading event and the resulting decrease in redox potential has been estimated to be six to eight weeks in some estuarine systems (Pearson and Stanley, 1979). Other studies have found that low DO near the sediment surface is not an immediate result of organic matter loading from phytoplankton, but occurs as a result of the microbes decomposing accumulated organic matter from the previous season (Taft et al., 1980). The delay in both redox and DO response to organic loading implies that these factors are dependent upon the respiration of the benthic organisms rather than directly dependent upon amounts of organic matter present in the water column at a given time. The relationship of the mean yearly chl *a* levels in the water with redox potential in the spring, but not in later seasons could be a result of this delay in response. The increase in benthic respiration rates with increased temperatures in the spring would reduce the oxygen and other electron acceptors in the soils and lower the redox potential at the soil surface (Taft et al., 1980). Sites that receive large amounts of organic matter throughout the year would not show a response in oxygen or redox levels until the spring when excess organic matter is decomposed by more active benthos. Redox potentials take approximately eight

months to return to their original level after organic loading is stopped (Pearson and Stanley, 1979). Thus, low energy sites such as those in Greenwich Bay that have been receiving large amounts of organic matter input continually for many years would have continued lowered redox readings, while sites that have intermittent or seasonal accumulations of organic matter could recover to higher redox potentials within a year.

Profile Darkness Index

The Profile Darkness Index (PDI) has been used for subaerial soils to relate hydrology to the thickness and color of the A horizon (Thompson et al., 1997; Reuter and Bell, 2003). I modified the PDI to include the top 25 cm of soil to test if this approach could be used in subaqueous environments as an indicator of water quality. The hypothesis was that soils in poor water quality areas would have more organic carbon and monosulfides that would result in a darker soil color. In general, soils in low energy depositional environments had lower Munsell values (2.5-3) than those soils found on high energy, sandy landscapes (Munsell values 3-6; Appendix 1). The PDI was used in order to numerically differentiate between soils with high value and those with lower values. Profile Darkness Index values ranged from 2.03 to 25 with an average of 8.6 for 55 profiles analyzed. Means were not significantly different between bays or landscape units (Figure 2.21). A positive relationship was seen between PDI and percent organic carbon in the surface horizons (R^2=0.34; Figure 2.22), as well as a slight negative relationship with springtime redox readings at 5 cm (R^2=0.17; Figure 2.23). A greater amount of organic carbon in soils would make the soils appear darker, with lower Munsell values and higher PDI. The relationship with

redox readings in the spring indicate that those soils with higher PDI and low Munsell values are generally those soils that have more negative redox values at a depth of five cm. This could be a result of the greater amount of organic carbon available at these sites to fuel reduction as well as the greater amount of black monosulfides that form in these highly reduced soils. These relationships are slight, but suggest that with modified methods, a color index such as the one used here could be used to estimate organic carbon content of soils as well as a possible indication of the redox potentials. Because dark soil colors are the most difficult to match in the Munsell color system, the use of a chrometer to discriminate more accurately between dark colors would provide a better measurement of PDI.

Sediment Profile Imaging

In Greenwich Bay, six sites in high n-value landscape units including Bayfloor and Cove units were viewed with a SPI camera over the course of the sampling season. The SPI camera enables the visual identification of the depth to the first boundary in a redox profile where all oxygen has been depleted or reduced; known as the apparent redox potential discontinuity (aRPD) (URI Graduate School of Oceanography Paleomagnetics Laboratory; Hinchey and Schaffner, 2005). The area above this boundary, where oxygen is present in the soil, is referred to as the oxidized surface. An oxidized surface between 0.5 cm and 2.0 cm in depth was seen in the June at all sites. In July, two out of six sites had an oxidized surface, and by August, no sites had a visible oxidized layer. In the October monitoring period, the oxidized surface had once again returned for two of the sites measured. The thickness of the oxidized surface can be influenced by the grain size, organic matter content,

temperature of the sediment, bioturbation, oxygen consumption by benthos, as well as the movement and dissolved oxygen content of water above the sediment surface (Jorgensen, 1977; Knox, 1986).

Sites GR03 (Dc) and GR08 (By) were representative of the sites observed with the SPI camera in Greenwich Bay. These sites had thin oxidized surface layers in June and early July, followed by the lack of an oxidized surface through the beginning of October. Redox potential measurements reflect this trend with highest surface readings in the spring and late fall and lowest readings during the summer when no oxidized surface was seen (Figures 2.24 and 2.25). The oxidized material appears as an olive colored surface that is believed to be due to the presence of oxidized Fe (Germano and Rhoads, 1988). The dark color below the oxidized surface is typically due to monosulfide coatings (Figure 2.26). Iron is known to oxidize only at a redox potential of approximately +120 mV at a pH of 7 (Germano and Rhoads, 1988; Vepraskas and Faulkner, 2001), however, these redox profiles did not reach this value. The lack of redox readings above +120 in soils with oxidized surfaces could be due to the natural variation in redox potential as well as pH at these sites. Monosulfides are generally oxidized at a lower redox potential than Fe (Bohn et al., 1979). An alternate explanation for the lighter oxidized surface could be a lack of these reduced monosulfides that reveal the true color of the parent material in the surface horizons.

SUMMARY AND CONCLUSIONS

In this study, I examined a number of parameters to test if soil landscape units could be used as a way to stratify embayments in order to examine water quality

affects and issues. Of the three embayments that I examined, Greenwich Bay consistently had higher levels of chl *a*, was the only bay in which severely hypoxic DO levels were reached, and appears to have poorer water quality than either Little Narragansett Bay or Wickford Harbor. This was expected considering the history of impaired water quality in Greenwich Bay. Landscape unit was seen to have an affect on DO levels seen in the bays. Hypoxic and severely hypoxic conditions were seen most frequently in low energy, highly fluid soil landscapes including Drowned Channel, Cove, and Bayfloor. These landscapes also had slightly higher levels of chl *a*. TSS showed no significant difference among landscape units. A multimetric model consisting of salinity, chl *a* in early summer, DO in late summer, and redox potential measurements was created which was able to effectively differentiate sandy from high n-value landscape units, indicating that water quality on these low energy, soft bottom areas was consistently poorer than that on sandy landscape units. By stratifying bays according to landscape unit, areas of a bay that are more prone to severe hypoxia and excess phytoplankton growth can be identified.

The indicators of water quality that I examined were soil redox potential, PDI, and depth to the aRPD or oxidized surface. Evidence suggests that large amounts of organic loading over time can lower the redox potential of the surface of the soil beneath estuarine waters. I found that redox potentials were lowest in low energy, soft-bottom landscape units (Bayfloor, Drowned Channel, Cove, and Fluviomarine Bottom). The large amount of organic matter, high percent silt and clay sized particles, and poor flushing that occur within these units promote greater reduction within the soil leading to low redox potentials. Potentials were lowest in Greenwich

Bay, the bay with the lowest measured DO and the highest organic loading from high levels of phytoplankton. Redox potentials measured in the spring correlated most closely with the amount of chl *a* in the overlying water through the course of this study, indicating that organic loading from phytoplankton through the season may have most impact on the redox potential of soils in the spring when water temperatures warm and microbes become more active. Although redox potentials are variable over the course of a year, monthly or springtime monitoring of redox potentials could be more indicative of nutrient enrichment in a system than water quality measurements made at the same intervals.

The use of redox potentials as an indication of long-term nutrient enrichment in estuarine systems would show a more complete picture of the health of an estuary than occasional water quality monitoring due to the cumulative impact in which high amounts of organic loading over the course of a year or season can lower redox potentials for as much as eight months. Many factors impact the redox potential in subaqueous soils including benthic respiration, bioturbation by benthic infauna, deposition of organic material, and water movement and flushing. Thus, soil redox potential represents a composite of many different parameters that determine the health of a water body. Redox potential also has important impacts on chemical processes that occur in the soil such as denitrification, changes in forms of Fe, Mn, or S, and the solubility of heavy metals (Teasdale et al., 1998; Tomaszek, 1995).

The modified Profile Darkness Index (PDI) for subaqueous soils has the potential to indicate areas with greater accumulations of organic carbon as well as areas that are highly reducing and contain dark monosulfide coatings. Spring redox

measurements at 5 cm showed a weak negative relationship with PDI, indicating that soils with very black colors generally had lower redox potentials than soils with brighter colors. This approach needs to be more rigorously tested.

Use of SPI technology to visually identify the aRPD depth appears to correlate with measured redox potentials. The thickness of the oxidized surface and the redox potential of the soil surface change through the course of a year, but high redox readings were associated with thicker oxidized surfaces, indicating that these two methods are measuring similar trends. Although this technology appears to be an effective indicator of redox potential in highly fluid soils, it is more difficult to use in sandy soils where the camera cannot penetrate. Further research would need to be done in order to determine the exact redox potentials of the apparent oxidized surface of the soil versus the underlying reduced material in order to draw conclusions about the degree of reduction occurring in these profiles.

Table 2.1. Water quality measurements by landscape unit in each bay measured in four monitoring seasons.

Landscape Unit	Chlorophyll a (ug L^{-1})				Total Suspended Solids (mg L^{-1})				Dissolved Oxygen (mg L^{-1})				Salinity (ppt)			
	S*	ES*	LS*	F*	S	ES	LS	F	S	ES	LS	F	S	ES	LS	F
Wickford Harbor																
By	8.8	3.3	5.0	2.9	15	18	18	52	9.5	7.9	5.3	6.5	26	26	35	31
Cv	3.7	7.4	8.8	5.2	19	20	22	125	12.5	3.5	5.1	6.2	26	30	35	27
Dc	2.7	7.1	3.3	3.6	19	19	26	49	12.0	6.6	4.8	5.4	25	24	35	29
Dp	17.5	6.1	3.1	1.7	17	14	30	58	8.8	6.3	6.7	6.1	27	29	32	30
Fb	9.4	12.2	17.7	3.5	23	28	40	91	9.6	5.6	5.4	6.1	30	24	27	27
Pt	7.6	5.1	4.9	2.6	10	19	36	51	7.4	6.8	6.1	6.9	30	30	34	30
Sg	13.6	4.2	6.4	3.7	10	26	19	49	6.6	7.9	5.8	6.4	21	26	35	29
Greenwich Bay																
By	13.5	9.7	15.7	11.7	19	28	9	78	9.6	4.2	3.2	8.4	30	30	35	27
Cv	10.7	21.0	27.8	5.2	11	30	13	46	10.8	1.2	1.8	7.9	28	27	34	30
Dc	29.2	25.3	30.4	33.5	13	28	16	65	10.0	2.3	1.4	8.6	24	25	33	27
Dp	14.5	11.9	13.1	2.2	14	23	13	83	11.5	6.4	6.6	9.8	26	28	36	24
Dp	18.7	12.4	13.6	3.5	21	32	9	95	11.1	6.5	7.7	9.2	27	29	35	32
Dp	15.6	7.3	8.6	7.1	18	24	7	92	11.2	7.2	8.2	9.7	27	30	35	30
Fb	18.1	19.3	20.9	9.5	16	45	17	45	11.9	7.7	9.1	8.9	18	29	35	30
Pt	17.5	11.7	22.8	3.7	28	17	11	66	7.1	4.0	10.2	10.1	29	30	35	32
Little Narragansett Bay																
By	15.2	6.2	7.4	1.2	11	16	61	50	10.3	8.9	6.1	8.9	25	29	35	29
Cv	11.9	7.1	7.8	1.5	20	21	50	85	10.3	7.0	7.8	8.0	13	33	30	31
Cv	6.2	8.3	3.4	4.1	19	12	32	23	8.9	8.6	5.5	8.1	10	24	20	10
Dc	6.0	9.5	17.2	1.6	21	33	42	56	10.4	6.8	5.5	8.1	23	24	23	29
Sg	11.3	1.8	4.3	1.3	15	16	89	55	11.0	8.9	5.7	8.2	28	33	35	30
Wf	10.1	3.4	5.0	1.3	18	25	51	92	10.3	7.6	6.7	8.2	28	30	35	33

*S = spring; ES = early summer; LS = late summer; F = fall

Table 2.2. Percent of hypoxic and severely hypoxic DO readings (<5 mg L^{-1}) in each monitored landscape unit.

Landscape Unit	GB n	GB % DO<5 mg L^{-1}	LNB n	LNB % DO<5 mg L^{-1}	WH n	WH % DO<5 mg L^{-1}	Total % DO<5 mg L^{-1}
By	8	38	8	0	8	0	**13**
Sg	8	0	0	-	8	0	**0**
Pt	8	25	0	-	8	0	**13**
Dc	8	50	4	0	8	25	**25**
Dp	24	0	0	-	8	0	**0**
Fb	8	0	4	0	8	13	**6**
Cv	8	50	16	0	8	38	**22**
Wf	0	-	8	0	0	-	**0**
Total	**72**	**18**	**40**	**0**	**56**	**11**	**17**

Table 2.3. Bottom type predicted by the five most significant water quality parameters (redox at 5 cm in fall, redox at 1 cm in late summer, DO in late summer, chl *a* in early summer, and salinity) based on a stepwise regression model.

Landscape Unit	Bay	True bottom type	Bottom type predicted by model
By	WH	fine	fine
By	WH	fine	fine
By	GB	fine	fine
By	GB	fine	fine
By	LNB	fine	fine
By	LNB	fine	fine
Cv	WH	fine	fine
Cv	WH	fine	fine
Cv	GB	fine	fine
Cv	GB	fine	fine
Cv	LNB	fine	fine
Cv	LNB	fine	sandy
Cv	LNB	fine	fine
Cv	LNB	fine	fine
Dc	WH	fine	fine
Dc	WH	fine	fine
Dc	GB	fine	fine
Dc	GB	fine	fine
Dc	LNB	fine	fine
Dp	WH	sandy	sandy
Dp	WH	sandy	sandy
Dp	GB	sandy	fine
Dp	GB	sandy	sandy
Dp	GB	sandy	sandy
Dp	GB	sandy	sandy
Dp	GB	sandy	sandy
Dp	GB	sandy	sandy
Fb	WH	fine	fine
Fb	WH	fine	fine
Fb	GB	fine	fine
Fb	GB	fine	fine
Fb	LNB	fine	fine
Pt	WH	sandy	sandy
Pt	WH	sandy	sandy
Pt	GB	sandy	sandy
Pt	GB	sandy	sandy
Sg	WH	sandy	fine
Sg	WH	sandy	fine
Sg	LNB	sandy	sandy
Sg	LNB	sandy	sandy
Wf	LNB	sandy	sandy
Wf	LNB	sandy	sandy

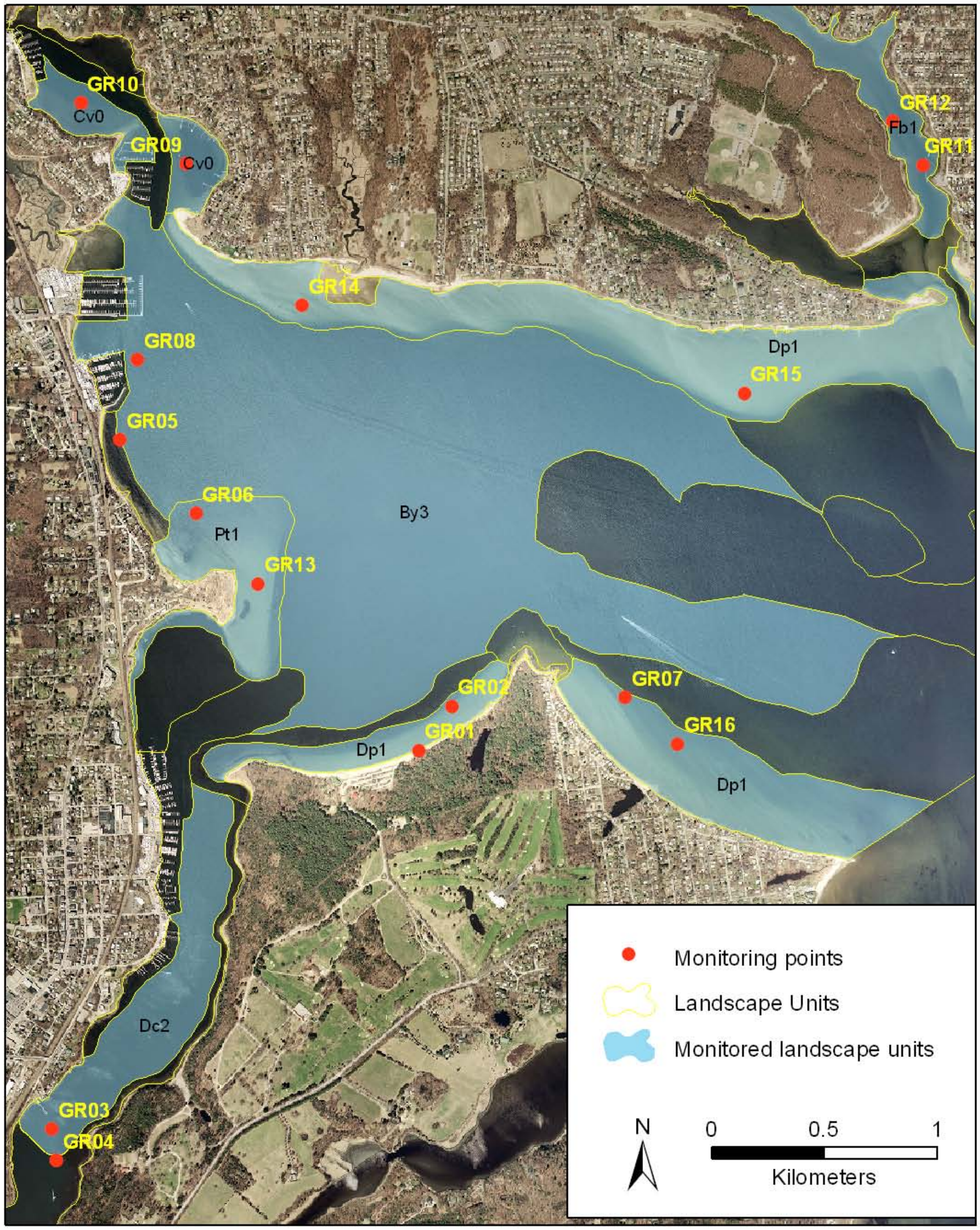

Figure 2.1: Monitoring locations in Greenwich Bay. Water quality and redox measurements were made seasonally. Landscape units monitored include Cove (Cv), Bayfloor (By), Mainland Shoreface (Dp), Spit (Pt), Drowned Channel (Dc), and Fluviomarine Bottom (Fb).

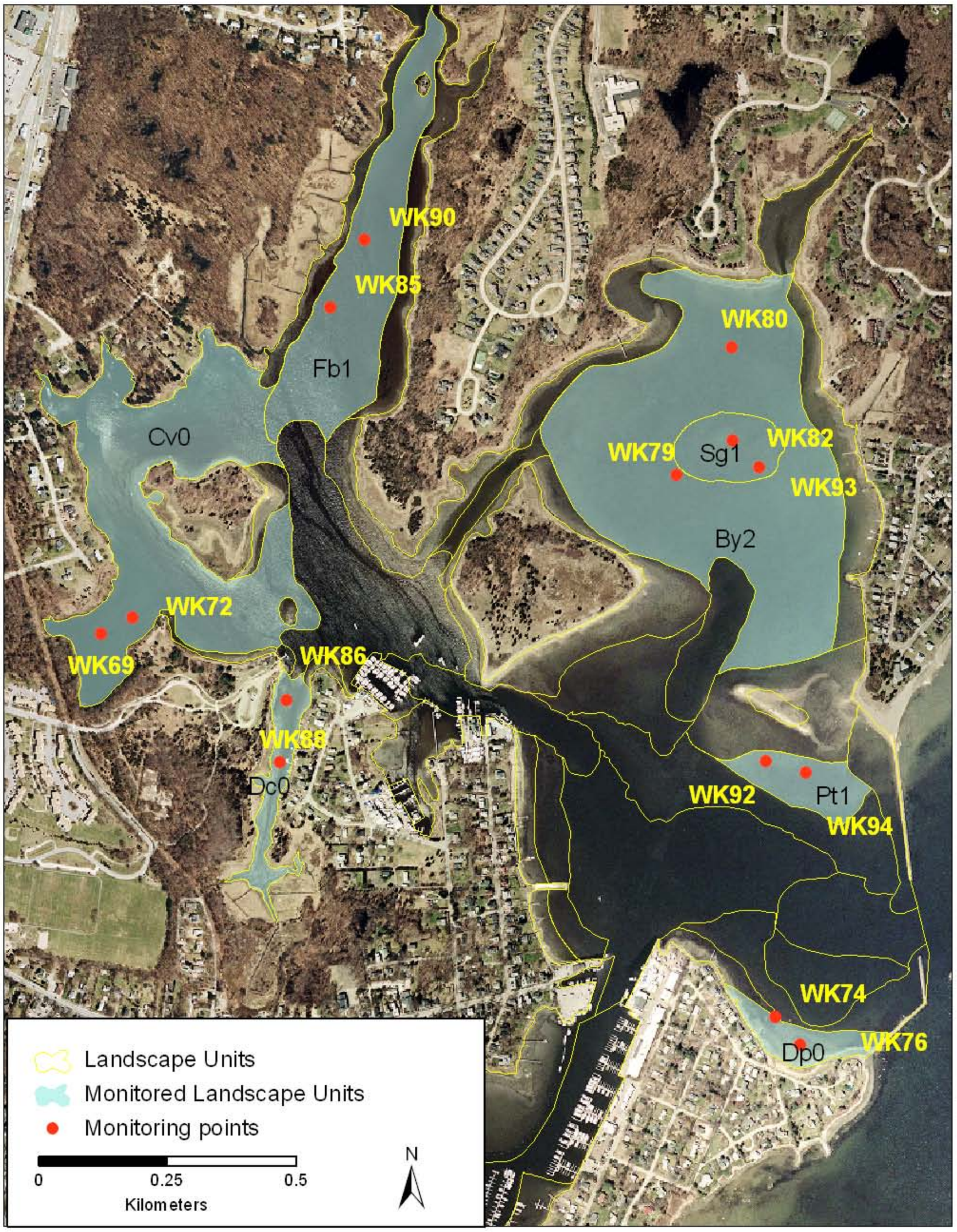

Figure 2.2: Monitoring locations in Wickford Harbor. Water quality and redox measurements were made seasonally. Landscape units monitored include Cove (Cv), Bayfloor (By), Mainland Shorface (Dp), Spit(Pt), Drowned Channel (Dc), Shoal (Sg), and Fluviomarine Bottom (Fb).

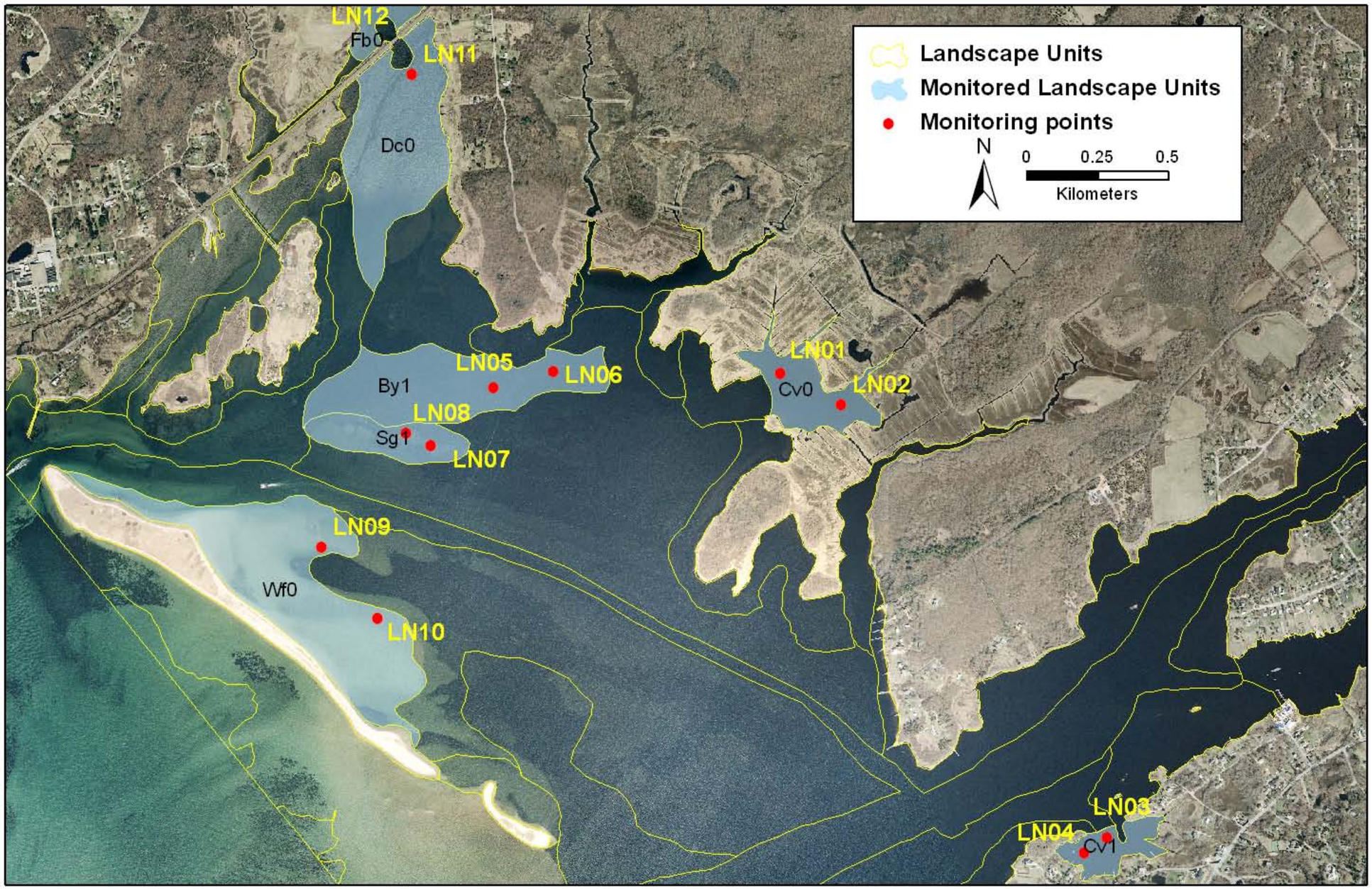

Figure 2.3: Monitoring locations in Little Narragansett Bay. Water quality and redox measurements were made seasonally. Landscape units monitored include Cove (Cv), Bayfloor (By), Drowned Channel (Dc), Shoal (Sg), and Washover Fan (Wf).

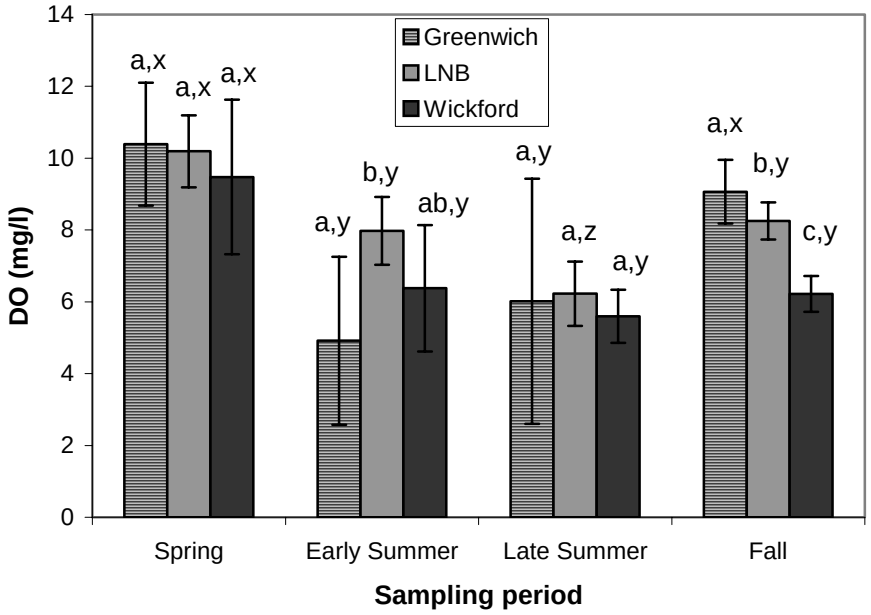

Figure 2.4. Average DO levels for the four sampling periods. Means with different letters are significantly different at the 0.05 level according to Tukey's HSD test. Comparisons among bays for the same sampling period use a,b, and c. Comparisons among sampling periods for the same bay use x,y, and z. Bars represent standard deviations. (WH n=14, LNB n=12, GB n=16 for each sampling period).

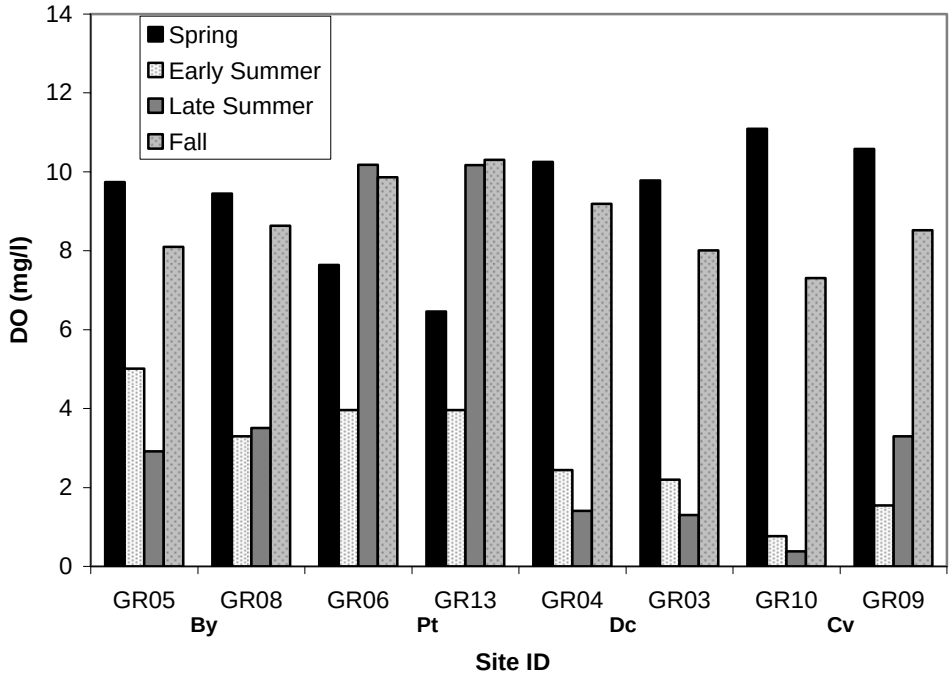

Figure 2.5. Sites in Greenwich Bay that reached hypoxic DO levels (DO<5 mg L^{-1}). Sites are in Bayfloor (By), Spit (Pt), Drowned Channel (Dc), and Cove (Cv) landscapes.

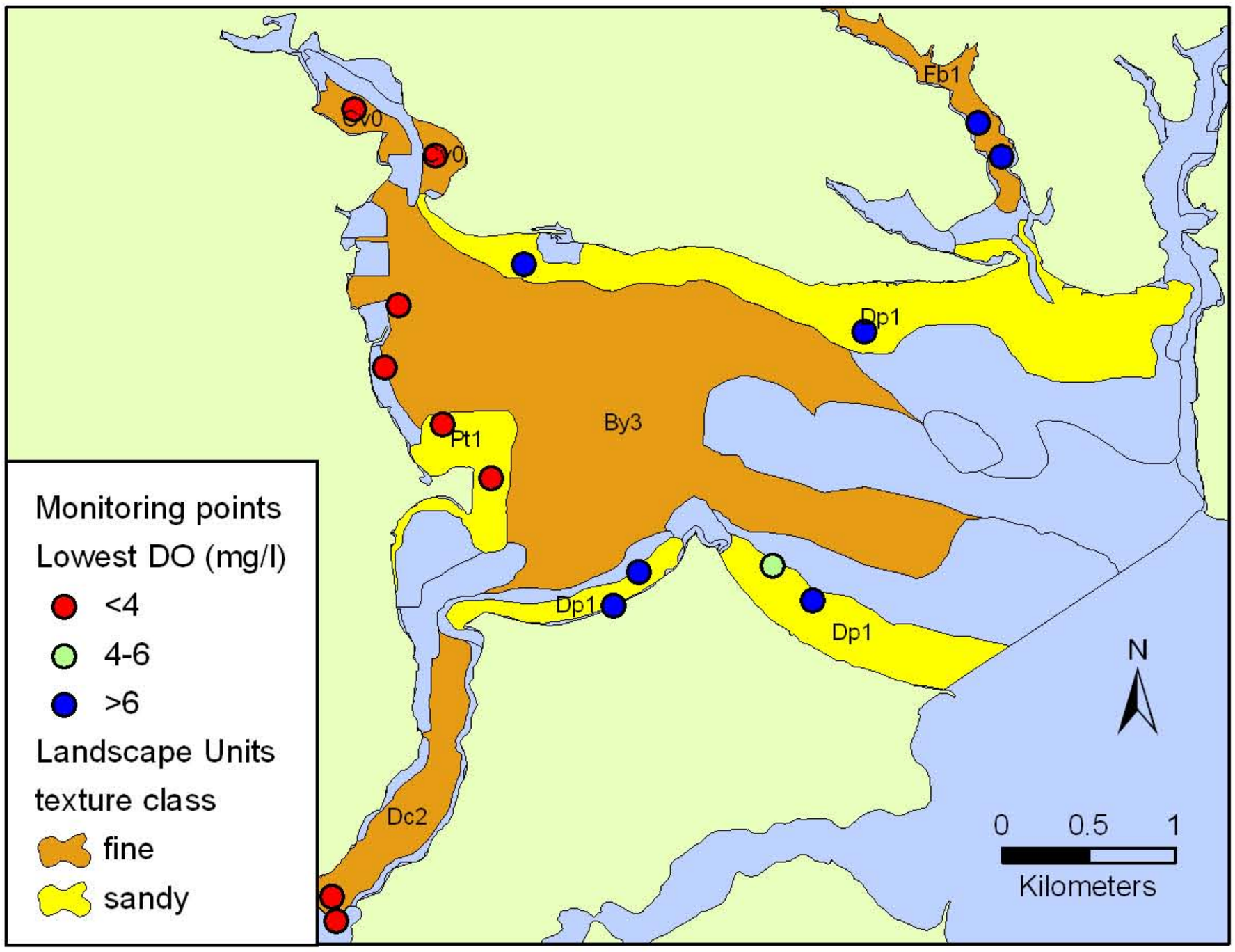

Figure 2.6. Lowest DO measurements recorded in Greenwich Bay stratified by soil texture class.

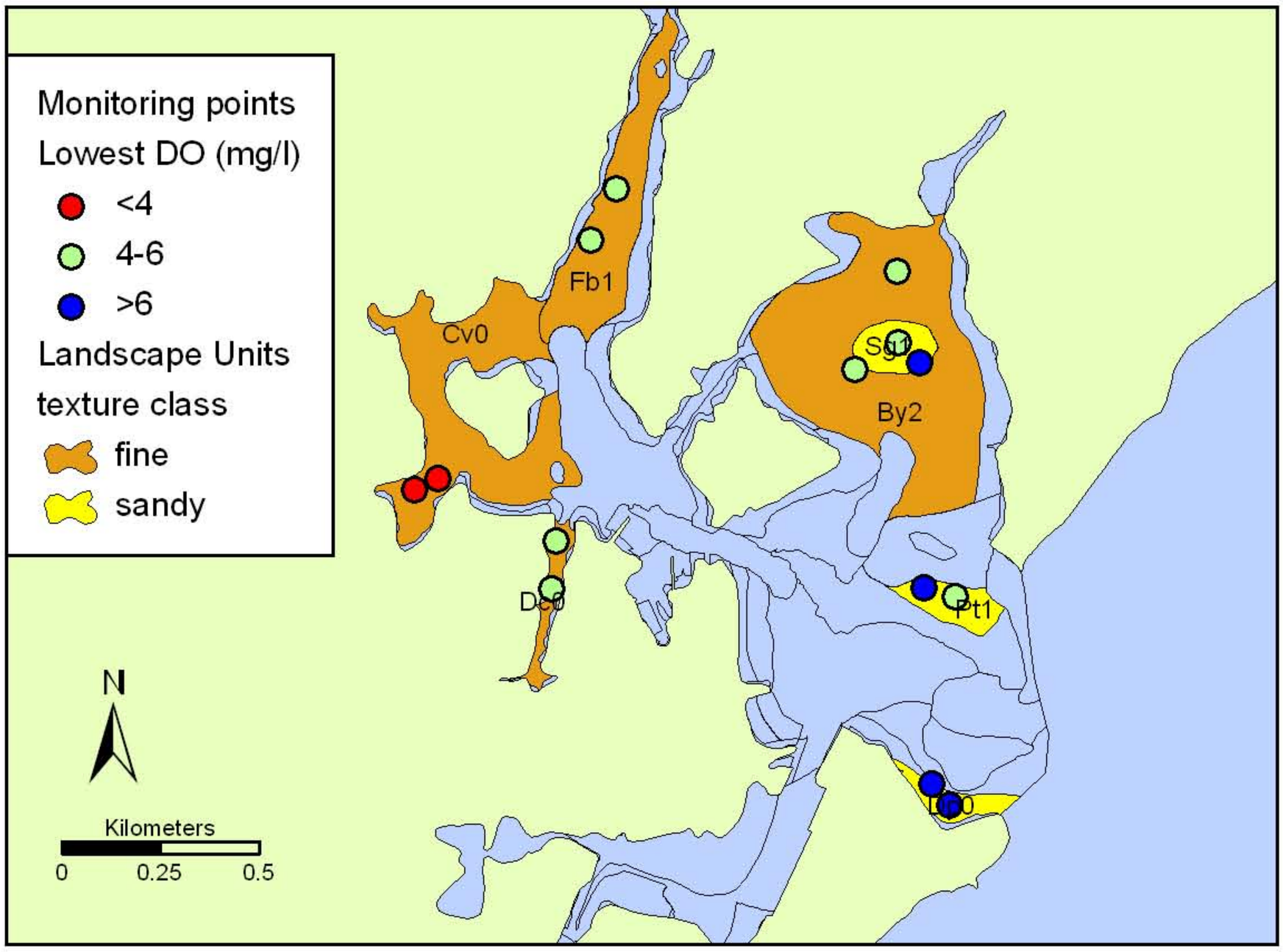

Figure 2.7. Lowst DO measurements recorded in Wickford Harbor stratified by soil texture class

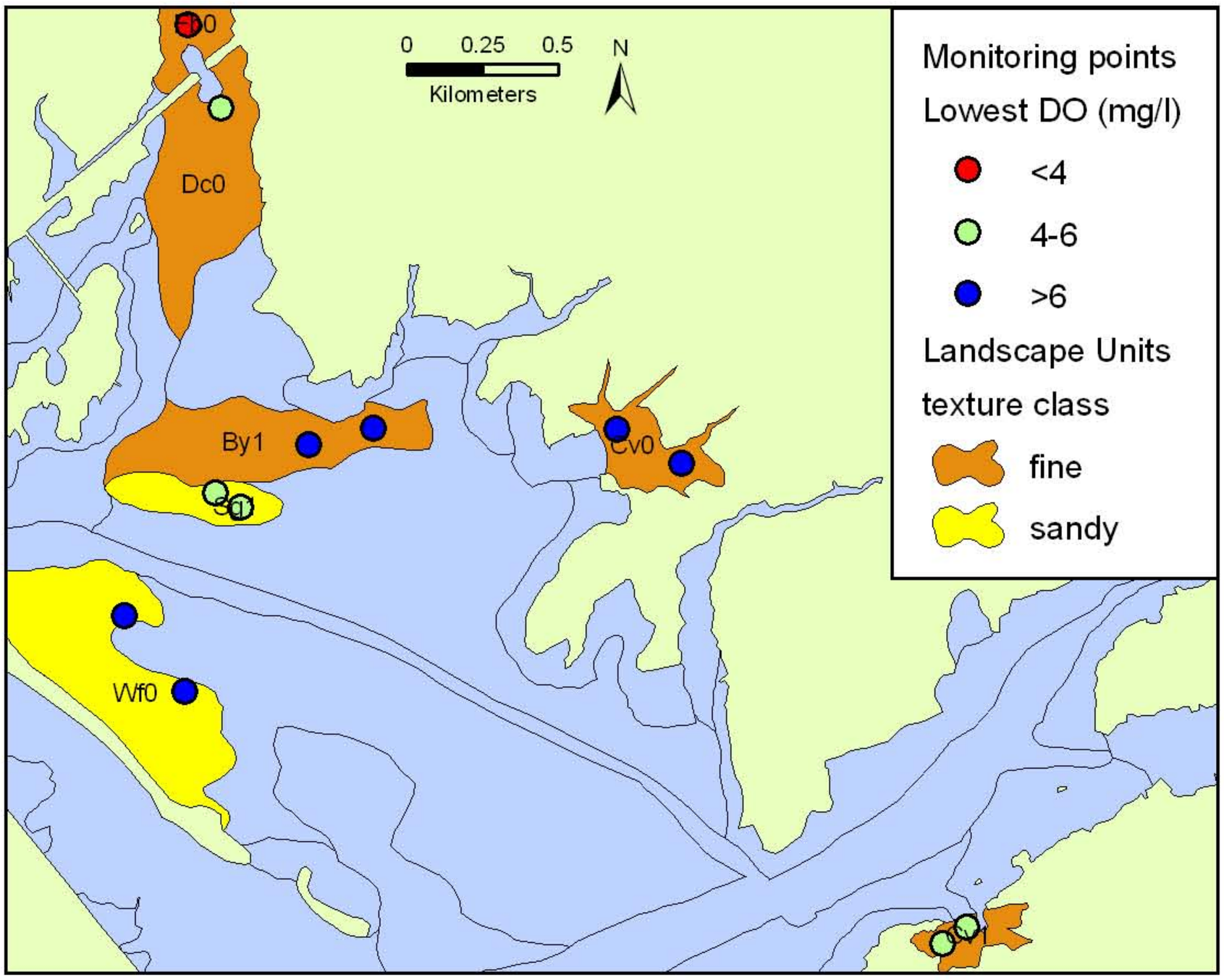

Figure 2.8. Lowest DO measurements recorded in Little Narragansett Bay stratified by soil texture class.

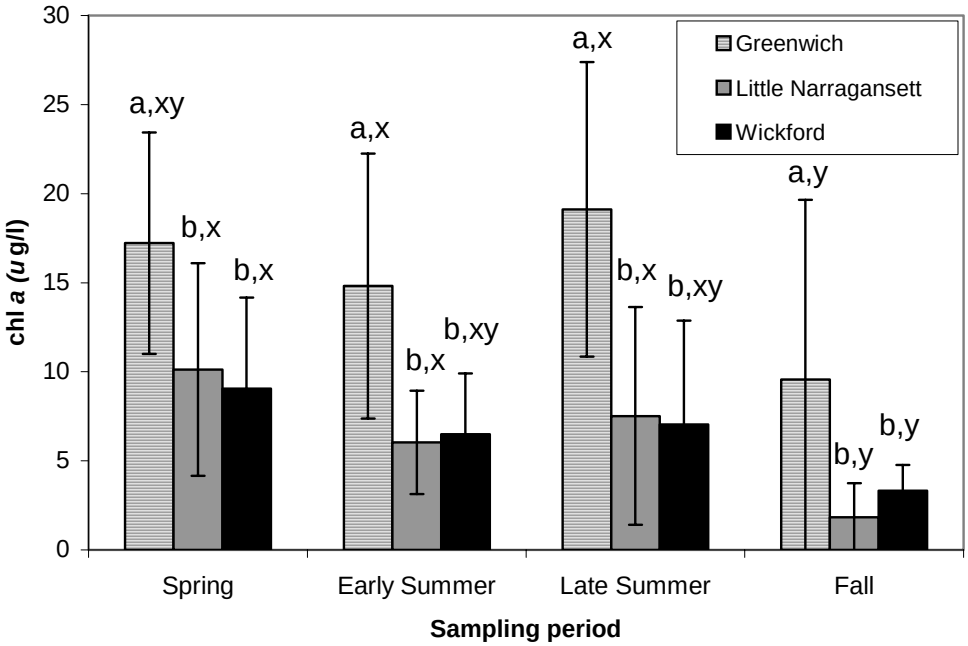

Figure 2.9. Chlorophyll *a* levels in the four sampling periods. Means with different letters are significantly different at the 0.05 level according to Tukey's HSD test. Comparisons among bays for the same sampling period use a,b, and c. Comparisons among sampling periods for the same bay use x,y, and z. Error bars represent standard deviations (WH n=14, LNB n=12, GB n=16 for each sampling period).

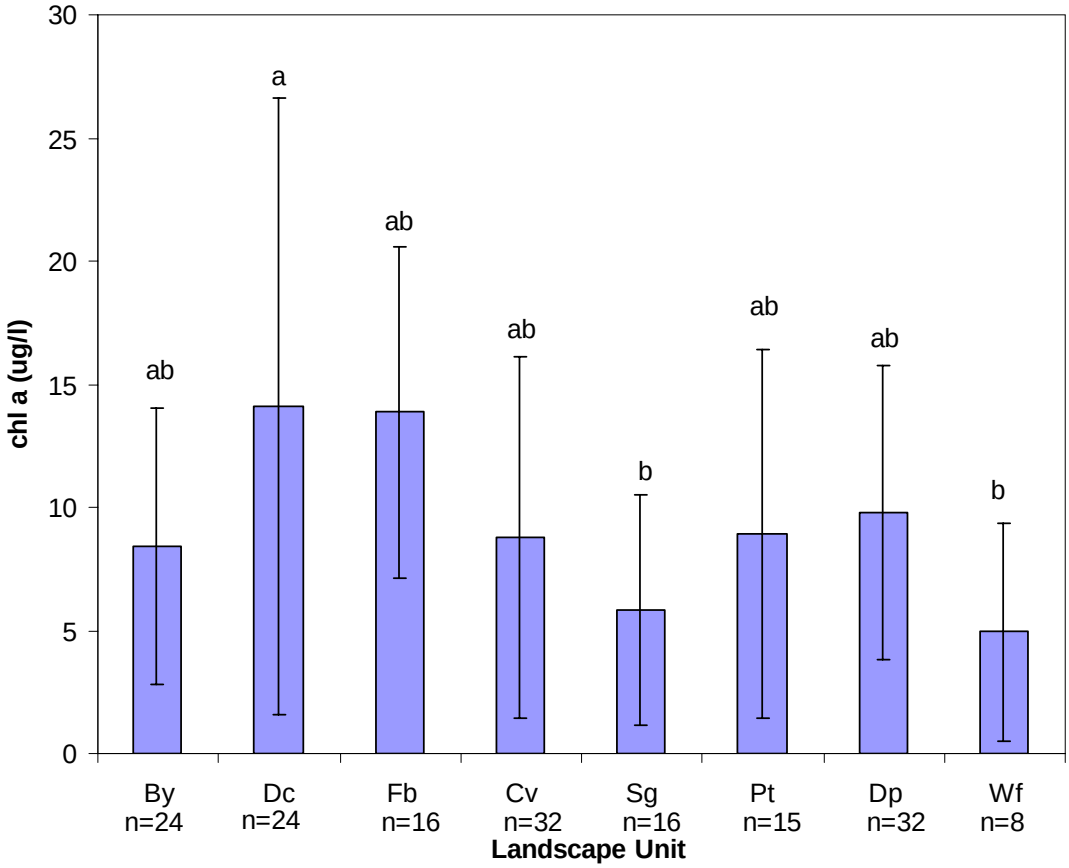

Figure 2.10. Average chl *a* levels in each landscape unit. Means with different letters indicate significant differences at the p=0.05 level. Error bars represent standard deviation. (By = Bayfloor, Dc = Drowned Channel, Fb = Fluviomarine Bottom, Cv = Cove, Sg = Shoal, Pt = Spit, Dp = Mainland Shoreface, Wf = Washover Fan)

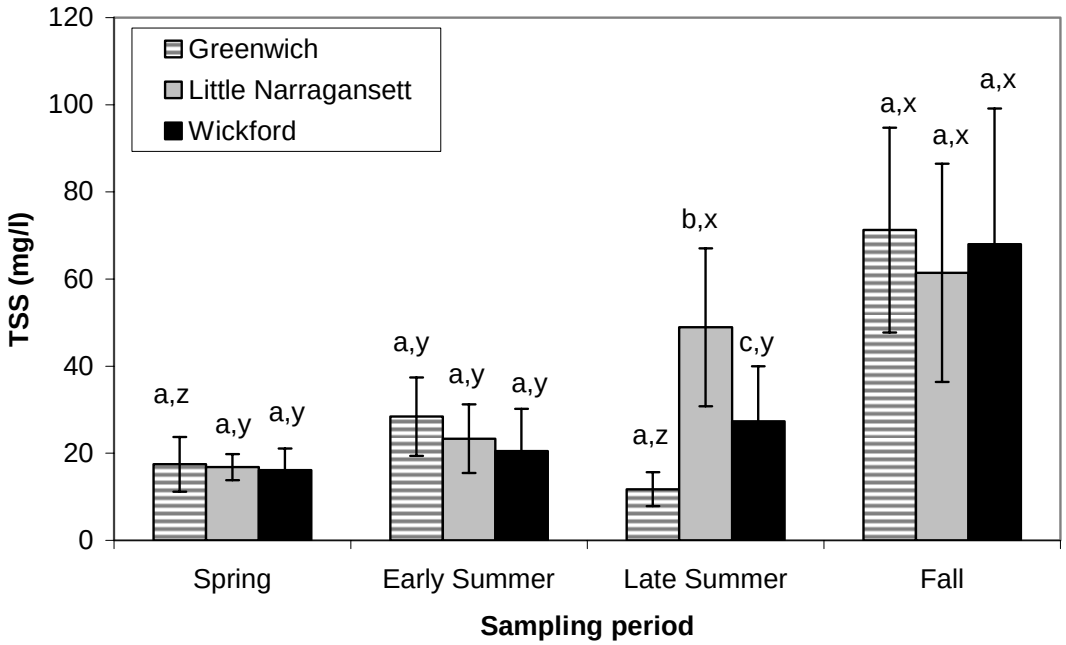

Figure 2.11. Mean TSS during each sampling period. Means with different letters are significantly different at the 0.05 level according to Tukey's HSD test. Comparisons among bays for the same sampling period use a,b, and c. Comparisons among sampling periods for the same bay use x,y, and z. Error bars represent standard deviation (WH n=14, LNB n=12, GB n=16 for each sampling period).

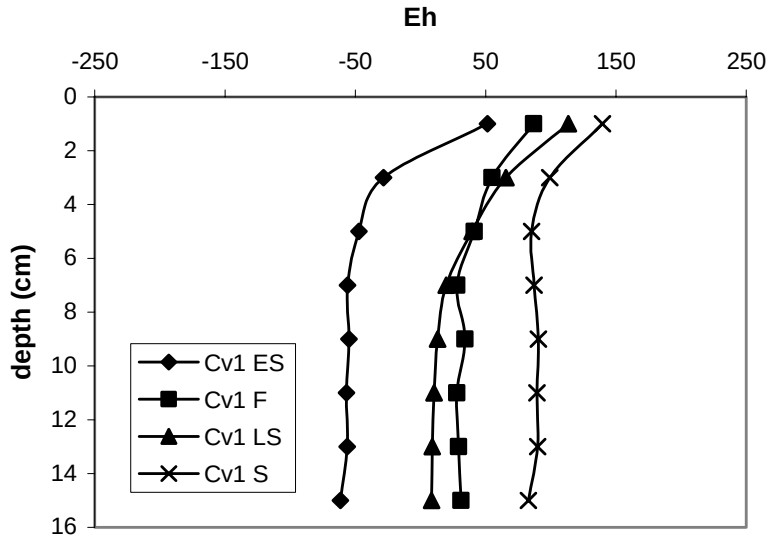

Figure 2.12. A typical redox curve for the top 15 cm of subaqueous soil in Little Narragansett Bay Cove landscape unit (sites LN01 and LN02). The highest curve occurred in the spring (S), while the lowest occurred in the early summer (ES). Fall (F) and late summer (LS) curves were very similar (n=4 for each sampling period).

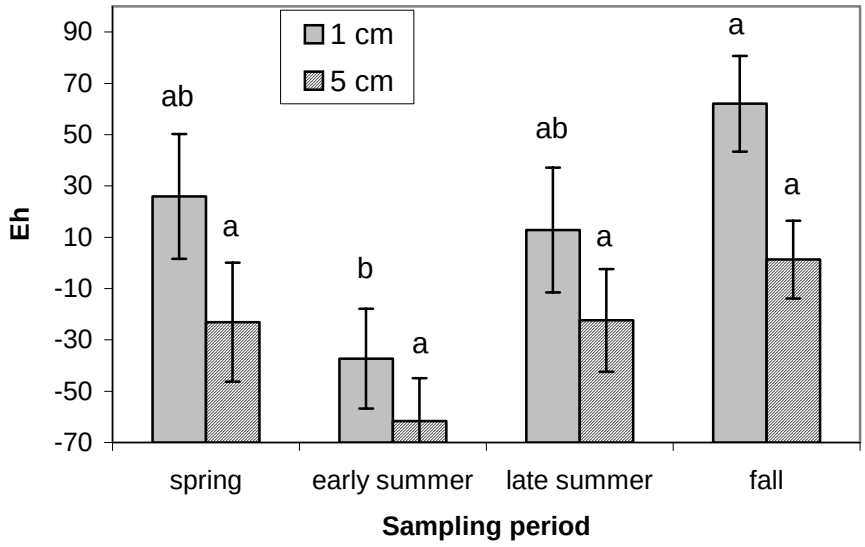

Figure 2.13. Redox potential measurements at the 1 cm and 5 cm depths in each sampling period for soft-bottom landscape units (Cv, By, Fb, and Dc). Measurements were compared among seasons within each sampling depth. Means with different letters are significantly different at the p=0.05 level. Error bars represent standard error (n=42 for each sampling period).

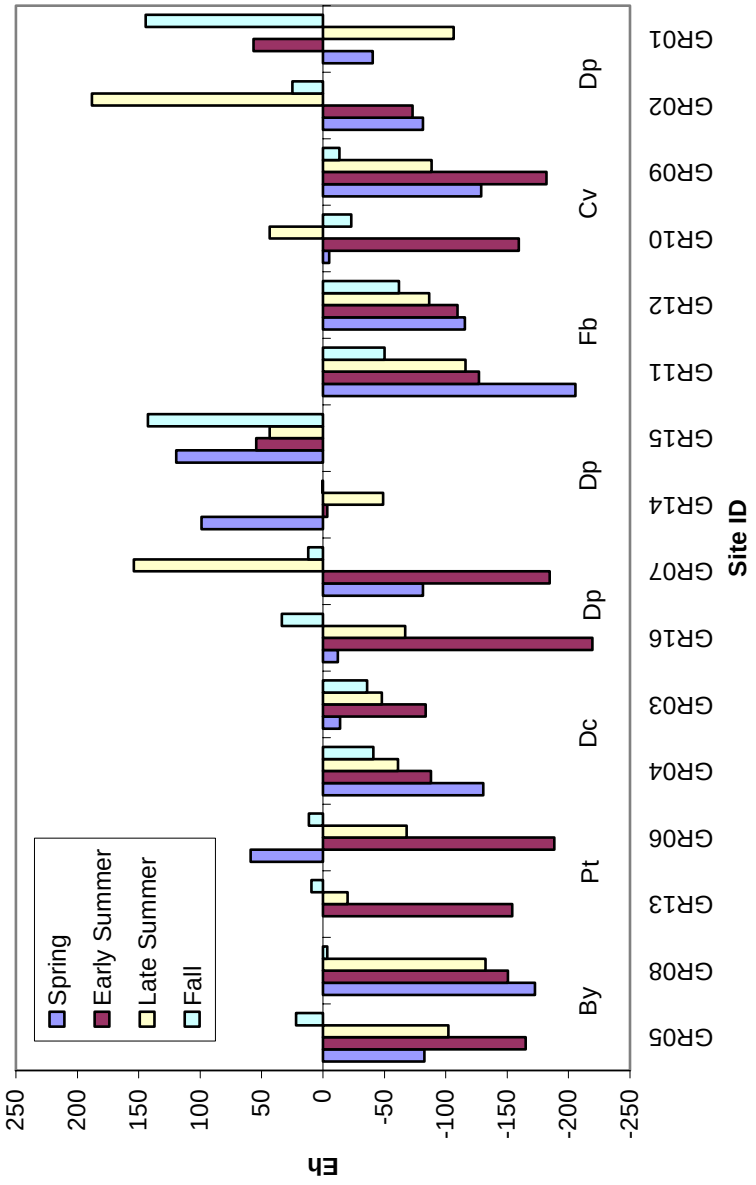

Figure 2.14. Seasonal averages of redox potential at 5 cm for each sampling site in Greenwich Bay (n=2 for each sample site).

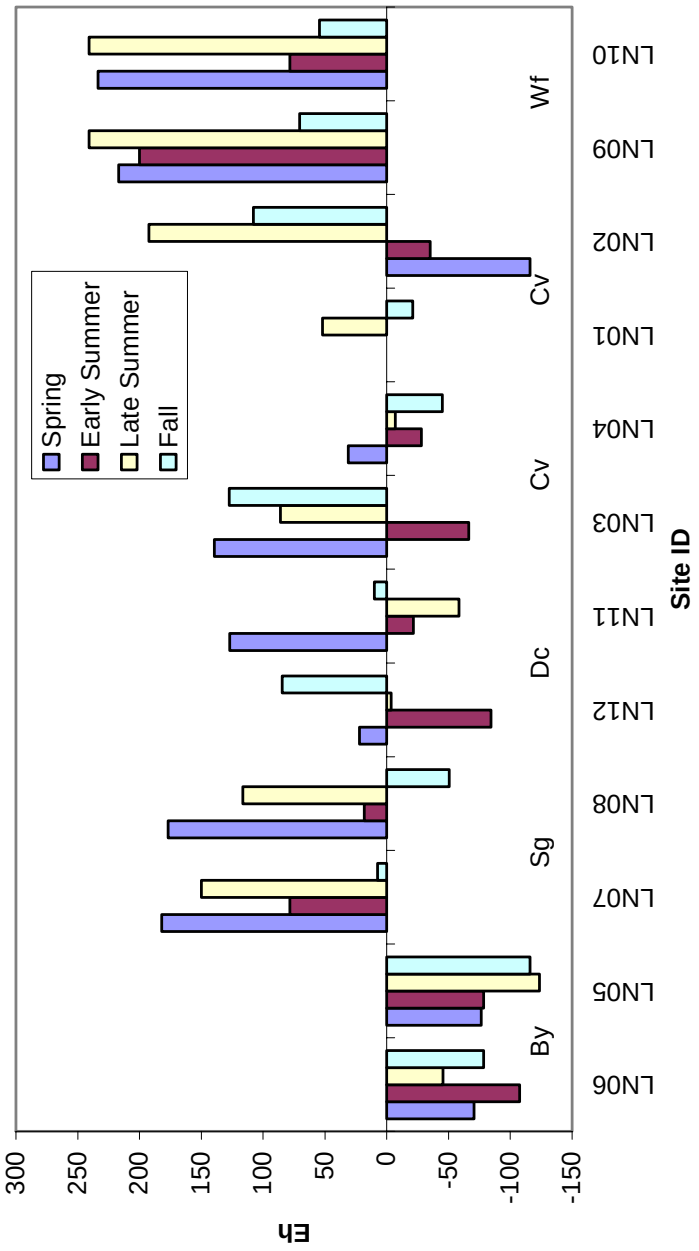

Figure 2.15. Seasonal averages of redox potential at 5 cm for each sampling site in Little Narragansett Bay (n=2 for each sample site).

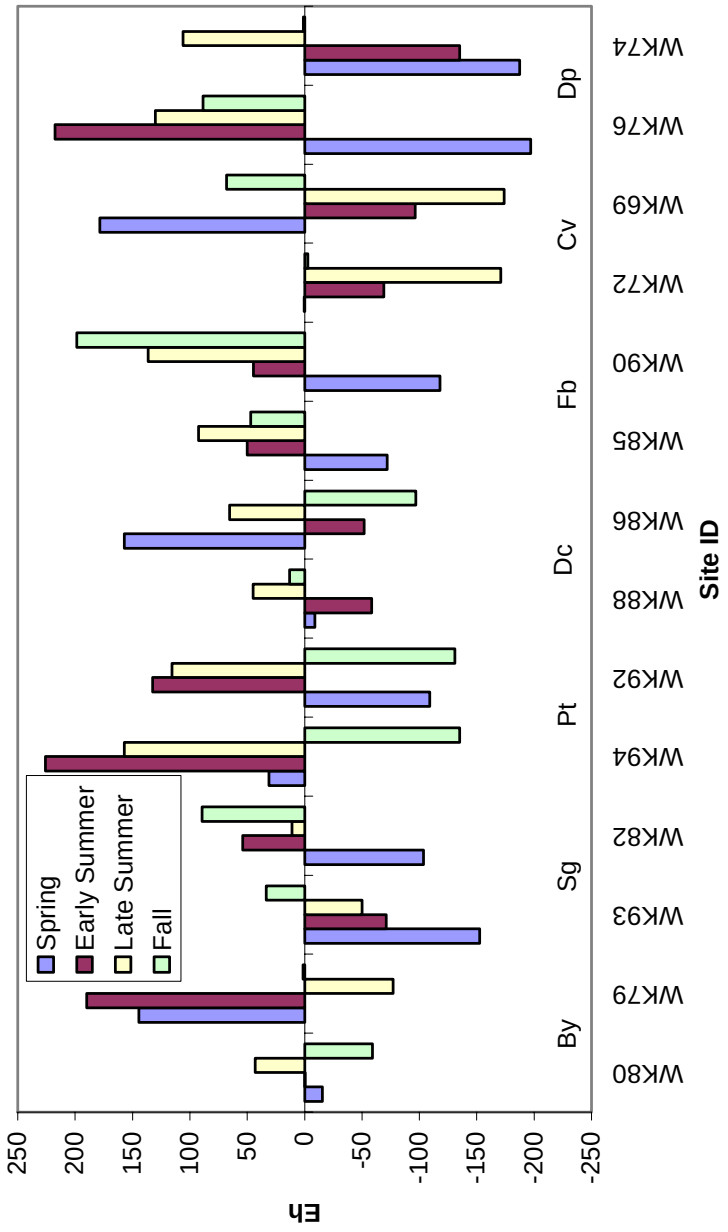

Figure 2.16. Seasonal averages of redox potential at 5 cm for each sampling site in Wickford Harbor (n=2 for each sample site).

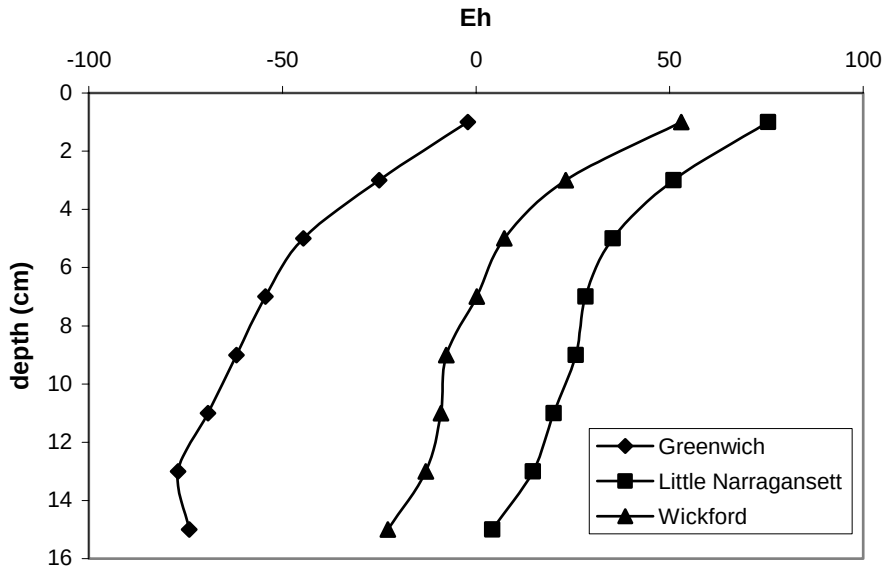

Figure 2.17. Average redox potential trends for each bay. Greenwich Bay has significantly lower Eh at 1 and 5 cm depths than both Little Narragansett Bay and Wickford Harbor (Tukey's HSD p=0.05, GB n=128, WH n=112, LNB n=96).

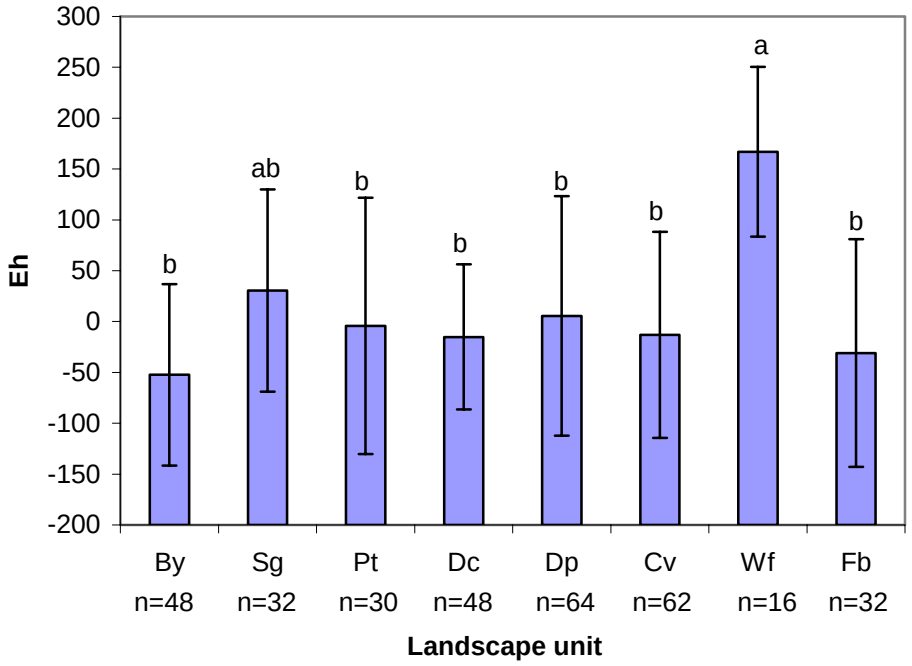

Figure 2.18. Redox potential (Eh) at the 5 cm depth for each landscape unit. Means with different letters are significantly different at the 0.05 level.

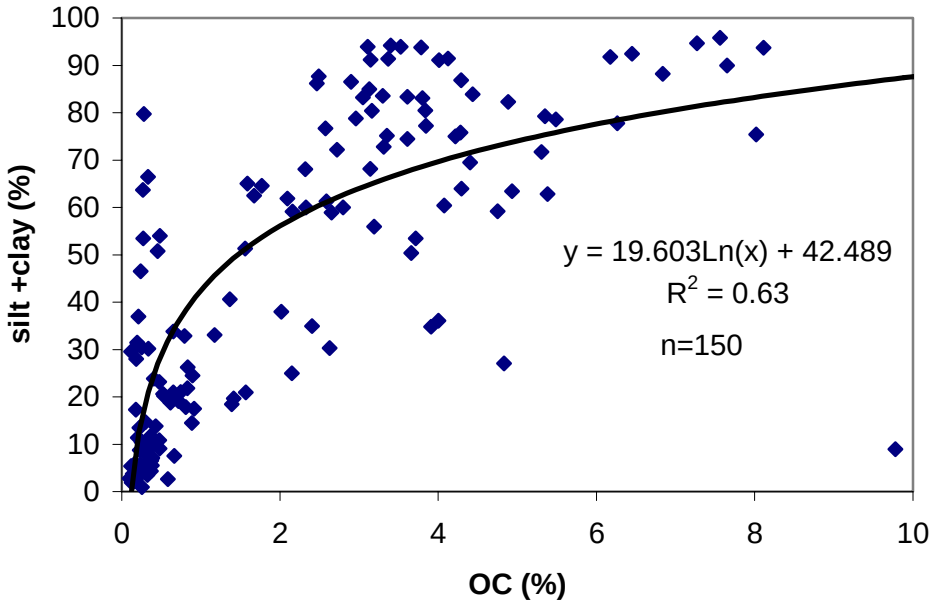

Figure 2.19. Percent organic carbon (OC) and silt + clay percent. Organic carbon content is highly related with percent fine particles (silt + clay) found in a soil sample. One outlier is likely sandy human transported material deposited on top of a highly organic soil (WK82).

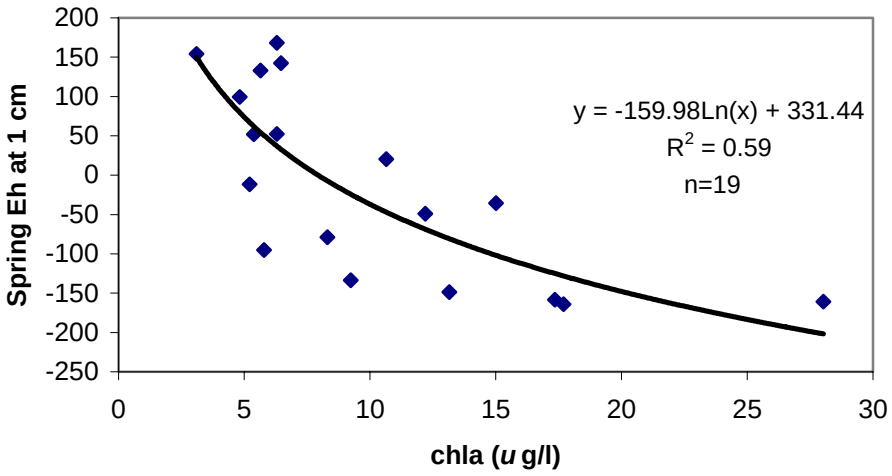

Figure 2.20. Redox potential (Eh) at 1 cm and chl *a* in low energy, depositional landscape units. A negative relationship was seen between redox potential (Eh) in the spring sampling period and average monitored chl *a* content on low energy, depositional landscapes.

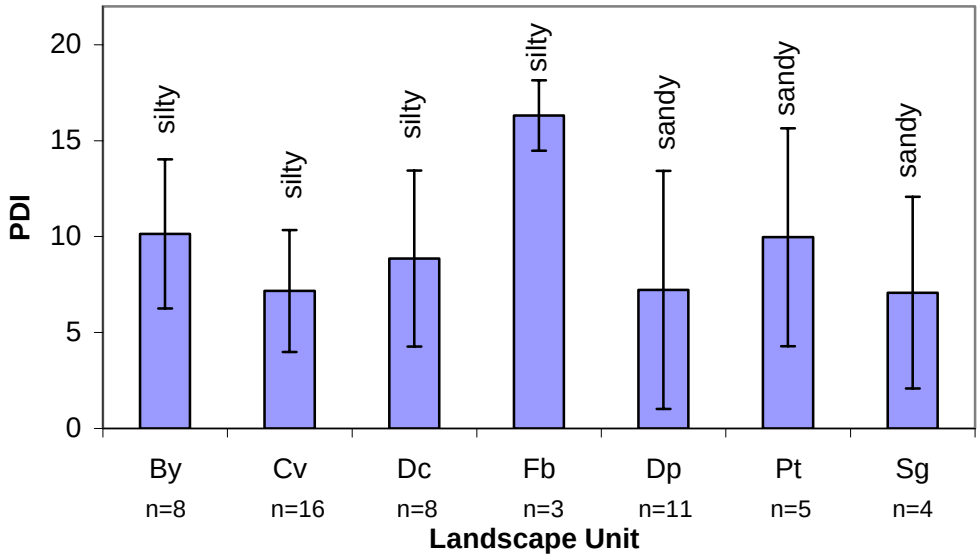

Figure 2.21. Distribution of PDI values among landscape units. There was no significant difference in PDI values among landscape units (p=0.15).

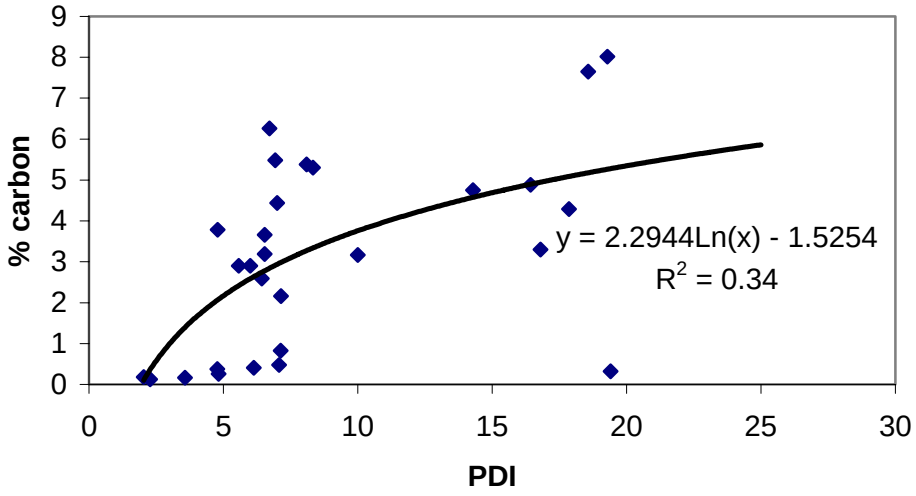

Figure 2.22. The relationship of PDI values and percent carbon. PDI has a slight positive relationship with % carbon in the surface horizon of the soils (n=30).

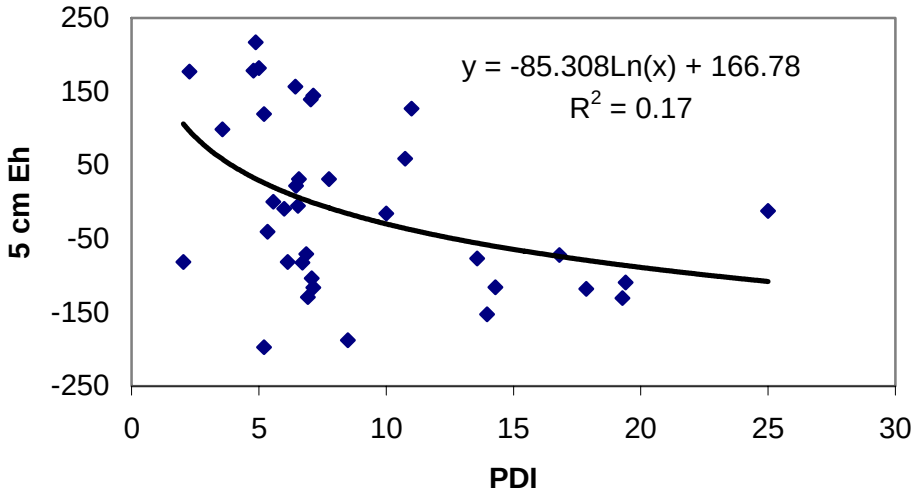

Figure 2.23. The relationship between PDI and spring Eh at the 5 cm depth. PDI is very slightly negatively related with redox measurements at the 5 cm depth in the spring (n=38).

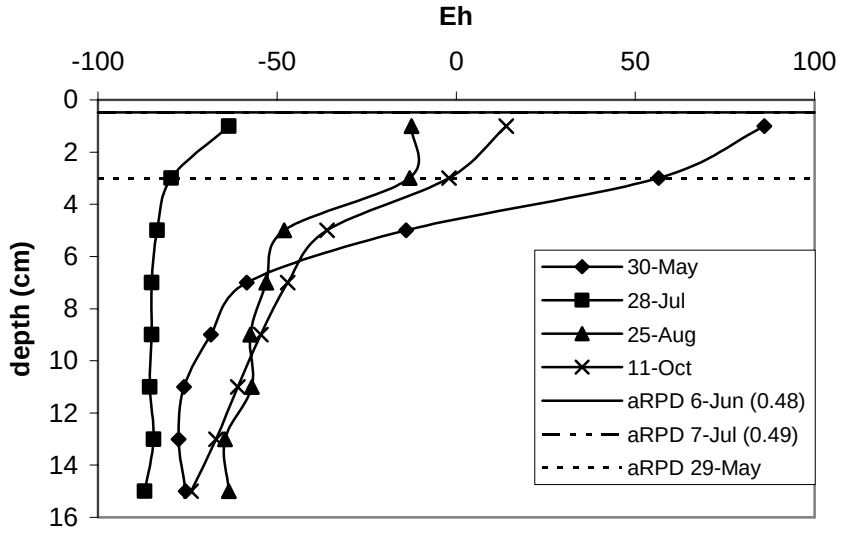

Figure 2.24. Redox potential profiles for Greenwich Bay site GR03 and corresponding aRPD depths measured with a SPI camera. Other SPI camera readings on August 2, August 31, and October 4 found no oxidized surface present.

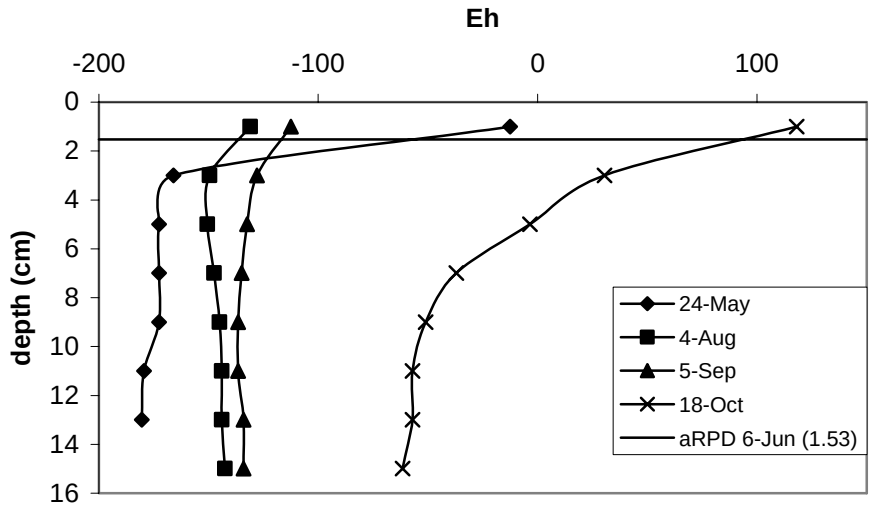

Figure 2.25. Redox potential profiles for Greenwich Bay site GR08 and corresponding aRPD depths measured with a SPI camera. SPI camera images taken on July 7, August 2, and August 31 found no oxidized surface present.

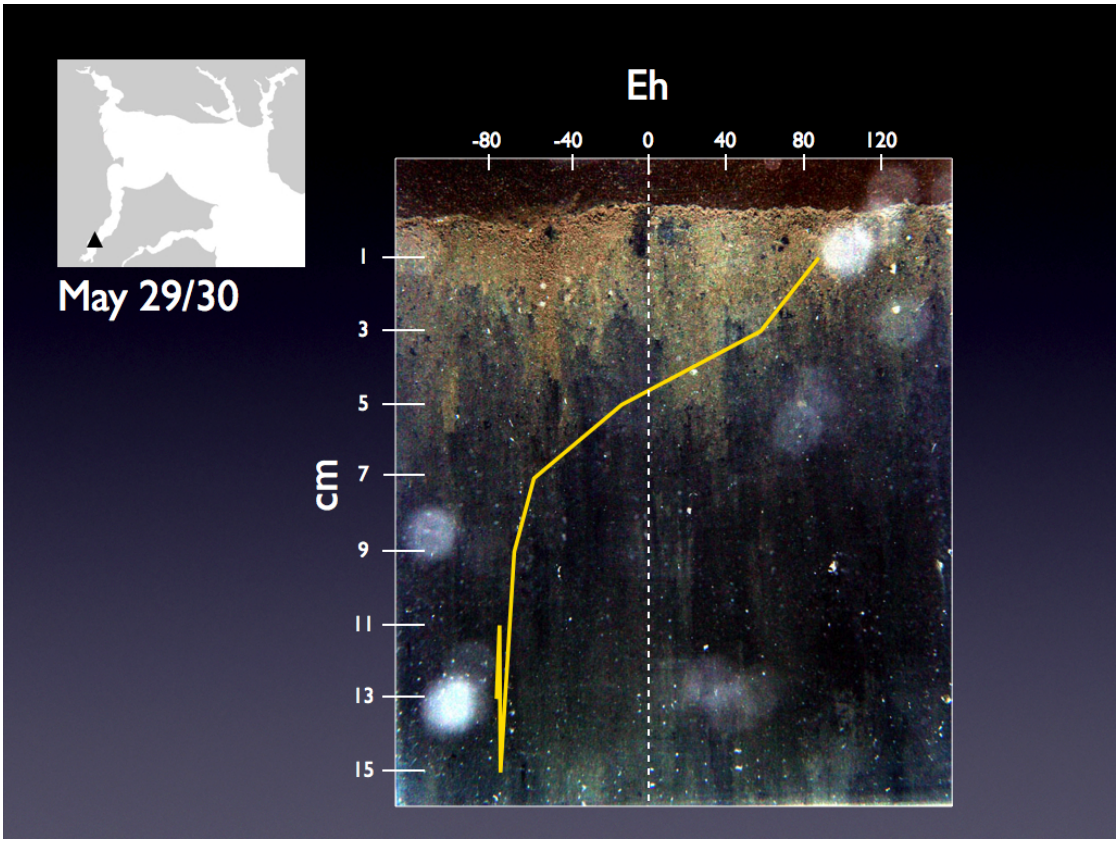

Figure 2.26. Sediment profile image of site GR03 with corresponding redox profile measured on May 29 and 30. The lighter colored oxidized surface has a higher Eh than the reduced dark colored soil material below.

CHAPTER 3:

SULFIDE DISTRIBUTION IN SUBAQUEOUS SOIL SYSTEMS

ABSTRACT

Sulfidization, or the accumulation of sulfides, is an important soil forming process in estuarine and marine soils. Sulfidic materials in subaqueous soil are important in determining areas ideal for growth of submerged aquatic vegetation and placement of dredged material. Prior to 1992, Soil Taxonomy defined sulfidic materials based on sulfide and $CaCO_3$ levels. The definition has since changed to a classification based on incubation pH measurements. The objectives of this research were to determine the distribution of sulfides in subaqueous landscapes and to evaluate sulfide levels in relation to other soil properties including carbon content, calcium carbonate content, soil texture, soil salinity, incubation pH, and soil salinity after oxidation with peroxide. Fifty-two soil samples from three shallow estuaries in Rhode Island were analyzed for acid volatile sulfides (AVS), chromium reducible sulfur (CRS), incubation pH, and salinity after oxidation with peroxide. Total sulfide measurements (CRS+AVS) ranged from 20 – 11592 μg g^{-1} with an average of 2965 μg g^{-1}. In most cases, CRS represented nearly 100% of the total sulfides measured. Nearly half of all samples measured (47%) had incubation pH readings ≤4.0. Only two out of 17 pedons (7 of 52 soil samples) contained sulfidic materials as previously defined by sulfide content, while incubation pH measurements showed 11 of 17

pedons (27 of 52 soil samples) to meet current criteria for sulfidic materials. Soils that reached an incubation pH ≤4 showed no significant difference in carbon content from those that had an incubation pH >4, and samples with higher incubation pH values had significantly higher levels of calcium carbonate than those with low incubation pH. Carbon content and particle size appear to be the two factors that were the most strongly related to the distribution of sulfides. Total dry weight of salts after oxidation with hydrogen peroxide showed a stronger relationship with total sulfides (R^2=0.70) than incubation pH (R^2=0.19). Sulfide content and incubation pH showed similar trends among landscape units with high sulfide levels, low incubation pH, and high carbon and calcium carbonate contents on low energy, silty landscape units.

INTRODUCTION

Sulfidization, or the accumulation of sulfides, is an important soil forming process in estuarine and marine soils (Fanning and Fanning, 1989). In these settings, sulfate, the second most common anion in seawater, is reduced to sulfide through the metabolism of sulfate-reducing bacteria in the subsurface anaerobic soil (Jorgensen, 1977; Day et al., 1989). Sulfide is most often trapped in the sediment by binding with metal ions such as Fe (Jorgensen, 1977). Sulfides in subaqueous soils are commonly classified as either acid volatile sulfide (AVS), consisting primarily of Fe monosulfide (FeS), or chromium reducible sulfur (CRS), in minerals such as pyrite (FeS_2) (Lasorsa and Casas, 1996).

The ratio of AVS to CRS is dependent upon many factors including percent soil organic matter, levels of dissolved sulfides, and availability of oxygen.

Monosulfides are transformed to pyrite only in the absence of air and in the presence of both dissolved sulfide and organic matter (Berner, 1970). In the presence of oxygen, pyrite can form directly from aqueous sulfate (Fanning and Fanning, 1989). The amount of organic carbon in sediments can be a limiting factor in the transformation of AVS to pyrite (Westrich and Berner, 1984). Higher CRS levels have been found in subaqueous soils with higher organic matter because of inputs from eelgrass (Holmer and Nielsen, 1997). Thus, in subaqueous environments, sulfide levels and the distribution of the two common forms of sulfide may be indications of organic matter levels or dissolved oxygen concentrations in the soil.

Sulfide content is important in many ecological, use, and management aspects of soils. For example, sulfides precipitate with a number of toxic metals, limiting the bioavailability of these metals (Griffin et al., 1989; Leonard et al., 1996). The sulfide content in subaqueous soils has been shown to have an impact on the suitability of the soil for eelgrass growth, with levels of total sulfide > 400 μM causing significant decreases in eelgrass productivity (Goodman et al., 1995). At levels below this cutoff, eelgrass coverage has been shown to have a positive relationship with AVS concentrations (Bradley and Stolt, 2006). Sulfide content of soils is also important when considering marine construction and dredging projects. If sulfide bearing subaqueous soils are dredged and placed in a subaerial environment, sulfides will oxidize, creating sulfuric acid, drastically lowering soil pH, and resulting in acid sulfate soils (Fanning and Fanning, 1989). Acid sulfate soils may persist for a number of years and are uninhabitable for plants and animals. If deposited near water, these

acid sulfate soils can also create runoff that is toxic to aquatic systems (Demas et al., 2004).

Potential acid sulfate soils are identified based on the presence of sulfidic materials at a shallow depth (Fanning and Fanning, 1989). Prior to 1992, Soil Taxonomy (Soil Survey Staff, 1990) defined sulfidic materials as:

> waterlogged mineral or organic soil materials that contain 0.75 percent or more sulfur (dry weight), mostly in the form of sulfides, and that have less than three times as much carbonate ($CaCO_3$ equivalent) as sulfur.

In 1992 (Soil Survey Staff, 1992) the definition of sulfidic materials was changed to those materials that:

> contain oxidizable sulfur compounds, and are mineral or organic soil materials with a pH value of more than 3.5 which, if incubated as a layer 1 cm thick under moist aerobic conditions (field capacity) at room temperature show a drop in pH of 0.5 or more units to a pH value of 4.0 or less within eight weeks.

The reason why the definition of sulfidic materials was changed is unclear. One reason to change the definition of sulfidic materials is that incubation pH or potential acidity measurements are much easier to perform than sulfide analysis. Measurements of monosulfides and pyrite can be made in the laboratory by determining amounts of sulfide gas produced when soil is reduced with acid or chromium (Brouwer and Murphy, 1994) and takes a considerable amount of effort.

Incubation pH provides a direct indication of natural formation of acidic conditions (USDA-NRCS, 2007). These values may be deceiving, however, as additional factors such as the buffering capacity, rate and extent of acid production, weathering, and leaching due to environmental factors are not considered in this approach. For example, in a moist incubation, a small amount of sulfide would lower the pH in a sandy soil with low organic carbon because of the limited amount of

buffering capacity. In such soils, the amount of acid produced would be much less than a soil with a similar incubation pH but a higher buffering capacity because of a finer texture or greater organic matter levels. In a natural setting, a small amount of acid could potentially leave a sandy, minimally buffered soil very quickly as the acidity generated by oxidation would be washed out of the system as a result of precipitation and leaching. In contrast, acid sulfate conditions may remain for years in a fine-textured, buffered soil. Thus, a sandy soil may not remain an acid sulfate soil very long relative to a soil with a similar incubation pH but more extensive acid production.

In subaqueous soil mapping it would be beneficial to be able to predict sulfide levels based on landscape unit or soil physical properties and to have relatively simple field or lab tests that could estimate the amount of the various forms of sulfide in a soil. The objectives of this section of my thesis were: i) to assess the distribution of concentrations of AVS and CRS in subaqueous soils; ii) to evaluate the value of incubation pH measurements and oxidized salinity as indications of sulfide concentrations; and iii) to determine if relationships exist between sulfide concentrations and various soil properties (salinity, particle size, soil organic carbon, and calcium carbonate contents).

MATERIALS AND METHODS

Soil samples were collected in selected landscape units using a Macaulay peat sampler or vibracore (See Chapter 1, Figures 1.8, 1.9, and 1.10). Vibracores were sealed on both ends and stored in the refrigerator until they could be cut and sampled.

Vibracore samples were immediately placed in plastic bags and frozen. Samples from the Macaulay were placed in plastic bags with most air removed, sealed, and put on ice until returning to the lab where they were frozen until they could be analyzed.

The first indication that sulfide is present in a soil sample is the hydrogen sulfide or "rotten egg" odor associated with strongly reduced soils. The presence and strength of the hydrogen sulfide odor was recorded in the field for the soils (Appendix 1; Schoeneberger et al., 2002).

Laboratory analysis of acid volatile sulfides (AVS) and chromium reducible sulfur (CRS) was carried out on 52 samples that covered a range in incubation pH, particle size, organic carbon content, and calcium carbonate content. Sulfide extraction was done according to the diffusion method and sulfides were trapped in a sulfide antioxidant buffer (SAOB) (Fossing and Jorgensen, 1989; Brouwer and Murphy, 1994; Ulrich et al., 1997; Boothman, 1998; Bradley and Stolt, 2006). One gram of frozen soil was added to 150 ml serum bottles that contained a 10 x 75 mm vial containing 3 ml SAOB. Bottles were immediately filled with N_2 gas and stoppered. A second set of samples were weighed and dried overnight in a 105 ˚C oven to determine dry weight. Soils were reacted with 12 ml of O_2-free 2N HCl added with a syringe to the sample bottle. Bottles were rotated for one hour at 150 rpm, after which SAOB traps were removed for analysis. A second SAOB trap was inserted into the same bottle. The bottle was purged of O_2 with N_2 gas and reacted with 4 ml of O_2-free 12N HCl and eight ml of Cr^{2+} added with a syringe. The Cr^{2+} solution was prepared by adding 1M $CrCl_3 \cdot H_2O$ in 0.5N HCl to a modified Jones Reductor built from a separatory funnel filled with mossy Zinc and a glass wool filter (Fossing and

Jorgensen, 1989). Bottles were rotated at 150 rpm for 20 hours and SAOB traps were removed for CRS analysis. Concentrations of AVS and CRS in the SAOB traps were determined using a silver/sulfide ion specific electrode standardized to known concentrations of sulfide in $Na_2S \cdot 9H_2O$ and SAOB solutions (Thermo Electron, 2003). Sulfide concentrations were determined as μg sulfide per g dry soil.

Incubation pH was measured on all horizons sampled. Approximately 10 g of frozen sample was placed in 25 ml beakers and mixed with DI water to make a 1:1 by volume soil to water mixture. Soil pH was measured using an Accumet pH probe immediately after thawing, each day for the first two weeks, and then once per week for two months. Final pH measurements were defined as those made after eight weeks of incubation (incubation pH). Samples were stirred periodically in order to prevent the accumulation of salts on the beaker glass. Deionized water was added when needed to keep samples moist during incubation (Soil Survey Laboratory Staff, 2004).

Salinity measurements were carried out using an Oakton WD-35607 hand-held conductivity meter using the saturated paste method (Soil Survey Laboratory Staff, 2004). Immediately after removal from the freezer, samples were thawed and water was added to make a saturated paste. After overnight refrigeration, water was extracted from samples by vacuuming through a glass-fiber filter and the salinity of the extracted water was measured. The residual salinity samples were treated with 30% H_2O_2 in order to oxidize and remove organic matter (Soil Survey Laboratory Staff, 2004). Salinity was measured again for the same samples after this treatment. Dry weight of salt present in samples after treatment with peroxide was calculated as:

$$\text{salt (ppt)} = (\text{salinity}_E \cdot H_2O_E/\text{weight}_S)$$

in which $salinity_E$ = salinity in ppt of water extracted from saturated paste, H_2O_E = ml of water extracted from saturated paste, and $weight_S$ = dry weight of soil after treatment with H_2O_2.

Statistical analyses were carried out using JMP IN and Excel software (SAS, 2003; Microsoft, 2003). Single factor ANOVA and Tukey's HSD test were carried out to determine differences in total sulfides and pH among landscape units. Incubation pH values were grouped based on rate of change in pH. Soil properties were compared among the groups using single factor ANOVA and Tukey's HSD test. Samples that qualified as sulfidic materials were compared to those that did not using a t-test. A variance-covariance matrix and p-values were produced based on standardized data and principal components were determined using JMP IN software (SAS, 2003). Correlation values and best-fit lines were determined in Excel.

RESULTS AND DISCUSSION

A descriptive approach to determining if sulfides are present in a soil is the identification of hydrogen sulfide odor. Hydrogen sulfide was recognized for most horizons as indicated by a slight, moderate, or strong odor (Appendix 1). This approach provides some indication of the quantity of reduced sulfur in the soil, but consistent and accurate determinations of odor strength is difficult because olfactory fatigue makes the hydrogen sulfide odor much less potent after extended exposure. For this reason, more sophisticated laboratory methods of sulfide determination are required.

Total sulfide measurements (CRS+AVS) ranged from 21 – 11592 μg g^{-1} with an average of 2965 μg g^{-1} (Appendix 5). CRS measurements ranged from 21 – 11591 while AVS ranged from 0 - 442 μg g^{-1}. In most cases, CRS represented nearly 100% of the total sulfides (TS) measured, with an insignificant amount of AVS. Previous studies (Bradley and Stolt, 2003) found higher AVS and lower CRS concentrations in subaqueous soils than I found in this study. High levels of CRS, or pyrite, in a soil sample are often indicative of anoxic conditions that promote the transformation of monosulfides to pyrite (Berner, 1970; Boothman, 1998). The high ratios of CRS: AVS in the samples in my study may be due to the anoxic conditions in the majority of the soils.

Initial soil pH values ranged from slightly acidic to slightly alkaline (6.52 to 8.41), with an average of 7.55 (n=178). Nearly half of all horizons (47%) had incubation pH readings ≤4.0 (Figure 3.1). A majority (80%) of samples contained enough reduced sulfur to lower the pH to ≤6.0 within eight weeks of incubation (Appendix 1). In some soils, all horizons contained sulfidic materials, while in others only one horizon had a significant drop in pH (Figures 3.2 and 3.3).

Sulfide distribution is in part a function of landscape unit and soil texture. Significantly higher levels of TS were measured in soils found in Cove landscape units with lower levels found on Mainland Shoreface and Spit units (Figure 3.4). Soil texture also influenced the amount of sulfide measured with lower TS levels found in soils with higher sand contents (R^2=0.67; Figure 3.5). A significant difference was seen in incubation pH among landscape units. High energy, sandy units had higher

incubation pH values than low energy units (Figure 3.6). The strong relationship with sand content that was seen for TS content was not seen for incubation pH (Table 3.1).

The two traditional methods of identifying sulfidic materials (sulfide measurement and incubation pH) showed very different results. Only two out of 17 pedons (7 of 52 soil samples) contained enough sulfides to meet the definition of sulfidic materials under the 1990 criteria (Soil Survey Staff, 1990). Eleven of 17 pedons (27 of 52 soil samples) described and analyzed had at least one horizon within 100 cm of the surface with incubation pH ≤4.0 that would qualify as sulfidic materials using the current definition (Soil Survey Staff, 2006). If these two methods of analysis measure the same soil properties, incubation pH and TS content should be highly correlated. These two measurements, however, are only slightly correlated (R^2 = 0.19; Figure 3.7). This discrepancy indicates that there are other factors that impact incubation pH in addition to amount of sulfides present.

Of those soils that showed a drop in pH, some samples showed consistent drops every week, while others had a very rapid decline in the first two weeks, followed by a gradual drop or leveling off of pH values in the following weeks (Figure 3.8). Other samples showed little or no change in pH over the eight week incubation. In subaerial soils, soil organic matter is known to act as a pH buffering agent, reducing the change in soil pH when acids or bases are added to the soil (Bailey et al., 1989; Curtin et al., 1996; Weaver et al., 2004). In a similar manner, I expected carbon to buffer the acidity formed during oxidation and to slow down the rate of acidification. No significant difference, however, was seen in carbon levels between those samples that reached a pH ≤4 and those with an incubation pH >4 (Figure 3.9).

Calcium carbonate is another material that has the potential to neutralize acidity (Brady and Weil, 2002). In subaerial environments, $CaCO_3$ is often applied to acidic soils through liming in order to raise the pH. Large amounts of $CaCO_3$ are often present in subaqueous soils (in general 5-10 times more $CaCO_3$ was measured than TS, Appendix 5). Despite the high $CaCO_3$ levels, samples with incubation pH values ≤ 4 had significantly higher levels of $CaCO_3$ than those with incubation pH values >4 ($t<0.05$; Figure 3.9). In these subaqueous soils, the carbonates consist of shell fragments, many of which are large fragments (>2 mm). The reactivity of $CaCO_3$ has been shown to be dependent on the particle size of the carbonates (Dobson et al., 1983; Scott et al., 1992). The large size of shell fragments may be the reason that $CaCO_3$ in these soils appears not to neutralize the acidity formed in oxidized soil samples.

Initial salinity of saturated paste extracts ranged from five to 69 with a mean of 32 mS. Saturated paste salinity after oxidation with hydrogen peroxide ranged from two to 238 with a mean of 57 mS (Appendix 1). The mean salt content of peroxide oxidized samples calculated as ppt of dry soil weight (dry salt content) ranged from 0.1 to 62.8 with a mean of 6.6 ppt (Appendix 5). Oxidation with hydrogen peroxide is a method used to speed up the naturally occurring, bacteria-mediated oxidation process, to quickly oxidize all reduced species present in a soil sample (McElnea, 2002). In order to assess the difference in oxidation with peroxide and moist-incubation oxidation, the salinity of eight samples was measured after peroxide oxidation as well as after eight weeks of moist incubation oxidization. The salinity values of moist incubation samples were greater than initial salinity and not

significantly different from salinity after oxidization with peroxide (t=0.5; Figure 3.10), indicating that peroxide oxidation and bacteria-mediated moist incubation results in a similar end result.

When sulfide becomes oxidized, sulfate salts form, often in association with Fe. These Fe-sulfate salts can be seen as a white (rozenite) or yellow (copiapite) precipitate when present in high concentrations (Fanning and Fanning, 1989). Salts raise the conductivity of the soil sample and are measured as an increase in salinity. The change in saturated paste salinity with peroxide oxidation correlated with TS content of soils (R^2=0.28), however, a large amount of the variation in saturated paste, peroxide oxidized salinity was not explained by the amount of sulfides in the soil samples (Figure 3.11). By calculating the total dry weight of salts (dry salt content) after peroxide oxidation, a much greater correlation was seen between TS content and dry weight of salts after oxidation (r=0.83, p<0.001; Figure 3.11). The intention of the saturated paste extract approach to measuring salinity is to measure the amount of salts that go into solution at a given relative moisture content (saturation). Soils with greater water holding capacities result in less concentrated salinity values than those soils that can hold more water at saturation. Thus, measuring salts on a dry weight basis is much more indicative of the actual amount of salt present in a soil sample.

Although a significant correlation was observed between incubation pH values and TS content (r=-0.37, p=0.02), this correlation was not as strong as those observed for other variables (Table 3.1). A much stronger correlation was seen between TS content and dry salt content after peroxide oxidation (r=0.83, p<0.001; Figure 3.11). A stepwise linear regression model of the factors measured as indications of total

sulfide content (AVS, dry salt content, change in salinity with peroxide oxidation, and incubation pH) showed that dry salt content after peroxide oxidation was the most predictive measure of sulfide content.

Total sulfide level was significantly correlated to five of six physical soil properties assessed, although many variables were collinear (Table 3.1). Carbon content was highly correlated with TS ($r=0.83$, $p<0.001$; Figure 3.12). This correlation is consistent with previous studies that have shown carbon to be a limiting factor in the development of pyrite in subaqueous soils and sediments (Berner, 1970). Studies in Long Island Sound have shown that sulfate reduction is in direct proportion with amount of planktonic carbon added to a soil (Westrich and Berner, 1984). Carbonate content also has a strong correlation with percent carbon ($r=0.97$, $p<0.001$), which may account for the significant correlation between $CaCO_3$ and TS levels ($r=0.88$, $p<0.001$). Bradley (2001) found a similarly strong correlation between carbon and $CaCO_3$ contents.

Two principal components accounted for 87% of the variance in the six physical soil properties measured. The first principal component was strongly loaded (68%) by soil texture (sand, silt, and clay contents), carbon, and calcium carbonate content (Table 3.2). Salinity (saturated paste before peroxide treatment) was the strongest loading for the second principal component. The first principal component is closely related to TS content ($R^2=0.77$, $p<0.001$; Figure 3.13). The strong relationship of TS with these physical variables is an indication that sulfide content could be predicted based on a combination of physical variables including soil texture, carbon, and calcium carbonate content.

IMPLICATIONS

Sulfide distribution is an important factor when assessing the use and management of subaqueous soils. For example, a relationship of sulfide content with landscape unit allows interpretations of potential acid sulfate soils as well as suitability for eelgrass habitats to be made based on landscape unit type. Carbon content and particle size appear to be the two factors that most influence the distribution of sulfides in these soils. Sandy materials were found to be less likely to contain considerable amounts of sulfides than finer textured soils. Thus, the disposal of dredged material into an oxidizing environment from landscape units dominated by sandy materials could be done with far less concern for acid sulfate formation than disposal of dredge material from landscape units dominated by finer textured soil materials.

Although incubation pH is a simple determination of the acidity formed in a laboratory environment, this approach may not be the best method to decide the potential for acid sulfate soil formation in a natural environment. One reason is that incubation pH is influenced by more factors than just the sulfide content of the soils. Typically calcium carbonate acts to neutralize acidity in the soil. I found, however, that in these subaqueous soils, calcium carbonate levels were highest in the soils with the highest sulfide and potential acidity levels. This is a significant observation and suggests that the forms of carbonate present in subaqueous soils may not be reactive enough to neutralize acidity generated from oxidizing sulfides. This needs further investigation.

In addition to incubation pH, other parameters can be measured to assist in determination of sulfidic materials, including the total salts generated upon oxidation with peroxide. This approach closely reflects the amount of total sulfides present in a soil sample and may be a method of estimating sulfide content. Measurements of total salts made after peroxide oxidization related well with the amount of sulfides present. Complete oxidation of sulfides using hydrogen peroxide appears to be a valid method to quickly assess relative levels of reduced sulfur in a soil sample.

Table 3.1. Correlation matrix of sulfide contents and factors related to sulfide content. Correlations significant to the p=0.05 level are indicated in bold print (n=52).

		salts (ppt)†	Carbon‡	$CaCO^3$‡	Sand‡	Silt‡	Clay‡	AVS†	CRS†	TS†	incubation pH†	salinity change†	initial salinity‡
salts (ppt)		1.00											
	sig.												
Carbon		**0.87**	1.00										
	sig.	***<0.001***											
$CaCO^3$		**0.88**	**0.97**	1.00									
	sig.	***<0.001***	***<0.001***										
Sand		**-0.82**	**-0.80**	**-0.84**	1.00								
	sig.	***<0.001***	***<0.001***	***<0.001***									
Silt		**0.76**	**-0.77**	**0.78**	**-0.96**	1.00							
	sig.	***<0.001***	***<0.001***	***<0.001***	***<0.001***								
Clay		**0.73**	**0.65**	**0.72**	**-0.80**	**0.60**	1.00						
	sig.	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***							
AVS		0.19	0.24	0.18	-0.23	0.20	0.21	1.00					
	sig.	0.23	*0.09*	*0.19*	*0.11*	*0.15*	*0.14*						
CRS		**0.83**	**0.82**	**0.83**	**-0.81**	**0.73**	**0.76**	0.04	1.00				
	sig.	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	*0.06*					
TS		**0.83**	**0.83**	**0.85**	**-0.85**	**0.79**	**0.78**	*0.78*	**0.99**	1.00			
	sig.	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	*0.06*	***<0.001***				
incubation pH		**-0.37**	-0.25	-0.23	0.23	-0.22	-0.17	0.17	**-0.29**	**-0.31**	1.00		
	sig.	**0.02**	*0.07*	*0.10*	*0.10*	*0.11*	*0.22*	*0.23*	***<0.001***	***<0.001***			
salinity change		**0.61**	**0.66**	**0.60**	**-0.51**	**0.48**	**0.41**	0.02	**0.53**	**0.54**	**-0.36**	1.00	
	sig.	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.01***	*0.89*	***<0.001***	***<0.001***	***<0.001***		
initial salinity		0.25	**0.33**	**0.34**	-0.20	0.22	0.08	0.16	0.11	0.12	-0.07	-0.10	1.00
	sig.	*0.11*	***0.02***	***0.01***	*0.16*	*0.11*	*0.58*	*0.25*	*0.42*	*0.41*	*0.64*	*0.48*	
pH change		**-0.34**	**-0.40**	**-0.33**	0.20	-0.14	-0.26	-0.06	-0.27	-0.29	**0.59**	**-0.46**	0.07
(2 wk)	*sig.*	**0.04**	***<0.01***	***0.02***	*0.16*	*0.32*	*0.06*	*0.65*	*0.06*	*0.06*	***<0.001***	***<0.001***	*0.59*

Salts ppt=dry weight of salts measured after peroxide oxidation; salinity change=difference in saturated paste salinity after peroxide oxidation; pH change (2 wk)=change in pH after the first two weeks of incubation

†factors compared as sulfide analysis procedures.

‡ factors compared as physical soil properties indicative of sulfide content.

Table 3.2. Principal components and rotated factor loadings for physical variables related to sulfide content.

Variable	PC1	PC2
Organic Carbon	0.89	0.30
Calcium Carbonate	0.91	0.29
Sand	-0.97	-0.07
Silt	0.90	0.14
Clay	0.85	-0.09
Salinity	0.11	0.98
Variation Explained	**68%**	**19%**

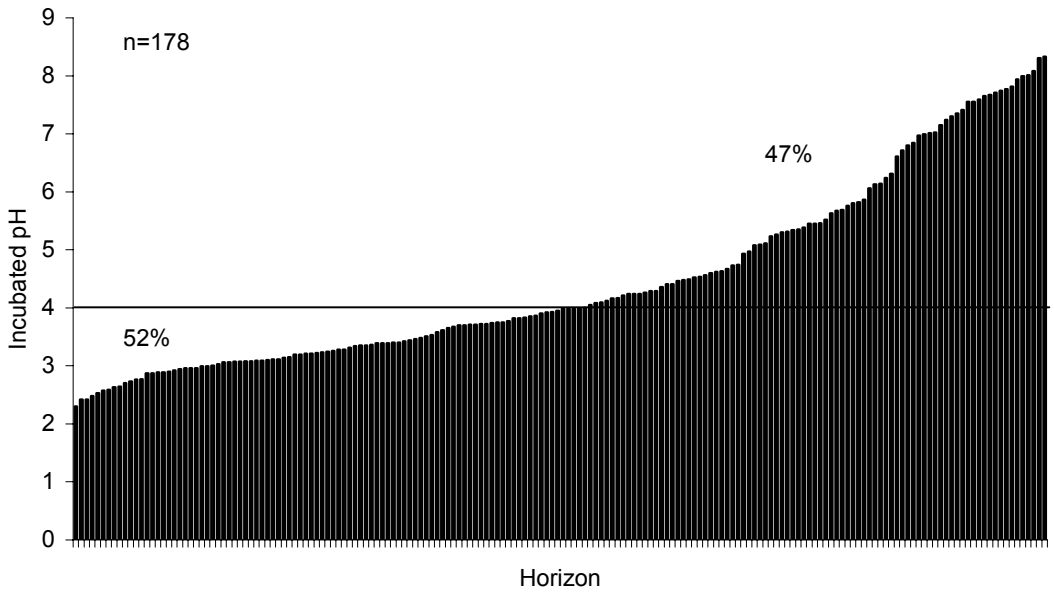

Figure 3.1. Distribution of incubation pH measurements for all horizons analyzed. 52% of all samples reached a pH ≤4 after eight weeks and were classified as sulfidic materials.

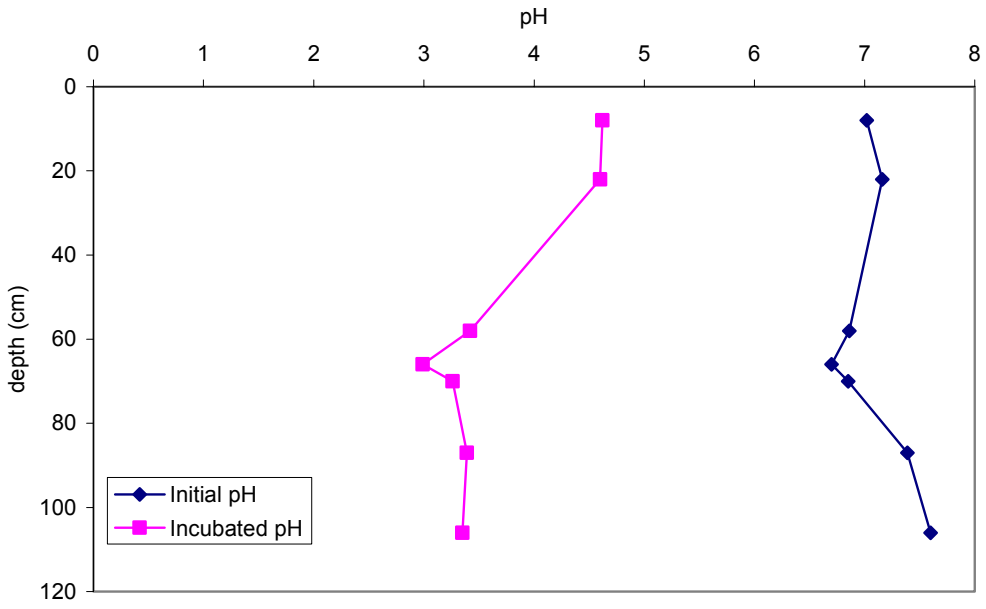

Figure 3.2. Initial and incubation pH with depth in a Cove landscape unit in Little Narragansett Bay (Pedon ID: S06CT011009). Typical of most of the Sulfiwassents, incubation pH was much lower than initial pH throughout the soil and sulfidic materials were observed in many horizons.

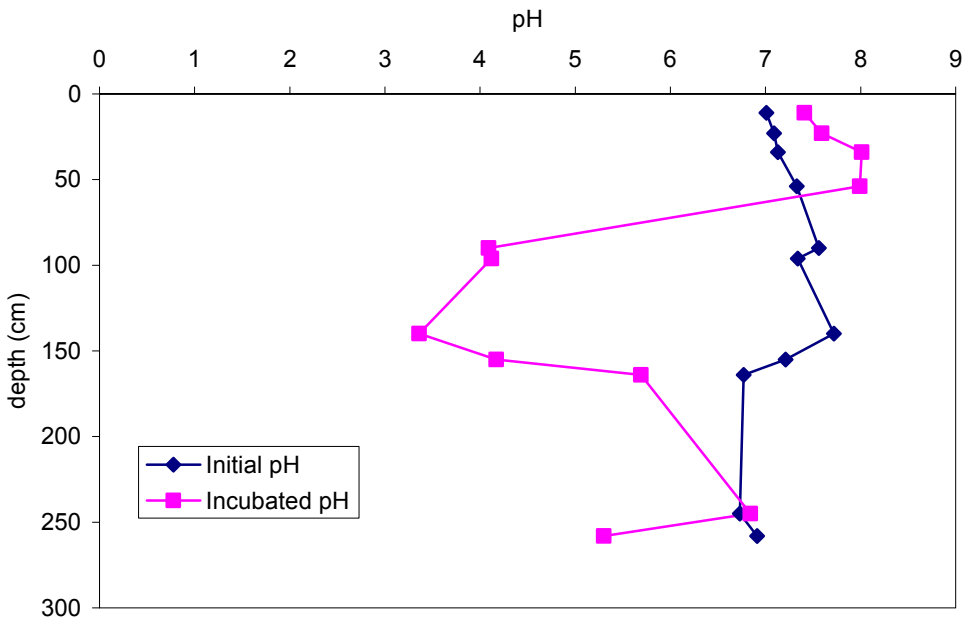

Figure 3.3. Initial and incubation pH with depth in a Mainland Shoreface landscape unit in Greenwich Bay (Site ID: RI009-2006-005-GR). Soils such as this site showed very little change in pH with incubation in the upper 50 cm, thus did not classify as Sulfiwassents.

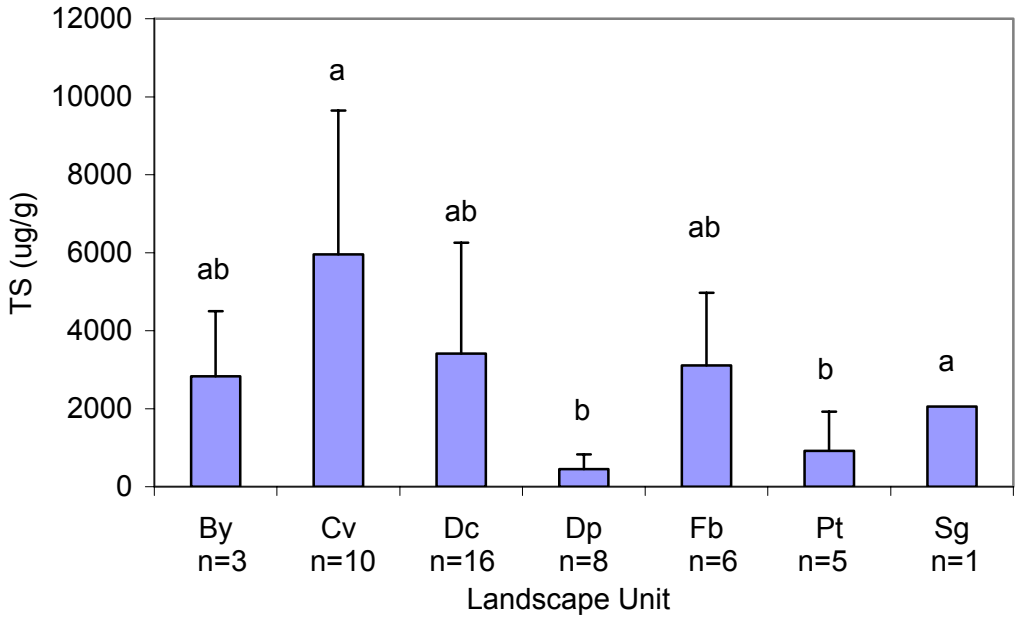

Figure 3.4. Mean total sulfides by landscape unit in all horizons. High-energy landscape units (Mainland Shoreface (Dp) and Spit (Pt)) had significantly lower TS levels than low energy landscape units (Cove (Cv)). Means with different letters are significantly different at the p=0.05 level using Tukey's HSD test. Bars represent standard deviation.

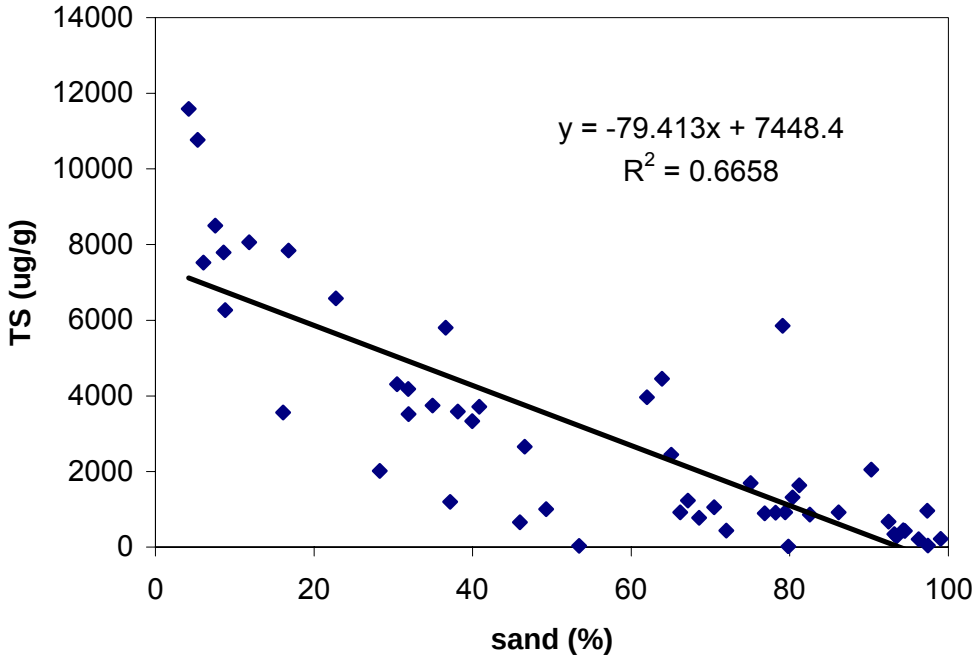

Figure 3.5. Total sulfide and sand contents. Samples with higher sand contents correlate with lower levels of sulfide (n=52).

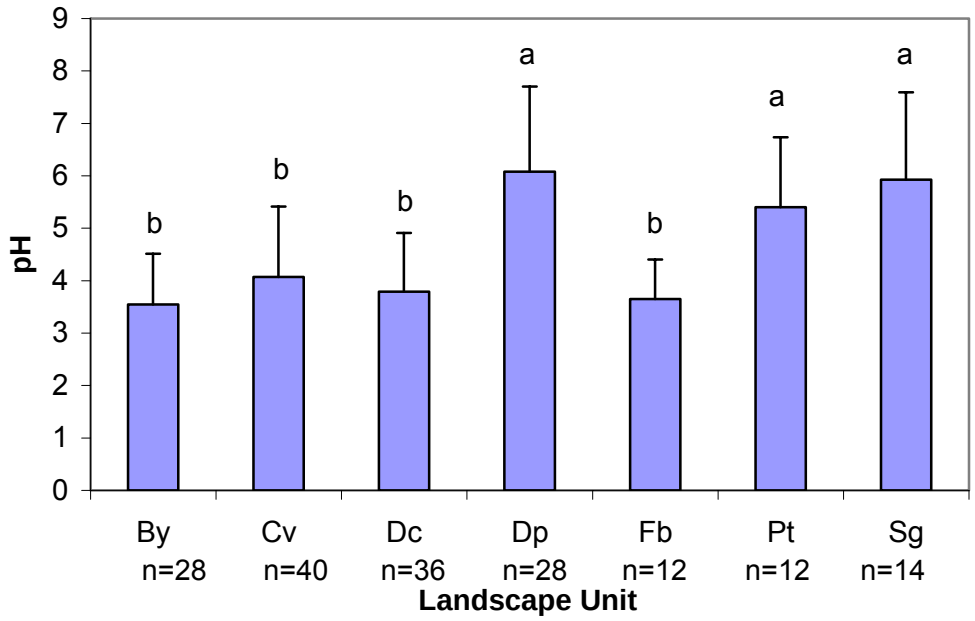

Figure 3.6. Mean incubation pH by landscape unit for all horizons. Low energy landscape units (Cove (Cv), Drowned Channel (Dc), Fluviomarine Bottom (Fb), and Bayfloor (By)) had significantly lower incubation pH values than high-energy landscape units (Mainland Shoreface (Dp), Spit (Pt), and Shoal (Sg)). Means with different letters are significantly different at the p=0.05 level using Tukey's HSD test. Bars represent standard deviation.

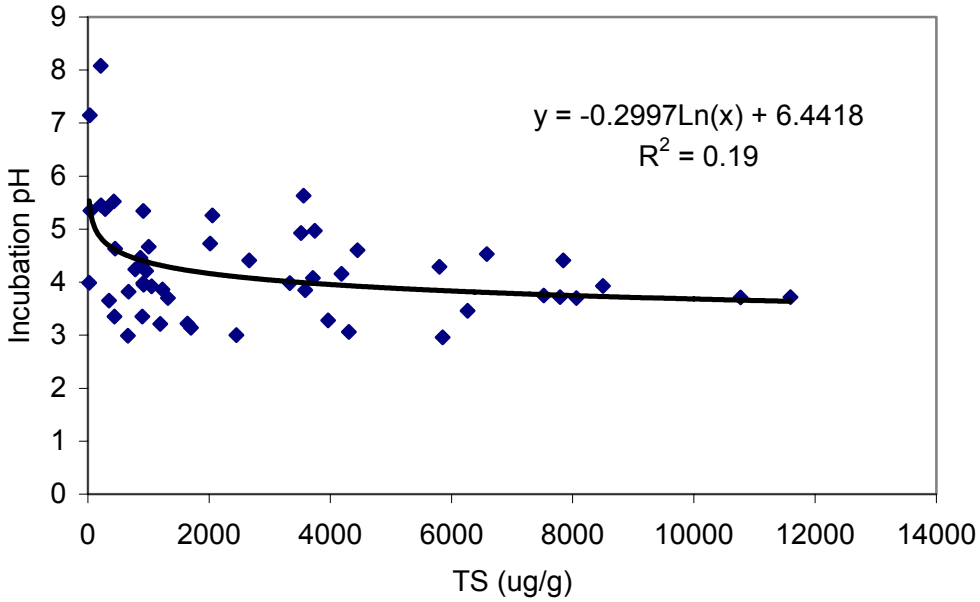

Figure 3.7. Incubation pH and total sulfide concentration. These two measurements are indications of sulfidic materials, however they are not highly related with one another (n=52).

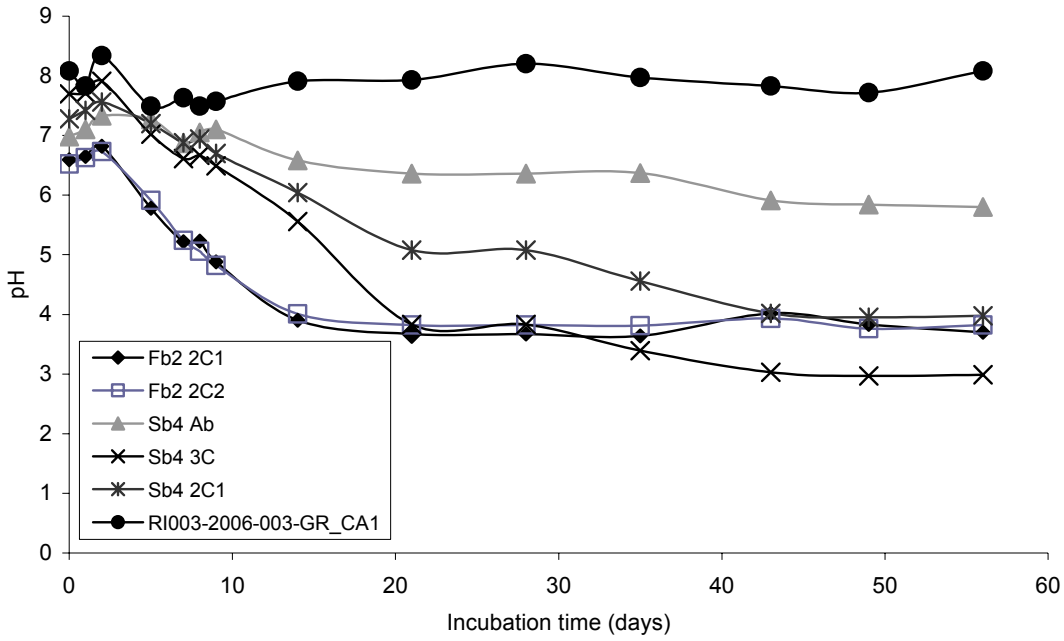

Figure 3.8. The rate of change in pH values over the 8-week incubation period. Of those that reached pH values ≤4 after eight weeks, some horizons had very rapid declines within the first two weeks before leveling off (Fb2 2C1 and 2C2). Other horizons had a more gradual and steady decline (Sb4 3C and 2C1), while some did not show a significant change in pH over time (RI003-2006-003-GR_CA1 and Sb4 Ab).

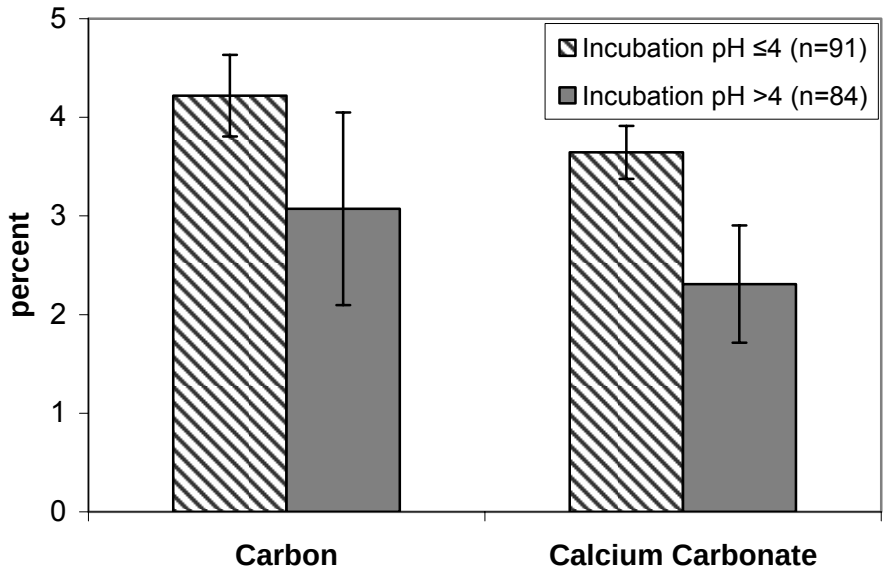

Figure 3.9. Percent organic carbon and calcium carbonate ($CaCO_3$) and incubation pH. Samples with pH dropping to ≤4 in eight weeks of moist incubation had carbon values similar to those of samples with incubation pH values >4 ($t=0.28$). Calcium carbonate contents were significantly higher in samples with incubation pH ≤4 ($t<0.05$).

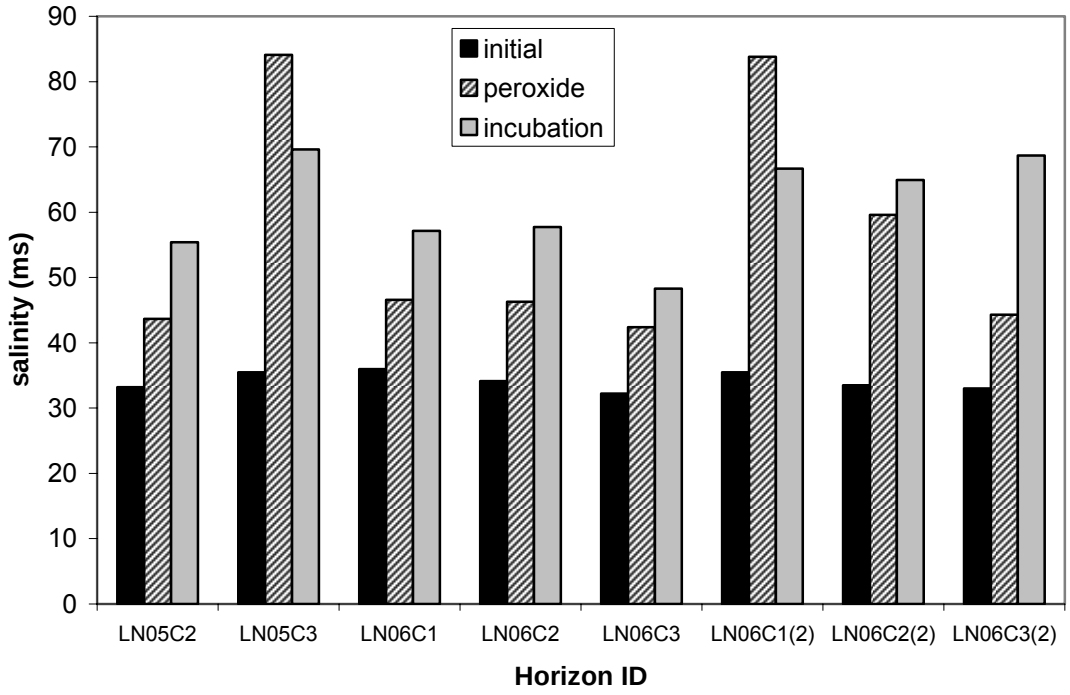

Figure 3.10. Initial salinity, salinity after peroxide treatment, and salinity after moist incubation. Initial salinity of most samples was between 30-40 mS. Salinity after moist incubation was not significantly different from salinity after oxidation with hydrogen peroxide (t=0.5).

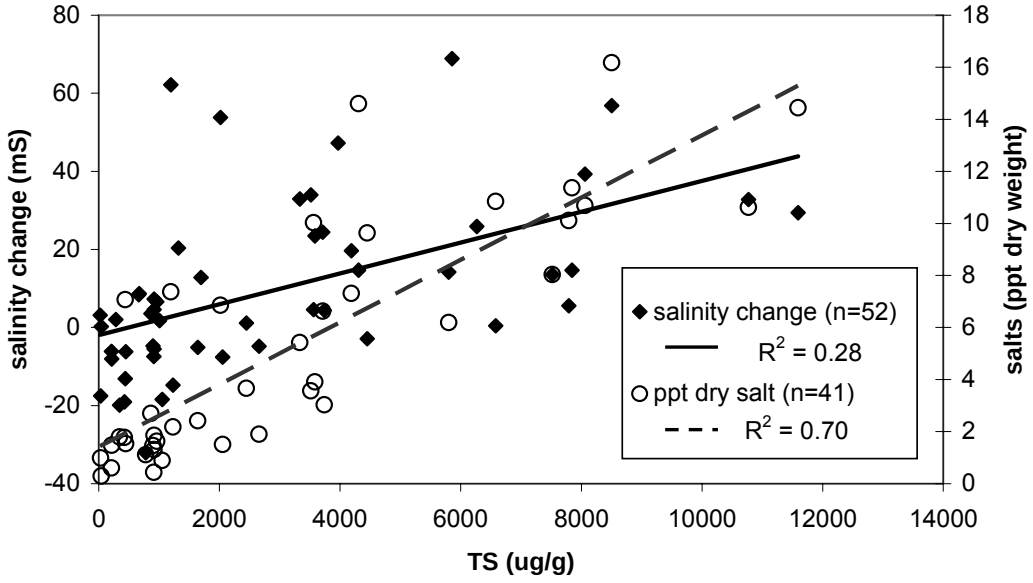

Figure 3.11. Total sulfides, salt content, and change in salinity with peroxide oxidation. Calculation of salt content dry weight is a more consistent indication of TS concentration than salinity change before and after peroxide oxidation measured using the saturated paste method (n=41).

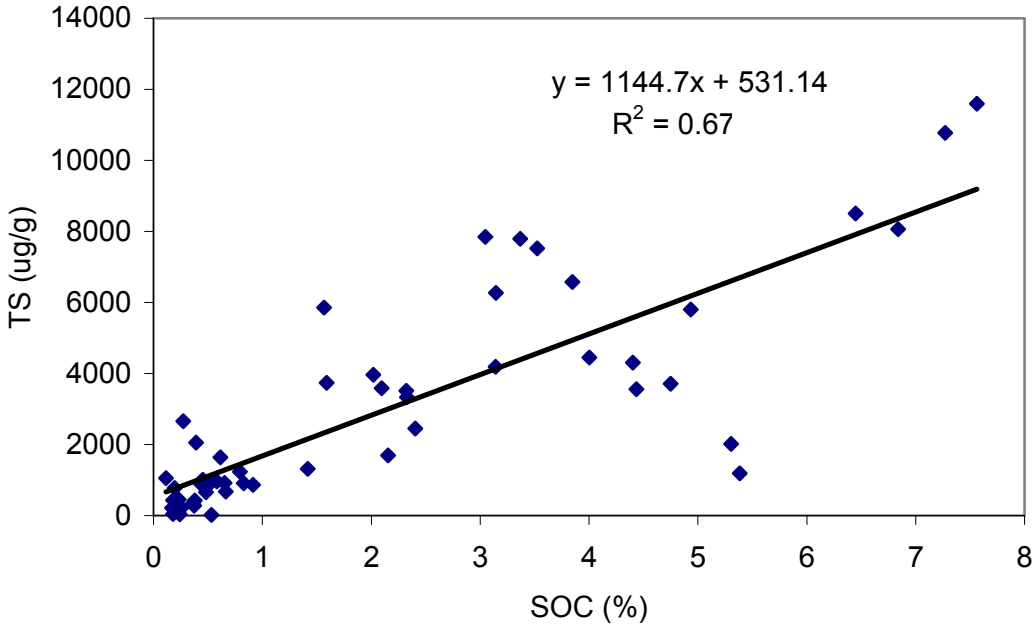

Figure 3.12. Total sulfides and soil organic carbon content. Carbon content is highly related with sulfide content ($p<0.001$; $n=52$).

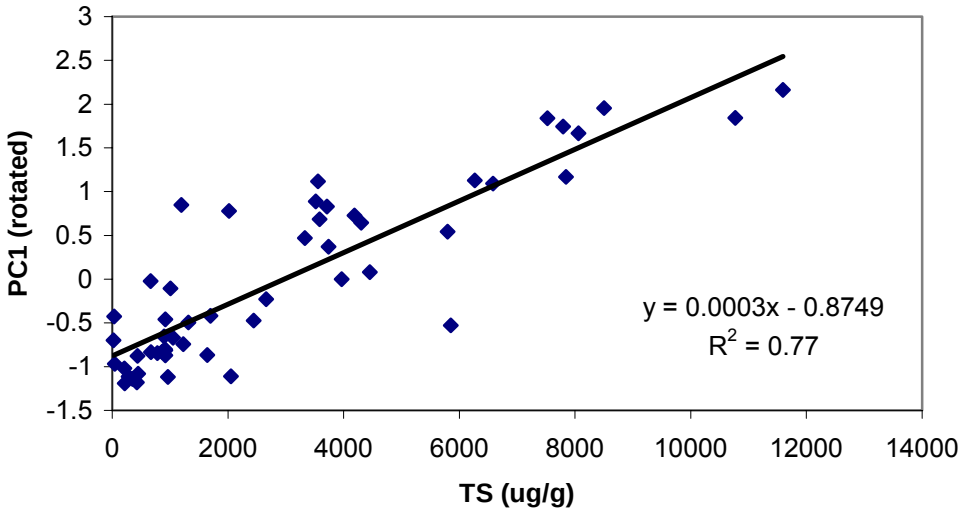

Figure 3.13. Total sulfides and soil physical properties principal component ($p<0.001$; $n=52$). Principal component consists of loadings from soil texture, carbon content, and calcium carbonate content.

Site ID **S06CT011008** **Typic Psammowassents**

LN06 **Bayfloor Sandy**

UTM	easting	northing
19T	259359	4580065

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor
		%	Hue	Value	Chroma				
A1	0-2	100	N	2.5	0	s		1	strong
A2	2-12	100	2.5Y	2.5	1	s		0	mod
C	12-18	100	2.5Y	3	1	cos		0	mod
Cg	18-28	100	2.5Y	4	2	cos		0	0
C'	28-32	100	2.5Y	3	2	s		0	0

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A1	5	17	26	16	14	78	22	0	24	ls
A2	11	22	27	14	9	83	16	1	8	lcos
C	18	25	20	9	7	79	18	3	42	lcos
Cg	23	23	20	10	5	81	16	3	23	lcos
C'	19	24	20	10	6	79	18	3	22	lcos

(continued)
Site ID S06CT011008 **Typic Psammowassents**
LN06 **Bayfloor Sandy**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A1	2.60	0.077	0.829	0.85	32.79	25.36	7.44	5.34	-2.1	0.44
A2	1.45	0.087	0.914	0.95	30.91	34.42	7.63	4.46	-3.17	2.69
C	1.34	0.075	0.746	0.76	35.87	95.77	7.56	4.52	-3.04	1.20
Cg	1.39	0	0.717	0.67	32.94	34.09	7.64	4.26	-3.38	2.42
C'	1.48	0.043	0.523	0.66	30.96	38.28	7.48	4.36	-3.12	1.30

Site ID **S06CT011007** **Sandy Typic Fluviwassents**

LN07 **Shoal**

	UTM	easting	northing
	19T	258801	4579743

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
Cg1	0-27	100	5Y	5	2	cos		0	0	
Cg2	27-35	100	2.5Y	4	1	s		0	0	
Cg3	35-46	100	2.5Y	5	1	s		0	0	*1
Cg4	46-63	80	2.5Y	5	1	s		0	0	*2
		20	2.5Y	3	1					
Ab	63-72	100	2.5Y	3	1	s		0	0	*3
2C1	72-80	100	2.5Y	3	2	lcos	10	0	0	
2C2	80-98	100	2.5Y	3	2	lcos	40	0	0	

Notes:

*1 Clam shell

*2 Striations of sand in two colors

*3 Mussel shell

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg1	22	35	31	8	2	98	0	2	9	cos
Cg2	6	19	54	17	1	97	3	0	2	s
Cg3	3	21	53	19	1	97	1	2	1	s
Cg4	1	9	46	34	5	95	3	2	1	s
Ab	6	13	25	33	14	91	8	1	5	s
2C1	27	27	22	9	6	91	7	2	23	cos
2C2	22	24	23	11	6	86	10	4	53	lcos

(continued)

Site ID S06CT011007 **Sandy Typic Fluviwassents**

LN07 **Shoal**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
Cg1	1.90	0	0.127	0.34	16.56	12.97	7.75	7.55	-0.20	0.81
Cg2	1.46	0	0.137	0.54	20.37	10.70	8.12	5.86	-2.26	1.04
Cg3	1.86	0	0.096	0.44	31.99	17.43	7.97	7.24	-0.73	1.40
Cg4	2.11	0	0.119	1.21	32.07	18.27	8.16	7.65	-0.51	2.27
Ab	2.33	0.035	0.478	0.91	34.15	25.68	7.95	8.30	0.35	1.55
2C1	1.88	0.022	0.281	0.52	38.94	20.19	7.74	6.31	-1.43	1.78
2C2	2.28	0.03	0.301	0.43	36.57	19.78	6.92	6.71	-0.21	1.11

Site ID	**S06RI009-002-LN**	**Fine-silty Fluvic Sulfiwassents**			
LN04		**Cove**	UTM	easting	northing
			19T	261157	4578181

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Notes
		%	Hue	Value	Chroma				
A1	0-16	100	N	2.5	0	sil		2	
A2	16-26	100	2.5Y	2.5	1	sil		2	
C1	26-77	100	2.5Y	3	2	sil		1	
C2	77-87	100	2.5Y	3	2	sil		2	
C3	87-121	100	2.5Y	3	2	sil		1	
C4	121-170	100	5Y	3	2	sil		1	
C5	170-179	100	5Y	2.5	1	sil		1	*1
Oab	179-210	100	10YR	2	1	organic		2	*2

Notes:

*1 5% unrubbed, 2% rubbed fibers

*2 Woody plant fragments; 20% unrubbed, 5% rubbed fibers

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A1	0	1	2	2	6	11	66	23	0	sil
A2	0	2	1	2	3	8	63	29	0	sicl
C1	1	0	1	1	8	11	72	17	0	sil
C2	0	1	1	1	1	4	77	19	0	sil
C3	1	0	0	1	2	4	71	25	0	sil
C4	1	0	1	2	3	7	66	27	0	sicl
C5	1	2	3	3	6	15	71	14	0	sil
Oab	nd	nd	nd	nd	nd	nd	nd	nd	0	organic

(continued)

Site ID S06RI009-002-LN **Fine-silty Fluvic Sulfiwassents**

LN04 **Cove**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A1	0.17	0.781	7.652	8.12	39.94	69.61	7.82	5.09	-2.73	1.40
A2	0.32	0.615	6.448	6.64	35.10	91.95	7.69	3.93	-3.76	16.17
C1	0.28	0.659	6.839	6.67	40.60	79.86	7.87	3.7	-4.17	10.69
C2	0.34	0.644	7.271	6.14	37.54	70.31	8.01	3.71	-4.30	10.62
C3	0.28	0.684	7.563	6.79	27.80	57.18	8.23	3.72	-4.51	14.45
C4	0.20	0.715	8.112	6.92	26.50	52.09	8.24	3.82	-4.42	23.82
C5	0.23	1.012	16.499	7.56	26.40	59.63	7.93	5.11	-2.82	5.42
Oab	0.10	0	73.142	20.97	19.66	nd	7.8	6.24	-1.56	nd

Site ID **S06-004-GB** **Fine-laomy Fluvic Sulfiwassents**
GR12 **Fluviomarine Bottom**

	UTM	easting	northing
	19T	299772	4618462

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
A	0-10	100	N	2.5	0	sil	0	2	mod	
C1	10-25	100	2.5Y	2.5	1	sil	0	1	mod	*1
C2	25-100	100	2.5Y	3	1	sil	0	1	mod	*2, *3

Notes:

*1 Common fine plant fragments
*2 Sand lens at 62 and 81 cm
*3 Common fine plant fragments
* MacCauley refusal at 100 cm

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	0	1	5	16	19	41	45	14	0	l
C1	0	1	6	11	14	32	48	20	0	l
C2	1	2	8	13	14	38	42	20	0	l

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy (dS m^{-1})	oxidized salinity (dS m^{-1})	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.22	0.567	4.75	4.00	25.00	49.41	7.99	4.08	-3.91	6.63
C1	0.41	0.271	2.322	2.10	7.96	41.96	8.14	4.93	-3.21	3.56
C2	0.55	1.275	2.096	1.79	11.18	34.65	7.84	3.85	-3.99	3.91

Site ID **S06-003-GB** **Coarse-loamy Haplic Sulfiwassents**

GR09 **Cove**

UTM	easting	northing
19T	296657	4618364

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Notes
		%	Hue	Value	Chroma				
A	0-10	100	2.5Y	2.5	1	sil	1 shell	2	
AC	10-19	100	2.5Y	2.5	1	sil	5 shell	1	
C1	19-50	100	5Y	3	1	sil	5 shell	0.7	*1
C2	50-60	100	5Y	3	1	l	1 shell	0	

Notes:

* Whole periwinkle shells throughout profile
* MacCauley refusal at 60 cm
*1 Clam shells

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	0	0	1	3	18	22	63	15	0	sil
AC	2	0	1	3	20	26	64	10	0	sil
C1	0	1	1	3	15	20	63	17	0	sil
C2	3	3	5	14	21	46	42	12	0	l

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.13	0.959	5.486	4.24	39.80	98.11	8.10	2.91	-5.19	8.67
AC	0.37	0.699	3.611	2.75	33.00	59.45	8.14	3.72	-4.42	10.46
C1	0.54	0.33	3.838	2.70	33.18	53.38	8.10	2.75	-5.35	7.30
C2	0.49	0.33	3.716	2.72	37.58	41.93	7.88	7.06	-0.82	2.30

Site ID	S06-002-GB	Coarse-silty Fluvic Sulfiwassents		
GR05		**Bayfloor**	UTM 19T	easting 296308	northing 4617155

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Notes
A	0-9	100	2.5Y	2.5	1	sil	1 shell	2	*1
AC	9-20	100	2.5Y	2.5	1	sil		1	
Cg	20-80	100	5Y	4	1	sil	1 shell	0.7	*2

Notes:

*1 Whole periwinkle shells

*2 Many small drill shells in 2 cm layer at 30 cm

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	8	2	2	3	8	23	60	17	0	sil
AC	1	1	1	1	5	9	73	18	0	sil
Cg	2	1	1	3	10	17	71	12	0	sil

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.14	0.623	6.264	4.49	44.10	95.18	7.98	2.54	-5.44	12.67
AC	0.59	0.43	6.175	3.39	41.50	70.37	8.37	3.37	-5.00	13.13
Cg	0.35	0.63	3.803	3.59	44.10	47.66	8.23	2.73	-5.50	8.67

Site ID **S06-001-GB** **Fine-silty Fluvic Sulfiwassents**

GR04 **Drowned Channel**

UTM	easting	northing
19T	295927	4613986

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
A	0-5	100	N	2.5	0	sil		2	0	
AC	5-17	100	N	2.5	0	sil		1	slight	
C	17-28	100	2.5Y	2.5	1	sil		1	slight	
Cg1	28-33	100	10Y	3	1	sil	1 shell	1	mod	*1
Cg2	33-136	100	10Y	3	1	sil		1	mod	*2
Cg3	136-150	100	10Y	3	1	sil		0.7	mod	*3

Notes:

*1 Many small drill shells

*2 Common medium plant fragments

*3 Few medium plant fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	1	2	2	6	14	25	56	19	0	sil
AC	0	1	1	4	14	20	63	17	0	sil
C	2	2	3	6	10	23	62	15	5	sil
Cg1	1	1	2	5	8	17	54	29	0	sicl
Cg2	0	1	1	2	2	6	58	36	0	sicl
Cg3	0	1	2	3	3	9	57	34	0	sicl

(continued)
Site ID S06-001-GB **Fine-silty Fluvic Sulfiwassents**
GR04 **Drowned Channel**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.35	0.609	8.02	6.12	30.60	47.54	7.71	7.02	-0.69	17.57
AC	0.34	0.407	5.348	4.93	29.20	42.65	7.8	7.71	-0.09	8.11
C	0.35	0.341	3.846	4.43	28.60	29.07	7.92	4.53	-3.39	10.85
Cg1	0.49	0.266	3.049	2.62	26.90	41.56	8.07	4.41	-3.66	11.36
Cg2	0.35	0.328	3.525	4.36	14.91	28.47	8.06	3.75	-4.31	8.03
Cg3	0.33	0.287	3.367	4.09	12.82	18.40	8.07	3.72	-4.35	10.11

Site ID S06-380-WICK **Coarse-loamy Fluvic Sulfiwassents**

Bayfloor

	UTM	easting	northing
	19T	296456	4606426

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value
		%	Hue	Value	Chroma			
A	0-6	100	5Y	2.5	1	sil		2
AC	6-19	100	5Y	2.5	1	sil		2
C	19-47	100	10Y	2.5	1	l		1

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	0	0	2	8	9	19	71	10	0	sil
AC	0	1	4	10	9	24	63	13	0	sil
C	2	3	8	19	9	41	45	14	0	l

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.28	0.348	3.164	3.41	51.00	51.00	7.27	4.74	-2.53	10.24
AC	0.48	0.272	2.574	2.88	49.40	49.40	7.49	3.48	-4.01	7.63
C	0.53	0.296	2.651	2.93	48.80	48.80	7.55	3.08	-4.47	9.65

Site ID RI009-2006-009-WH **Coarse-loamy Haplic Sulfiwassents**

Waypt254 **Mainland Shoreface** UTM 19T easting 296516 northing 4605048

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Notes
Cg	0-21	100	5Y	4	1	fs	3 gravel	0	*1
Ab	21-36	100	10YR	3	2	sl		0	*2
2Cg1	36-60	100	5Y	4	1	ls	20 gravel	0	*3
2Cg2	60-78	100	10Y	4	1	ls	5 gravel	0	
3Cg3	78-120	100	N	4	0	sil		0	

Notes:

*1 Gravel layer at bottom of C1 horizon

*2 Many medium and fine plant fragments

*3 Medium plant fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg	3	6	20	53	11	93	7	0	7	fs
Ab	3	7	21	36	18	85	15	0	12	s
2Cg1	3	7	14	24	19	67	33	0	38	fsl
2Cg2	2	5	9	16	17	49	51	0	5	sil
3Cg3	2	4	9	15	15	45	55	0	2	sil

(continued)

Site ID RI009-2006-009-WH **Coarse-loamy Haplic Sulfiwassents**

Waypt254 **Mainland Shoreface**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change
Cg	0.92	0.02	0.373	0.13	23.17	25.19	7.31	5.38	-1.93
Ab	1.26	0.046	0.884	0.32	35.77	19.40	6.98	5.8	-1.18
2Cg1	0.67	0	0.651	0.42	12.51	17.10	7.28	3.98	-3.30
2Cg2	1.20	0	0.453	0.35	8.85	10.60	7.37	4.67	-2.70
3Cg3	0.52	0	0.481	0.29	7.77	16.12	7.70	2.99	-4.71

Site ID RI009-2006-008-WH **Coarse-silty over sandy Haplic Sulfiwassents**

Waypt253 **Cove**

UTM	easting	northing
19T	295216	4605910

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Notes
		%	Hue	Value	Chroma				
A1	0-1	100	N	2.5	0	sil		2	
A2	1-10	100	10Y	2.5	1	sil		2	
AC	10-26	100	5Y	3	1	sil	1 shell	1	*1
C1	26-65	100	10Y	3	1	sil		0	
2C2	65-74	100	10Y	3	1	ls		0	
2C3	74-88	100	10Y	2.5	1	cos	20 gravel	0	

Notes:

*1 Medium and fine shell fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A1	0	0	1	1	4	6	82	12	0	sil
A2	1	0	1	1	2	5	80	15	0	sil
AC	0	1	1	3	4	9	78	13	0	sil
C1	0	2	3	5	6	16	68	16	0	sil
2C2	21	23	18	8	4	74	26	0	34	lcos
2C3	23	25	20	10	4	82	18	0	37	lcos

(continued)

Site ID RI009-2006-008-WH **Coarse-silty over sandy Haplic Sulfiwassents**

Waypt253 **Cove**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change
A1	0.15	0.4	3.783	4.59	53.19	77.41	6.77	2.94	-3.83
A2	0.25	0.317	3.402	4.26	47.70	52.96	6.91	3.11	-3.80
AC	0.36	0.312	3.145	3.36	30.20	33.63	7.41	3.46	-3.95
C1	0.18	0.248	3.128	2.87	23.30	33.85	7.37	4	-3.37
2C2	1.26	0.162	2.153	1.27	19.58	19.43	7.18	3.14	-4.04
2C3	0.90	0.048	0.81	0.36	6.98	13.98	7.38	5.45	-1.93

Site ID RI009-2006-007-WH **Coarse-loamy Fluvic Sulfiwassents**

Waypt252 **Fluviomarine Bottom** UTM 19T easting 295724 northing 4606602

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Notes
A	0-14	100	N	2.5	0	sil		2	*1
AC	14-30	100	5Y	3	1	sil		2	
C	30-53	100	5Y	3	1	sil		1	
2Ab	53-60	100	2.5Y	3	1	sl		0	*2
2C1	60-71	100	2.5Y	3	3	ls		0	*3
2C2	71-97	100	5Y	3	2	s	5 gravel	0	*4

Notes:

*1 Few fine shell fragments

*2 Common fine and medium plant fragments

*3 Common fine and medium plant fragments

*4 Few fine plant fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	0	1	1	7	8	17	67	16	0	sil
AC	1	1	4	9	9	24	60	16	0	sil
C	1	2	6	11	8	28	55	17	0	sil
2Ab	2	6	16	36	19	79	21	0	0	lfs
2C1	2	4	15	36	22	79	19	0	23	lfs
2C2	3	5	18	51	16	93	7	0	0	fs

(continued)
Site ID RI009-2006-007-WH **Coarse-loamy Fluvic Sulfiwassents**
Waypt252 **Fluviomarine Bottom**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change
A	0.25	0.316	3.299	5.39	48.10	90.87	7.46	5.08	-2.38
AC	0.34	0.326	3.353	5.12	44.60	68.05	7.48	3.39	-4.09
C	0.47	0.258	2.72	3.87	41.20	59.53	7.31	2.73	-4.58
2Ab	1.71	0.086	1.567	0.50	11.01	79.90	6.58	2.96	-3.62
2C1	1.24	0.144	1.417	0.66	6.60	26.94	6.59	3.7	-2.89
2C2	0.71	0	0.664	0.38	6.46	15.12	6.52	3.82	-2.70

Site ID RI009-2006-006-WH **Coarse-loamy Fluvic Sulfiwassents**

Waypt251 **Drowned Channel** UTM 19T easting 295542 northing 4605695

Field Data

Horizon	Depth (cm)	Color %	Hue	Value	Chroma	Field texture	Coarse Frags (%)	n-value	Notes
A	0-5	100	5Y	2.5	1	sl		2	*1
AC	5-14	100	5Y	3	1	l	1 shell	2	
C1	14-33	100	5Y	3	1	l		1	
C2	33-53	100	5Y	3	1	l		1	
C3	53-64	100	5Y	3	1	fsl		0	*2
2Cg1	64-74	100	N	4	0	ls		0	
2Cg2	74-95	100	2.5Y	4	2	ls		0	*3
2C	95-96	100	2.5Y	4	3	sl	15 gravel	0	*4

Notes:

*1 Few fine plant fragments
*2 Few fine plant fragments
*3 3% 5YR 3/4 iron concentrations
*4 1% 10YR 3/4 iron concentrations

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A										
AC	1	2	7	14	14	40	43	17	6	l
C1	0	2	5	12	8	27	47	26	3	l
C2	1	3	7	18	10	39	48	13	1	l
C3	6	6	12	27	11	62	30	8	1	fsl
2Cg1	6	8	14	32	21	81	19	0	3	ls
2Cg2	24	16	16	18	6	80	17	3	22	lcos

(continued)
Site ID RI009-2006-006-WH **Coarse-loamy Fluvic Sulfiwassents**
Waypt251 **Drowned Channel**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change
A	0.25	0.295	2.899	3.09	49.70		6.82	3.53	-3.29
AC	0.40	0.277	2.797	3.03	48.00	220.33	7.37	3.31	-4.06
C1	0.42	0.331	3.312	3.77	53.28	97.50	8.02	4.24	-3.78
C2	0.50	0.2	2.587	2.16	17.45	76.83	7.18	3.71	-3.47
C3	1.16	0.177	2.019	1.54	15.42	62.68	7.32	3.28	-4.04
2Cg1	1.65	0	1.393	0.36	6.58	6.29	6.58	6.14	-0.44
2Cg2	0.92	0.025	0.533	0.17	17.11	20.25	7.26	3.99	-3.27

Site ID RI009-2006-005-WH **Coarse-loamy Fluvic Sulfiwassents**

Waypt267 **Bayfloor**

UTM	easting	northing
19T	296406	4606408

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
A	0-13	100	N	2.5	0	sil		2	slight	*1
AC	13-22	100	10Y	2.5	1	sil		2	slight	
C1	22-46	100	10Y	2.5	1	sil		1	slight	*2
C2	46-109	100	10Y	2.5	1	sl		1	mod	*3
C3	109-113	100	2.5Y	2.5	1	sl		1	mod	*4
2C4	113-119	50	5Y	4	1	ls		0	mod	
		50	10Y	3	2					

Notes:

* 6 cm sil at bottom of core (119 cm) with intact quohog. Possible contamination in vibracore

*1 Worm casings 1cmx5cm; common fine plant fragments

*2 Worm casings 1cmx5cm

*3 Sandy lens at 46-48 cm

*4 Wood fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	1	1	3	7	5	17	64	19	0	sil
AC	1	4	7	12	8	32	49	19	0	l
C1	1	4	10	17	8	40	44	16	1	l
C2	3	5	9	14	7	38	43	19	3	l
C3	4	8	14	25	14	65	29	6	14	fsl
2C4	5	12	30	43	8	98	2	0	4	s

(continued)
Site ID RI009-2006-005-WH **Coarse-loamy Fluvic Sulfiwassents**
Waypt267 **Bayfloor**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.42	0.472	4.884	7.51	36.20	68.29	7.55	4.48	-3.07	5.96
AC	0.50	0.312	3.142	2.80	31.40	51.06	7.65	4.16	-3.49	7.31
C1	0.51	0.242	2.329	2.75	31.30	64.23	7.66	3.98	-3.68	5.43
C2	0.86	0.111	1.675	2.09	30.40	56.26	7.69	3.61	-4.08	4.03
C3	1.15	0.222	3.912	4.19	30.72	62.45	7.91	3.21	-4.7	6.45
2C4	1.37	0.041	0.582	0.63	25.25	31.87	7.84	4.21	-3.63	1.62

Site ID RI009-2006-004-WH **Coarse-loamy Haplic Sulfiwassents**

Waypt266 **Shoal**

	UTM	easting	northing
	19T	269471	4606233

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
^A1	0-2	100	5Y	3	1	sl		1	0	
^A/C	2-25	70	10Y	2.5	1	ls		0	0	*1
		30	5Y	3	1					
^C1	25-44	90	5Y	3	1	ls		0	0	
		10	10Y	2.5	1					
^C2	44-62	100	5Y	3	1	sl		0	mod	
C3	62-88	100	2.5Y	2.5	1	sl		1	mod	
C4	88-123	100	2.5Y	2.5	1	sil		1	mod	*2
Oab	123-132	100	10YR	2	1	hpm			strong	*3
AC	132-140	100	10YR	3	2	sl		0	mod	*4, *5

Notes:

* Macroalgae clumps at surface
*1 Razor clam shells
*2 few plant fragments
*3 few fine plant fibers, 0% rubbed fibers
*4 few medium roots
*5 3 cm Oa layer at 135 cm

(continued)
Site ID RI009-2006-004-WH **Coarse-loamy Haplic Sulfiwassents**
Waypt266 **Shoal**

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
^A/C	8	13	26	34	8	89	10	1	2	s
^C1	5	9	27	39	10	90	8	2	9	s
^C2	3	6	19	37	14	79	17	4	4	ls
C3	2	6	19	35	12	74	20	6	3	fsl
C4	1	1	4	16	13	35	51	14	0	sil
Oab	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
AC	10	17	28	28	8	91	9	0	5	cos

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
^A/C	1.30	0.036	0.475	0.10	41.10	37.29	8.08	5.67	-2.41	1.04
^C1	1.62	0.027	0.39	0.28	33.88	26.31	8.00	5.26	-2.74	1.50
^C2	1.46	0.041	0.652	0.56	25.25	37.82	7.80	3.83	-3.97	2.13
C3	1.29	0.058	0.835	0.75	26.20	39.21	7.84	3.09	-4.75	3.06
C4	1.20	0.437	1.771	1.62	28.20	62.98	7.68	3.06	-4.62	8.51
Oab	0.22	0	32.863	44.37	27.20	nd	7.37	5.46	-1.91	nd
AC	1.87	0.13	9.777	0.41	24.20	37.44	7.38	6.97	-0.41	2.24

Site ID RI009-2006-003-WH **Sulfic Psammowassents**

Waypt268 **Spit**

	UTM	easting	northing
	19T	296475	4605584

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
C/A	0-18	40	N	2.5	0	s		0	0	
		60	5Y	4	1					
Cg	18-58	100	5Y	4	1	s	3 shell	0	0	*1
C1	58-96	100	5Y	3	1	s		0	slight	
C2	96-133	100	5Y	3	1	s	3 shell	0	0	
C3	133-144	100	5Y	3	1	ls	1 shell	0	slight	*2
C4	144-186	100	5Y	2.5	1	sl	1 shell	0.7	mod	*3, *4

Notes:

*1 Razor clam shell fragments

*2 Common 2 mm plant fragments

*3 Intact scallop shell at 147 cm

*4 Common fine and medium plant fragments

* Silt loam lens 144-147 cm

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
C/A	1	5	46	42	3	97	3	0	0	s
Cg	0	1	27	60	7	95	4	1	0	s
C1	0	2	29	54	8	93	5	2	0	s
C2	1	1	11	68	12	93	6	1	0	fs
C3	0	0	6	62	18	86	12	2	0	lfs
C4	0	0	1	45	29	75	20	5	0	fsl

(continued)
Site ID RI009-2006-003-WH **Sulfic Psammowassents**
Waypt268 **Spit**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
C/A	1.80	0.018	0.322	0.25	28.60	14.69	7.46	5.23	-2.23	1.47
Cg	1.72	0.019	0.379	0.37	33.21	14.16	8.1	5.52	-2.58	1.77
C1	1.44	0.023	0.386	0.32	32.70	20.21	8.21	4.24	-3.97	1.79
C2	1.49	0	0.361	0.37	31.50	11.61	8.41	3.65	-4.76	1.86
C3	1.29	0.019	0.427	0.57	23.60	18.06	8.09	3.95	-4.14	2.57
C4	1.15	0.059	0.894	0.81	23.30	20.58	8.14	4.49	-3.65	1.77

Site ID **RI003-2006-008-GB** **Coarse-silty Typic Hydrowassents**

GR09 **Cove**

	UTM	easting	northing
	19T	296671	4618356

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
A1	0-1	100	5Y	3	2	sil		2	mod	*1
A2	1-13	100	2.5Y	2.5	1	sil	1 shell	2	mod	*2
AC	13-26	100	2.5Y	2.5	1	sil	3 shell	2	mod	*3
C1	26-50	100	5Y	2.5	1	sil	1 shll	1	mod	*3
C2	50-91	100	5Y	3	1	sl	15 shell	0.7	mod	*4

Notes:

*1 Oxidized surface

*2 Periwinkle shells

*3 Periwinkle and clam shell fragments

*4 Razor clam, periwinkle, and scallop fragments; whole scallop and oyster shell at 86 cm

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
A2	0	1	1	2	12	16	63	21	0	sil
AC	0	1	1	2	20	24	66	10	0	sil
C1	0	0	1	2	6	9	70	21	0	sil
C2	2	2	4	9	18	35	60	5	0	sil

(continued)

Site ID RI003-2006-008-GB **Coarse-silty Typic Hydrowassents**

GR09 **Cove**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
A2	0.33	0.48	4.436	3.50	40.29	44.87	7.44	5.63	-1.81	10.03
AC	0.65	0.363	4.284	3.09	36.20	37.05	8.14	7.67	-0.47	4.84
C1	0.46	0.343	4.124	3.13	36.34	50.34	7.97	7.81	-0.16	5.72
C2	1.08	0.148	1.59	1.59	18.40	22.80	7.73	4.97	-2.76	3.02

Site ID **RI003-2006-007-GB** **Fluventic Psammowassents**

GR15 **Mainland Shoreface**

	UTM	easting	northing
	19T	299358	4617280

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
Cg	0-17	100	10Y	6	1	s		0	0	
C/A	17-31	50	10Y	6	1	s		0	0	
		50	10Y	3	1					
Ab	31-36	100	10Y	3	1	ls		0	0	
Cg'	36-41	100	5Y	5	2	s		0	0	
CA	41-64	90	5Y	4	1	s	2 shell	0	slight	*1
		10	5Y	3						*2
Cg''	64-96	100	5Y	5	1	ls	2 shell 1 gravel	0	mod	*3

Notes:

* 0.7 feet core collapse

*1 5Y 3/1 mucky sand lens at 52-54 cm

*2 few fine 2.5Y 2/1 mottles; few fine plant fragments

*3 clam shell fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg	0	0	8	79	11	98	2	0	0	fs
C/A	0	1	13	69	14	97	3	0	0	fs
Ab	0	2	15	62	15	94	5	1	1	fs
Cg'	3	7	29	54	5	98	2	0	2	fs
CA	1	1	17	69	8	96	3	1	0	fs
Cg''	2	5	28	59	3	97	2	1	2	fs

(continued)

Site ID RI003-2006-007-GB **Fluventic Psammowassents**

GR15 **Mainland Shoreface**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy (dS m^{-1})	oxidized salinity (dS m^{-1})	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
Cg	1.41	0	0.163	0.16	18.88	11.69	6.60	6.13	-0.47	0.79
C/A	1.70	0	0.151	0.22	25.86	14.14	7.37	7.01	-0.36	1.13
Ab	2.18	0	0.161	0.21	25.85	20.42	7.71	7.77	0.06	1.59
Cg'	2.02	0	0.137	0.17	25.98	15.12	7.62	6.8	-0.82	1.53
CA	1.59	0	0.138	0.19	31.65	17.61	7.60	5.82	-1.78	1.68
Cg''	1.28	0	0.138	0.33	29.04	18.54	7.62	7.94	0.32	1.93

Site ID **RI003-2006-005-GB** **Sulfic Psammowassents**

GR01 **Mainland Shoreface**

	UTM	easting	northing
	19T	297686	4615798

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
Cg	0-11	100	5Y	4	1	ls	1 shell	0	0	*1
Ab	11-23	100	5Y	2.5	1	ls	40 shell	0	0	*2
C	23-34	100	5Y	3	1	s	5 shell	0	0	*3
CA	34-54	80	5Y	3	1	s		0	0	
		20	5Y	2.5	1	sl				
Cg1	54-90	100	2.5Y	4	1	s		0	0	
Cg2	90-96	100	5Y	4	1	ls		0	0	
Cg3	96-140	100	2.5Y	4	1	s		0	0	
Cg4	140-155	100	10Y	3	1	cos	1 gravel	0	0	
2Cg5	155-164	100	5Y	4	1	ls	20 gravel	0	0	*4
2Cg6	164-245	100	5Y	4	1	fsl		0	0	*5
2Cg7	245-258	100	5Y	5	1	ls		0	0	

Notes:

* 1.1 feet of core collapse upon sampling

*1 Whole steamer shell

*2 Fine shell fragments

*3 Few medium shell fragments and many fine algal filaments

*4 20% medium and fine gravels

*5 2 mm layers of 2.5Y 4/3 fsl material between 3 mm layers of matrix color

(continued)

Site ID RI003-2006-005-GB **Sulfic Psammowassents**

GR01 **Mainland Shoreface**

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg	0	1	11	44	18	76	24	0	0	lfs
Ab	1	2	23	62	8	96	4	0	0	fs
C	1	2	18	48	21	90	10	0	1	fs
CA	1	5	30	42	12	92	8	0	1	s
Cg1	3	7	38	41	6	95	5	0	1	s
Cg2	7	15	36	21	7	86	14	0	3	s
Cg3	4	9	34	34	8	89	10	1	6	s
Cg4	8	9	26	33	16	92	8	0	7	s
2Cg5	10	9	20	17	13	69	31	0	41	sl
2Cg6	0	0	0	2	18	20	79	1	0	sil
2Cg7	2	3	20	31	15	71	29	0	1	sl

(continued)
Site ID RI003-2006-005-GB **Sulfic Psammowassents**
GR01 **Mainland Shoreface**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
Cg	1.83	0.032	0.403	0.30	16.82	10.20	7.01	7.41	0.4	1.13
Ab	1.13	0	0.369	0.23	17.10	9.41	7.09	7.59	0.5	0.88
C	1.51	0	0.25	0.26	24.87	10.19	7.13	8.01	0.88	1.66
CA	1.72	0	0.383	0.35	18.38	11.34	7.33	7.99	0.66	1.72
Cg1	1.50	0	0.24	0.22	21.73	15.84	7.56	4.09	-3.47	1.31
Cg2	2.72	0	0.223	0.22	12.86	7.27	7.34	4.12	-3.22	0.90
Cg3	1.96	0	0.201	0.21	16.63	12.33	7.72	3.36	-4.36	1.14
Cg4	1.80	0	0.225	0.25	24.60	8.90	7.21	4.17	-3.04	1.27
2Cg5	1.35	0	0.251	0.20	9.87	3.22	6.77	5.69	-1.08	0.11
2Cg6	1.72	0	0.277	0.33	5.46	2.67	6.73	6.84	0.11	0.10
2Cg7	1.35	0	0.335	0.29	7.71	6.92	6.91	5.3	-1.61	0.00

Site ID **RI003-2006-004-GB** **Coarse-loamy Typic Haplowassents**

GR06 **Spit**

UTM	easting	northing
19T	296884	4616626

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
Cg	0-9	100	5Y	5	2	s		0	0	
A	9-17	100	5Y	3	1	ls		0	0	*1
2C/A	17-30	70	5GY	3	1	fsl		0	0	
		30	5GY	3	1	ls				*2
2Cg1	30-55	100	5GY	4	1	fsl		0	0	
2Cg2	55-64	100	5GY	4	1	fsl		0	0	*3
2Cg3	64-82	70	5Y	5	2	ls		0	0	*4
		30	5GY	4	1	fsl				

Notes:

* 1.2 feet core collapse upon sampling

*1 Very tight, difficult to excavate from core with soil knife

*2 Sandy tongues of A horizon material from above

*3 20% 10YR 4/4 iron concentrations

*4 5% 10YR 4/4 iron concentrations surrounding sandier material

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg	2	10	49	37	1	99	1	0	0	s
A	3	9	28	42	6	88	11	1	3	s
2C/A	0	2	7	19	18	46	52	2	0	sil
2Cg1	0	0	1	9	23	33	65	2	0	sil
2Cg2	0	0	1	13	22	36	62	2	0	sil
2Cg3	0	0	0	51	32	83	16	1	0	ls

(continued)

Site ID **RI003-2006-004-GB** **Coarse-loamy Typic Haplowassents**

GR06 **Spit**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
Cg	1.93	0	0.256	0.22	23.17	15.13	6.58	5.45	-1.13	1.47
A	1.72	0	0.362	0.32	27.92	28.54	7.54	6.06	-1.48	1.89
2C/A	1.84	0	0.272	0.37	26.56	21.77	7.87	4.41	-3.46	1.10
2Cg1	1.96	0	0.331	0.44	26.90	12.55	7.09	7.3	0.21	1.57
2Cg2	1.70	0	0.266	0.44	26.00	13.00	6.85	6.99	0.14	0.33
2Cg3	1.32	0	0.176	0.28	21.48	11.54	7.24	7.55	0.31	1.40

Site ID RI003-2006-003-GB **Fluventic Psammowassents**
Mainland Shoreface

UTM	easting	northing
19T	298486	4615858

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
Cg	0-17	100	5Y	6	2	s	1 shell	0	0	*1
CA1	17-46	100	5Y	5	2	s	3 shell	0	0	*2
CA2	46-68	80	5Y	5	2	s	3 shell	0	0	*3
		10	5Y	3	2					
AC	68-111	100	10Y	3	1	s	5 shell	0	0	*4
2Cg	111-122	100	5Y	5	1	fs		0	0	
2C	122-137	50	5Y	4	2	lfs		0	0	
		50	5Y	2	2					

Notes:

*1 Razor clam
*2 Whole clam shells (2 mm)
*3 Whole 4 cm steamer shell at 50 cm
*4 3-7 cm clam shell fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
Cg	0	0	13	78	6	97	3	0	0	fs
CA1	0	0	7	76	12	95	4	1	0	fs
CA2	1	3	21	62	9	96	3	1	0	fs
AC	1	2	20	49	18	90	8	2	3	fs
2Cg	0	0	1	9	52	62	37	1	1	fsl
2C	0	0	0	2	51	53	46	1	0	vfsl

(continued)
Site ID RI003-2006-003-GB **Fluventic Psammowassents**
Mainland Shoreface

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
Cg	1.26	0	0.178	0.09	6.65	6.88	7.73	5.35	-2.38	1.36
CA1	1.67	0	0.17	0.21	14.59	8.45	8.08	8.08	0.00	0.61
CA2	1.49	0	0.233	0.27	23.72	17.52	7.87	4.63	-3.24	1.53
AC	1.63	0	0.305	0.26	28.58	16.56	8.30	8.33	0.03	0.99
2Cg	1.67	0	0.21	0.31	32.72	16.12	8.37	7.74	-0.63	0.29
2C	1.83	0.035	0.24	0.28	30.53	12.97	7.80	7.15	-0.65	1.32

Site ID **S06CT011004** **Coarse-loamy Haplic Sulfiwassents**

core 4 **Drowned Channel**

UTM	easting	northing
19T	303447	4580214

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value
		%	Hue	Value	Chroma			
A1	0-15	100	10YR	2	1	sil		2
A2	15-27	100	10YR	2	1	sil		2
AC	27-39	100	5GY	2.5	1	sil		2
C	39-78	100	10Y	3	1	sil		0
2Ab	78-91	100	10YR	2	1	sl		0
2CA1	91-112	100	10YR	2	1	sl		0
2CA2	112-122	100	2.5Y	2.5	1	sl		0
3C	122+	100	7.5YR	2.5	1	ls	30 gravel	0

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A1	2	3	3	11	10	29	71	0	0	sil
A2	3	2	3	15	13	36	64	0	1	sil
AC	1	2	4	16	13	36	59	5	1	sil
C	3	4	5	9	4	25	69	6	0	sil
2Ab	4	11	19	22	9	65	33	2	0	sl
2CA1	2	8	18	22	10	60	39	1	0	fsl
2CA2	5	13	22	19	8	67	31	2	0	sl
3C	8	18	28	20	7	81	18	1	5	lcos

(continued)

Site ID S06CT011004 **Coarse-loamy Haplic Sulfiwassents**
Drowned Channel

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A1	0.17	0.946	5.304	4.75	39.79	93.59	7.12	4.73	-2.39	6.85
A2	0.18	0.383	4.934	3.83	38.17	52.35	7.43	4.29	-3.14	6.19
AC	0.30	0.5	4.293	3.58	48.11	80.27	7.48	3.9	-3.58	9.62
C	0.27	0.386	4.217	3.48	33.43	61.14	7.23	2.53	-4.70	9.24
2Ab	0.53	0.237	2.405	1.38	43.26	44.38	6.83	3	-3.83	3.66
2CA1	0.62	0.082	1.368	1.28	32.63	34.44	6.64	3.98	-2.66	2.34
2CA2	0.61	0.04	0.794	0.75	44.99	30.20	6.71	3.86	-2.85	2.18
3C	0.52	0.038	0.615	0.52	30.45	25.35	6.73	3.22	-3.51	2.42

Site ID **S06CT011002** **Coarse-loamy Fluvic Sulfiwassents**

core 2 **Drowned Channel**

UTM	easting	northing
19T	261048	4578398

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value
		%	Hue	Value	Chroma			
A	0-20	100	10YR	2	1	l		2
AC	20-32	100	5Y	2.5	1	sil		2
C	32-57	100	2.5Y	3	2	sil		1
2Oa	57-72	100	10YR	2	1	organic		1
2C	72-99	100	10YR	2	1	sl		1
3Cg1	99-134	100	10Y	4	1	sl	10 gravel	0
3Cg2	134-144	100	N	4	1	sl	5 gravel	0
3Cg3	144-152	100	N	5	1	sl	30 gravel	0

Notes:

* Oxidized surface layer present
* Macroalgae cover

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	2	6	11	12	7	38	47	15	1	l
AC	2	4	8	9	7	30	56	14	0	sil
C	2	7	13	8	9	39	53	8	0	sil
2Oa	nd	nd	nd	nd	nd	nd	nd	nd	nd	organic
2C	9	13	19	20	8	69	26	5	11	sl
3Cg1	15	14	16	17	9	71	26	3	46	cosl
3Cg2	10	12	18	18	10	68	29	3	17	sl
3Cg3	15	17	16	14	9	71	25	4	41	cosl

(continued)
Site ID S06CT011002 **Coarse-loamy Thapto-histic Sulfiwassents**
Drowned Channel

Horizon	Bulk density (g/cm^{-3})	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.15	0.534	5.383	4.87	41.98	104.11	7.39	3.21	-4.18	7.07
AC	0.23	0.373	4.402	3.41	49.27	63.92	7.86	3.06	-4.8	62.82
C1	0.27	0.323	4.076	3.12	52.70	73.48	7.97	2.7	-5.27	1.93
2Oa	0.13	0.625	16.151	10.05	42.10	190.16	7.39	2.3	-5.09	1.11
2C2	0.45	0.176	2.63	1.97	42.10	76.60	6.92	3.07	-3.85	0.89
3Cg1	0.80	0	0.18	0.59	44.54	31.43	6.84	3.35	-3.49	7.37
3Cg2	0.77	0.027	0.194	0.93	49.85	17.71	7.44	4.24	-3.2	14.59
3Cg3	0.78	0	0.116	0.86	32.77	14.34	7.28	3.92	-3.36	10.32

Site ID LN12MC **Coarse-loamy Fluvic Sulfiwassents**
Drowned Channel

UTM	easting	northing
19T	258751	4581306

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
A	0-6	0	2.5Y	2.5	1	sil		2	0	
AC	6-20	0	5Y	3	1	sil		1	0	
C1	20-48	0	5Y	3	1	sil		1	slight	
C2	48-77	0	5Y	3	1	l		0.7	slight	*1

Notes:

*1 Few fine plant fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	3	9	10	16	12	50	39	11	3	l
AC	2	3	3	4	8	20	62	18	0	sil
C1	1	1	1	2	6	11	69	20	0	sil
C2	6	12	13	7	5	43	48	9	3	l

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.27	5.90	3.96	47.55	119.27	7.44	3.51	-3.93	14.35
AC	0.36	5.56	5.04	47.00	163.11	7.49	3.11	-4.38	8.85
C1	0.42	6.93	6.47	43.50	162.79	7.66	2.90	-4.76	11.73
C2	0.46	5.85	6.22	41.60	96.64	7.72	2.89	-4.83	6.76

Site ID LN11MC **Coarse-loamy Thapto-histic Sulfiwassents**

Drowned Channel

UTM	easting	northing
19T	258850	4581020

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor	Notes
		%	Hue	Value	Chroma					
A	0-6	100	N	2.5	0	sil		2	0	
AC	6-22	100	2.5Y	2.5	1	l		1	slight	
C	22-45	100	2.5Y	3	2	l		1	slight	*1
Oeb	25-80	100	N	2.5	0	organic		1	slight	*2

Notes:

*1 Few fine plant frags

*2 Many fine and medium roots and rhizomes

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	3	8	17	13	6	47	39	14	2	l
AC	5	11	22	13	5	56	33	11	6	sl
C	5	12	19	10	5	51	38	11	5	l
Oeb	4	11	9	5	5	34	49	17	3	l

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.22	6.12	5.32	46.31	102.90	7.23	3.44	-3.79	11.48
AC	0.49	4.51	3.47	63.89	130.14	7.29	3.4	-3.89	6.41
C	0.36	5.91	5.09	53.27	145.86	7.56	3.19	-4.37	9.91
Oeb	0.17	19.70	11.73	43.60	238.38	7.07	3.19	-3.88	12.41

Site ID LN06MC **Coarse-loamy Haplic Sulfiwassents**

Bayfloor

	UTM	easting	northing
	19T	259334	4579948

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Sulfide odor
		%	Hue	Value	Chroma				
A	0-9	100	2.5Y	2.5	1	sil		2	slight
AC	9-17	100	2.5Y	2.5	1	sil		1	slight
C1	17-28	100	2.5Y	3	1	sil		1	slight/ mod
C2	28-36	100	5Y	3	1	fsl		0.7	slight
C3	36-46	50	2.5Y	3	2	sl		0.7	slight
		50	2.5Y	2.5	1				

Notes:

* 20 cm algal mat on soil suface
* Very fluid soil surface
* MacCauley refulsal at 46 cm

(contintued)

Site ID LN06MC **Coarse-loamy Haplic Sulfiwassents**

Bayfloor

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	2	0	1	1	2	6	84	10	0	si
AC	1	0	1	1	6	9	79	12	0	sil
C1	1	2	5	7	27	42	54	4	0	sil
C2	2	4	10	13	25	54	40	6	0	fsl
C3	1	3	9	14	29	56	39	5	0	vfsl

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.25	7.83	7.22	46.10	120.95	8.14	3.1	-5.04	10.11
AC	0.64	2.21	2.19	45.10	90.33	7.79	2.76	-5.03	27.23
C1	0.81	2.65	2.34	36.00	77.69	8.21	3.34	-4.87	7.77
C2	0.87	2.40	2.09	34.10	77.18	7.92	2.89	-5.03	7.12
C3	0.80	2.54	2.51	32.20	70.66	8.24	2.87	-5.37	5.54

Site ID LN05MC **Coarse-loamy Haplic Sulfiwassents**

Bayfloor

UTM	easting	northing
19T	259117	4579898

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Notes
		%	Hue	Value	Chroma				
A	0-9	100	N	2.5	0	sil		2	
AC	9-14	100	2.5Y	2.5	1	sil		2	
C1	14-27	100	2.5Y	2.5	1	sil		1	
C2	27-34	100	5Y	3	1	sl		1	
C3	34-61	100	5Y	3	2	sl		0.7	*1

Notes: *1 Few fine plant fragments

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	0	1	1	2	12	16	75	9	0	sil
AC	0	0	1	3	19	23	75	2	1	sil
C1	0	1	4	9	21	35	56	9	0	sil
C2	1	3	7	17	30	58	39	3	0	vfsl
C3	5	14	18	12	14	63	30	7	3	sl

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.18	8.36	7.05	42.20	55.48	7.95	3.24	-4.71	13.14
AC	0.28	6.88	6.63	40.90	49.73	8.09	2.57	-5.52	8.19
C1	0.52	26.68	2.92	36.40	48.35	8.26	2.59	-5.67	9.18
C2	0.98	2.27	1.93	33.20	43.64	8.09	2.77	-5.32	7.15
C3	0.80	2.85	2.26	35.50	84.11	7.88	2.63	-5.25	7.24

Site ID LN04MC **Coarse-silty Fluvic Sulfiwassents**

Cove

UTM	easting	northing
19T	261256	4578236

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value
		%	Hue	Value	Chroma			
A	0-5	100	5Y	2.5	1	sil		2
AC	5-21	100	5Y	2.5	1	sil		1
C	21-112	100	5Y	3	2	sil		1

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	1	5	2	3	6	17	72	11	0	sil
AC	0	2	2	3	8	15	68	17	0	sil
C	0	2	3	7	7	19	64	17	0	sil

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.15	8.80	9.53	46.50	67.30	7.32	2.96	4.36	18.02
AC	0.26	8.23	9.62	44.60	54.46	7.40	3.07	4.33	16.86
C	0.26	8.15	8.36	41.20	58.23	7.38	2.48	4.90	9.78

Site ID **LN03MC** **Coarse-silty Fluvic Sulfiwassents Cove**

UTM	easting	northing
19T	261200	4578187

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value
		%	Hue	Value	Chroma			
AC	0-26	100	5Y	2.5	1	sil		2
C1	26-38	100	5Y	2.5	1	sil		1
C2	38-50	100	5Y	3	2	l		1

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
AC	1	3	2	4	10	20	64	16	0	sil
C1	1	5	4	5	10	25	62	13	0	sil
C2	1	2	3	6	12	24	61	15	0	sil

Horizon	Bulk density (g/cm^3)	SOC (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
AC	0.24	7.08	8.04	41.10	159.70	7.38	3.39	-3.99	10.06
C1	0.28	7.41	7.61	51.10	118.52	7.24	3.58	-3.66	8.63
C2	0.32	7.34	7.47	54.66	167.57	7.19	3.23	-3.96	8.12

Site ID **S06CT011009** **Coarse-loamy over sandy Haplic Sulfiwassents**

LN01 **Cove**

	UTM	easting	northing
	19T	259824	4580289

Field Data

Horizon	Depth (cm)	Color				Field texture	Coarse Frags (%)	n-value	Notes
		%	Hue	Value	Chroma				
A	0-8	100	2.5Y	2.5	1	sil		0.7	
AC1	8-26	100	2.5Y	3	1	fsl	5 gravel	0	
AC2	26-58	100	2.5Y	2.5	1	fsl		0	
AC3	58-66	100	2.5Y	2.5	1	sil		0	*1
CA	66-70	100	2.5Y	3	1	l		0	
2Cg1	70-87	100	N	4	0	s	2 gravel	0	
2Cg2	87-106	50	2.5Y	6	1	vfs		0	
		50	2.5Y	4	1				
2Cg3	106-108	100	10Y	5	1	s		0	

Notes:

*1 Mucky texture: 10% unrubbed, 1% rubbed fibers

Lab Data

Horizon	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand total (%)	silt (%)	clay (%)	CF (%)	Lab texture
A	2	5	9	13	20	49	42	9	1	l
AC1	2	3	8	17	32	62	38	0	2	vfsl
AC2	1	5	16	18	15	55	44	1	0	fsl
AC3	2	12	20	22	12	68	27	5	1	sl
CA	8	12	22	21	10	73	23	4	4	sl
2Cg1	12	18	31	27	6	94	6	0	6	s
2Cg2	1	2	4	22	48	77	23	0	1	fsl
2Cg3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

(continued)

Site ID S06CT011009 **Coarse-loamy Haplic Sulfiwassents**

LN01 **Cove**

Horizon	Bulk density (g/cm^3)	N (%)	C (%)	$CaCO_3$ (%)	salintiy ($dS\ m^{-1}$)	oxidized salinity ($dS\ m^{-1}$)	Initial pH	Incubation pH (8 week)	pH change	salts (ppt)
A	0.61	0.329	3.66	3.05	32.10	64.28	7.02	4.62	-2.40	8.12
AC1	0.63	0.396	4.004	3.75	28.70	25.80	7.16	4.6	-2.56	9.63
AC2	0.47	0.292	4.409	5.11	25.40	148.24	6.86	3.42	-3.44	4.09
AC3	0.59	0.417	6.885	6.37	19.51	182.69	6.7	2.99	-3.71	31.10
CA	0.79	0.249	4.833	1.93	18.33	85.17	6.85	3.26	-3.59	8.20
2Cg1	1.27	0.024	0.395	0.44	20.83	11.51	7.39	3.39	-4.00	1.57
2Cg2	1.31	0.036	0.475	0.41	16.11	11.35	7.6	3.35	-4.25	1.46
2Cg3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

APPENDIX 2: PROPOSED AMENDMENTS TO SOIL TAXONOMY

(Stolt, 2007)

Wassents

Wassents are subaqueous Entisols. Defined as Entisols that have a positive water potential at the soil surface for more than 21 hours of each day. These soils are the first suborder to classify out under Entisols. The formative element Wass is derived from the German (Swiss) word "wasser" for water.

Key to Great Groups

LAA. Wassents that have, in all horizons within 100 cm of the mineral soil surface, an electrical conductivity of <0.2 dS/m in a 5/1 by volume mixture of water and soil. **Frasiwassents**

LAB. Other Wassents that have less than 35 percent (by volume) rock fragments and a texture of loamy fine sand or coarser in all layers within the particle-size control section. **Psammowassents**

LAC. Other Wassents that have sulfidic materials within 50 cm of the mineral soil surface. **Sulfiwassents**

LAD. Other Wassents that have, in all horizons at a depth between 20 and 50 cm below the mineral soil surface, both an *n* value of more than 0.7 and 8 percent or more clay in the fine earth fraction. **Hydrowassents**

LAE. Other Wassents that have *either* 0.2 percent or more organic carbon of Holocene age at a depth of 125 cm below the mineral soil surface *or* an irregular decrease in content of organic carbon from a depth of 25 cm to a depth of 125 cm or to a densic, lithic, or paralithic contact if shallower. **Fluviwassents**

LAF. Other Wassents. **Haplowassents**

Fluviwassents

Key to Subgroups

LAEA. Fluviwassents that have sulfidic materials within 100 cm of the mineral soil surface. **Sulfic Fluviwassents**

LAEB. Other Fluviwassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Fluviwassents**

LAEC. Other Fluviwassents that have a buried layer of organic soil materials, 20 cm or more thick, that has its upper boundary within 100 cm of the mineral soil surface. **Thapto-Histic Fluviwassents**

LAED. Other Fluviwassents that have a chroma of 3 or more in 40% or more of the matrix of one or more horizons between a depth of 15 and 100 cm from the soil surface. **Aeric Fluviwassents**

LAEE. Other Fluvawassents. **Typic Fluviwassents**

Frasiwassents

Key to Subgroups

LAAA. Frasiwassents that have, in all horizons at a depth between 20 and 50 cm below the mineral soil surface, both an *n* value of more than 0.7 and 8 percent or more clay in the fine earth fraction. **Hydric Frasiwassents**

LAAB. Other Frasiwassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Frasiwassents**

LAAC. Other Frasiwassents that have less than 35 percent (by volume) rock fragments and a texture of loamy fine sand or coarser in all layers within the particle-size control section. **Psammentic Frasiwassents**

LAAD. Other Frasiwassents that have a buried layer of organic soil materials, 20 cm or more thick, that has its upper boundary within 100 cm of the mineral soil surface. **Thapto-Histic Frasiwassents**

LAAE. Other Frasiwassents that have *either* 0.2 percent or more organic carbon of Holocene age at a depth of 125 cm below the mineral soil surface *or* an irregular decrease in content of organic carbon from a depth of 25 cm to a depth of 125 cm or to a densic, lithic, or paralithic contact if shallower. **Fluvic Frasiwassents**

LAAF.Other Frasiwassents that have a chroma of 3 or more in 40% or more of the matrix of one or more horizons between a depth of 15 and 100 cm from the soil surface. **Aeric Frasiwassents**

LAAG. Other Frasiwassents. **Typic Frasiwassents**

Haplowassents

Key to Subgroups

LAFA. Haplowassents that have a sulfidic materials within 100 cm of the mineral soil surface. **Sulfic Haplowassents**

LAFB. Haplowassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Haplowassents**

LAFC. Other Haplowassents that have a chroma of 3 or more in 40% or more of the matrix of one or more horizons between a depth of 15 and 100 cm from the soil surface. **Aeric Haplowassents**

LAFD. Other Haplowassents **Typic Haplowassents**

Hydrowassents

Key to Subgroups

LADA. Hydrowassents that have sulfidic materials within 100 cm of the mineral soil surface. **Sulfic Hydrowassents**

LADB. Other Hydrowassents that have, in all horizons at a depth between 20 and 100 cm below the mineral soil surface, both an *n* value of more than 0.7 and 8 percent or more clay in the fine earth fraction. **Grossic Hydrowassents**

LADC. Other Hydrowassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Hydrowassents**

LADD. Other Hydrowassents that have a buried layer of organic soil materials, 20 cm or more thick, that has its upper boundary within 100 cm of the mineral soil surface. **Thapto-Histic Hydrowassents**

LADE. Other Hydrawassents. **Typic Hydrowassents**

Psammowassents

Key to Subgroups

LABA. Psammawassents that have sulfidic materials within 100 cm of the mineral soil surface. **Sulfic Psammowassents**

LABB. Psammawassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Psammowassents**

LABC. Other Psammowassents that have *either* 0.2 percent or more organic carbon of Holocene age at a depth of 125 cm below the mineral soil surface *or* an irregular decrease in content of organic carbon from a depth of 25 cm to a depth of 125 cm or to a densic, lithic, or paralithic contact if shallower. **Fluventic Psammowassents**

LABD. Other Psammowassents that have a chroma of 3 or more in 40% or more of the matrix of one or more horizons between a depth of 15 and 100 cm from the soil surface. **Aeric Psammowassents**

LABE. Other Psammowassents. **Typic Psammowassents**

Sulfiwassents

Key to Subgroups

LACA. Sulfiwassents that have a lithic contact within 100 cm of the mineral soil surface. **Lithic Sulfiwassents**

LACB. Other Sulfiwassents that have, in some horizons at a depth between 20 and 50 cm below the mineral soil surface, *either or both*: 1. An *n* value of 0.7 or less; *or* 2. Less than 8 percent clay in the fine-earth fraction. **Haplic Sulfiwassents**

LACC. Other Sulfiwassents that have a buried layer of organic soil materials, 20 cm or more thick, that has its upper boundary within 100 cm of the mineral soil surface. **Thapto-Histic Sulfiwassents**

LACD. Other Sulfiwassents that have *either* 0.2 percent or more organic carbon of Holocene age at a depth of 125 cm below the mineral soil surface *or* an irregular decrease in content of organic carbon from a depth of 25 cm to a depth of 125 cm or to a densic, lithic, or paralithic contact if shallower. **Fluvic Sulfiwassents**

LACE. Other Sulfiwassents that have a chroma of 3 or more in 40% or more of the matrix of one or more horizons between a depth of 15 and 100 cm from the soil surface. **Aeric Sulfiwassents**

LACF. Other Sulfiwassents. **Typic Sulfiwassents**

Wassists

Wassists are subaqueous Histosols. Defined as Histosols that have a positive water potential at the soil surface for more than 21 hours of each day. These soils are the second suborder to classify out under Histosols after Folists. The formative element Wass is derived from the German (Swiss) word “wasser” for water.

Key to Great Groups

BBA. Wassists that have, in all horizons within 100 cm of the mineral soil surface, an electrical conductivity of <0.2 dS/m in a 5/1 by volume mixture of water and soil. **Frasiwassists**

BBB. Other Wassists that have sulfidic materials within 50 cm of the mineral soil surface. **Sulfiwassists**

BBC. Other Wassists. **Haplowassists**

Frasiwassists

Key to Subgroups

BBAA. Other Frasiwassists that:

1. Have more thickness of fibric soil materials than any other kind of organic soil material either:

a. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

b. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; and

2. Do not have a sulfuric horizon that has its upper boundary within 50 cm of the soil surface; and

3. Do not have sulfidic materials within 100 cm of the soil surface.

Fibric Frasiwassists

BBAB. Other Frasiwassists that have more thickness of sapric soil materials than any other kind of organic soil materials either:

1. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

2. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier.

Sapric Frasiwassists

BBAC. Other Frasiwassists.

Typic Frasiwassists

Sulfiwassists

Key to Subgroups

BBBA. Other Sulfiwassists that have more thickness of fibric soil materials than any other kind of organic soil material either:

1. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

2. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier;

Fibric Sulfiwassists

BBBB. Other Sulfiwassists that have more thickness of sapric soil materials than any other kind of organic soil materials either:

1. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

2. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier.

Sapric Sulfiwassists

BBBC. Other Sulfiwassists.

Typic Sulfiwassists

Haplowassists

Key to Subgroups

BBCA. Other Haplowassists that have more thickness of fibric soil materials than any other kind of organic soil material either:

1. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

2. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier;

Fibric Haplowassists

BBCB. Other Haplowassists that have more thickness of sapric soil materials than any other kind of organic soil materials either:

1. In the organic parts of the subsurface tier if there is no continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier; or

2. In the combined thickness of the organic parts of the surface and subsurface tiers if there is a continuous mineral layer 40 cm or more thick that has its upper boundary within the subsurface tier.

Sapric Haplowassists

BBCC. Other Haplowassists.

Typic Haplowassists

APPENDIX 3: WATER QUALITY MEASUREMENTS BY SEASON

Landscape Unit	Site ID	Chlorophyll *a* (µg/l)				Total Suspended Solids (mg/l)			
		Spring	Early Summer	Late Summer	Fall	Spring	Early Summer	Late Summer	Fall
By	WK79	8.6	3.5	4.4	2.8	17.5	1.5	13.5	51.3
By	WK80	9.1	3.2	5.6	3.0	13.3	34.5	22.0	53.0
Cv	WK69	3.3	6.4	10.5	5.0	19.7	16.0	21.5	128.3
Cv	WK72	4.2	8.4	7.2	5.3	19.0	24.8	23.0	122.0
Dc	WK86	2.9	4.1	3.5	1.9	18.2	17.8	30.5	53.3
Dc	WK88	2.5	10.2	3.1	5.3	19.5	19.3	20.7	45.5
Dp	WK74	17.0	7.8	3.9	1.9	16.7	13.7	25.3	50.5
Dp	WK76	18.0	4.4	2.3	1.4	17.0	13.5	34.8	66.3
Fb	WK85	11.2	9.4	9.9	2.7	21.5	37.5	60.3	123.8
Fb	WK90	7.6	15.1	25.5	4.4	24.0	17.5	20.5	58.2
Pt	WK92	7.7	3.7	4.6	3.1	13.0	11.8	47.7	49.8
Pt	WK94	7.4	6.5	5.1	2.1	6.5	26.7	24.5	53.0
Sg	WK82	12.0	4.1	5.5	5.3	10.0	31.2	18.3	45.3
Sg	WK93	15.2	4.3	7.3	2.2	10.0	21.0	20.3	52.5
By	GR05	14.0	9.5	12.8	12.6	15.5	27.3	10.3	54.5
By	GR08	13.0	9.9	18.6	10.9	21.8	29.3	8.0	101.0
Cv	GR09	11.9	29.9	22.1	5.4	13.3	32.0	14.5	54.8
Cv	GR10	9.5	12.1	33.5	5.0	9.0	28.8	12.0	36.3
Dc	GR03	35.9	29.2	30.1	29.2	12.0	24.2	18.0	81.7
Dc	GR04	22.4	21.3	30.6	37.7	14.8	32.0	14.3	48.8
Dp	GR01	17.7	13.6	15.8	2.4	16.0	19.0	12.7	85.8
Dp	GR02	11.4	10.1	10.5	2.1	12.7	28.0	12.3	80.5
Dp	GR07	18.3	7.5	9.3	4.0	12.5	34.0	6.3	98.7
Dp	GR14	19.0	17.2	18.0	2.9	30.0	29.3	12.0	91.7
Dp	GR15	16.2	7.7	7.6	11.3	24.3	30.5	6.8	95.3
Dp	GR16	15.0	7.0	9.6	2.9	11.2	17.0	6.2	88.5
Fb	GR11	17.5	18.6	18.8	10.1	16.5	39.3	19.3	30.7
Fb	GR12	18.8	20.1	22.9	9.0	14.8	51.0	14.8	60.0
Pt	GR06	17.5	7.4	28.6	3.4	27.8	19.0	11.5	45.3
Pt	GR13	ND	16.0	17.1	4.0	ND	14.3	9.5	86.3
By	LN05	24.5	5.0	6.3	1.1	11.0	15.7	61.0	49.8
By	LN06	5.9	7.3	8.6	1.4	20.0	19.0	49.5	72.7
Cv	LN01	13.2	6.4	10.4	1.9	19.5	21.0	50.0	84.5
Cv	LN02	10.5	7.9	5.3	1.1	18.2	26.0	38.0	55.0
Cv	LN03	6.7	9.2	6.2	0.5	18.5	12.0	32.5	22.5
Cv	LN04	5.8	7.4	0.5	7.8	15.8	20.7	31.0	21.7
Dc	LN11	5.3	10.0	9.4	1.3	20.5	33.0	42.0	55.5
Dc	LN12	6.8	9.0	25.0	1.9	15.0	40.5	24.5	46.7
Sg	LN07	15.7	1.6	5.5	1.0	14.7	16.0	89.3	55.0
Sg	LN08	6.9	2.0	3.2	1.5	12.8	24.8	47.5	88.0
Wf	LN09	5.2	3.7	4.0	1.6	18.0	25.0	51.0	92.5
Wf	LN10	15.1	3.1	6.0	1.0	18.3	26.2	70.8	93.0

APPENDIX 3: WATER QUALITY MEASUREMENTS BY SEASON

Landscape Unit	Site ID	Salinity (ppt)				Dissolved Oxygen (mg/l)			
		Spring	Early Summer	Late Summer	Fall	Spring	Early Summer	Late Summer	Fall
By	WK79	26	26	35	30	8.6	6.7	5.5	6.1
By	WK80	26	26	35	31	10.4	9.1	5.2	6.8
Cv	WK69	26	30	35	27	12.5	4.0	4.8	6.4
Cv	WK72	25	30	35	27	12.5	3.1	5.4	6.1
Dc	WK86	25	24	35	29	12.5	4.6	5.2	5.1
Dc	WK88	25	24	34	29	11.5	8.7	4.3	5.7
Dp	WK74	27	29	31	30	8.9	6.3	6.5	6.1
Dp	WK76	27	29	33	30	8.7	6.3	7.0	6.1
Fb	WK85	30	24	27	26	9.1	6.2	5.7	6.4
Fb	WK90	29	24	27	27	10.1	5.1	5.0	5.8
Pt	WK92	29	30	34	30	7.3	7.2	6.3	6.7
Pt	WK94	30	30	34	30	7.5	6.5	6.0	7.1
Sg	WK82	21	26	35	29	7.3	7.4	5.2	6.1
Sg	WK93	20	26	35	29	5.9	8.4	6.4	6.7
By	GR05	30	30	35	26	9.7	5.0	2.9	8.1
By	GR08	29	30	35	28	9.5	3.3	3.5	8.6
Cv	GR09	29	28	35	30	10.6	1.5	3.3	8.5
Cv	GR10	26	26	33	30	11.1	0.8	0.4	7.3
Dc	GR03	24	25	33	27	9.8	2.2	1.3	8.0
Dc	GR04	24	25	33	26	10.3	2.4	1.4	9.2
Dp	GR01	25	26	36	23	11.4	6.4	6.6	9.0
Dp	GR02	26	29	35	25	11.6	6.3	6.6	10.5
Dp	GR07	26	29	35	32	12.4	5.9	6.6	9.4
Dp	GR14	28	29	35	32	9.8	7.0	8.9	9.0
Dp	GR15	29	30	35	28	9.5	7.1	9.6	10.3
Dp	GR16	25	29	35	32	12.8	7.3	6.8	9.1
Fb	GR11	20	29	35	30	11.3	7.6	8.7	8.9
Fb	GR12	16	29	35	30	12.5	7.7	9.5	8.9
Pt	GR06	27	30	35	32	6.5	4.0	10.2	10.3
Pt	GR13	30	30	35	32	7.6	4.0	10.2	9.9
By	LN05	20	29	35	29	11.5	8.4	6.1	8.8
By	LN06	30	28	35	28	9.1	9.4	6.1	9.0
Cv	LN01	11	35	30	31	10.6	6.9	8.2	8.2
Cv	LN02	14	31	30	31	10.1	7.1	7.4	7.8
Cv	LN03	9	24	20	10	9.3	8.6	5.6	8.2
Cv	LN04	10	24	20	10	8.5	8.6	5.5	8.0
Dc	LN11	25	25	25	28	10.9	7.1	5.9	7.4
Dc	LN12	21	22	20	30	9.8	6.6	5.0	8.8
Sg	LN07	25	32	35	30	12.0	8.8	5.9	8.8
Sg	LN08	30	34	35	30	10.0	9.0	5.6	7.6
Wf	LN09	30	30	35	30	10.0	7.6	6.7	8.1
Wf	LN10	26	30	35	35	10.6	7.6	6.8	8.4

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

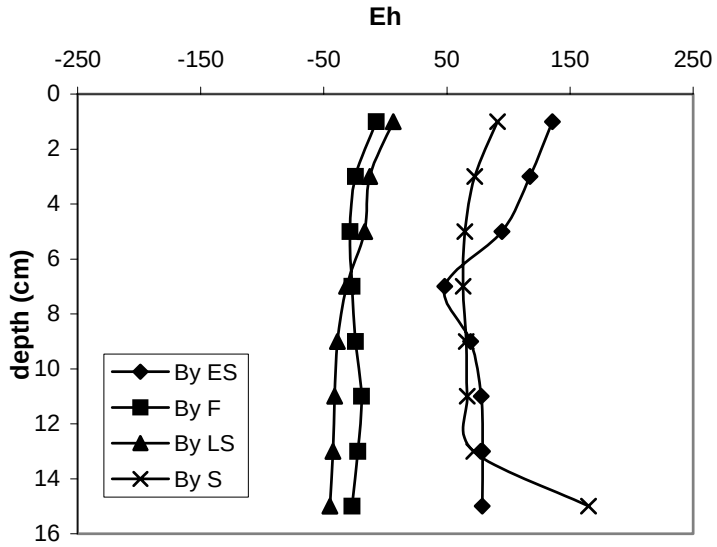

Figure A.1. Wickford Harbor, Bayfloor (WK79 & WK80). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

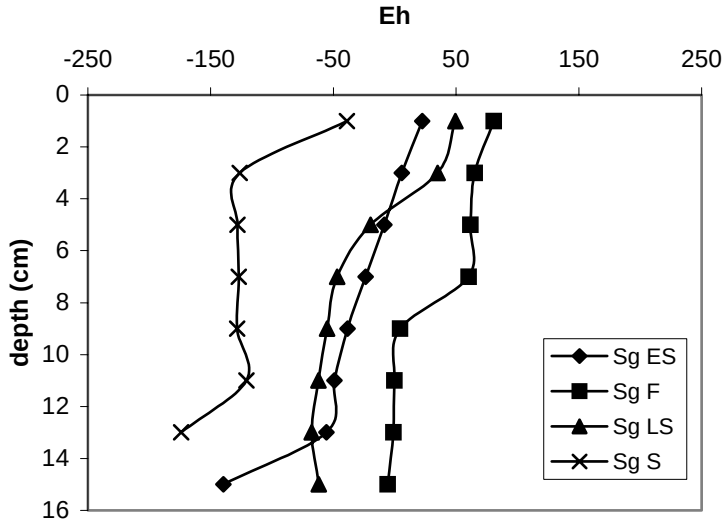

Figure A.2. Wickford Harbor, Shoal (WK82 & WK93). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

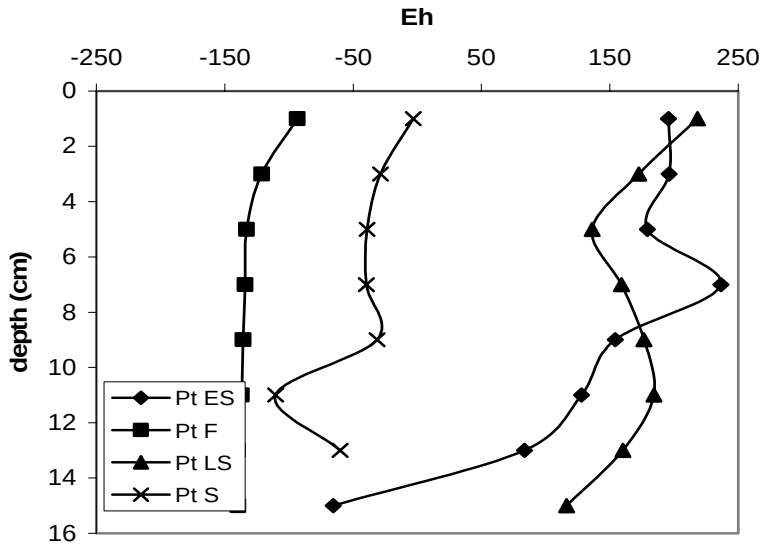

Figure A.3. Wickford Harbor, Platform (WK92 & WK94). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

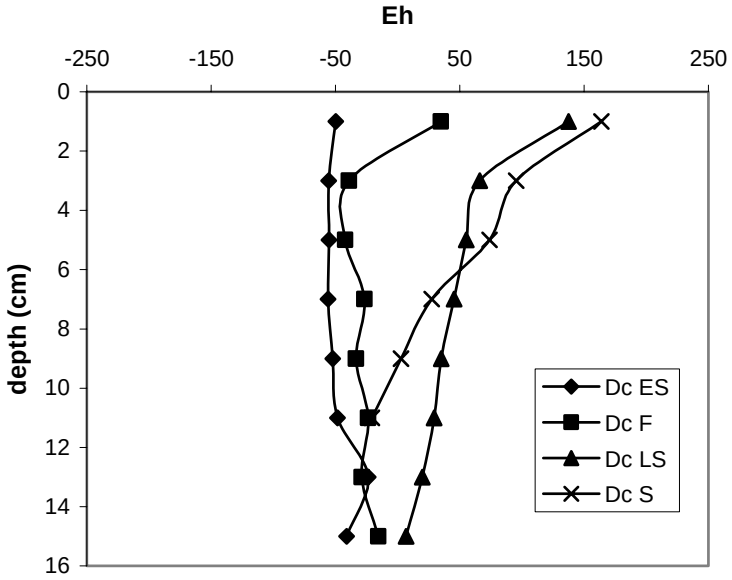

Figure A.4. Wickford Harbor, Drowned River Channel (WK86 & WK88). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

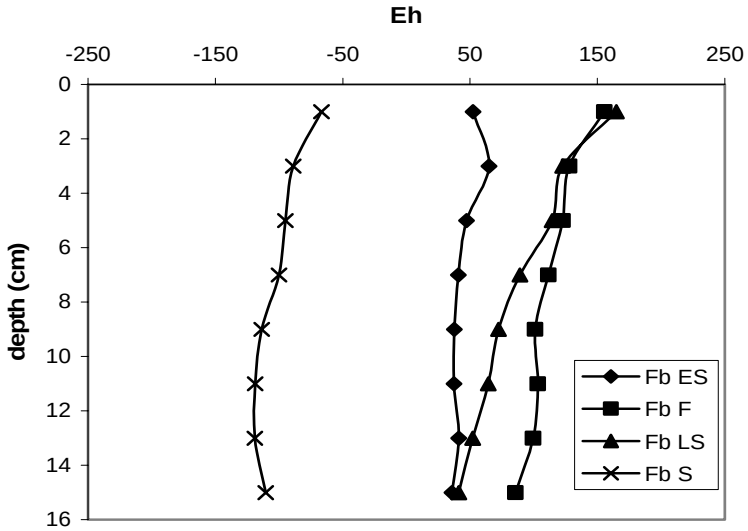

Figure A.5. Wickford Harbor, Fluviomarine Bottom (WK90 & WK85). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

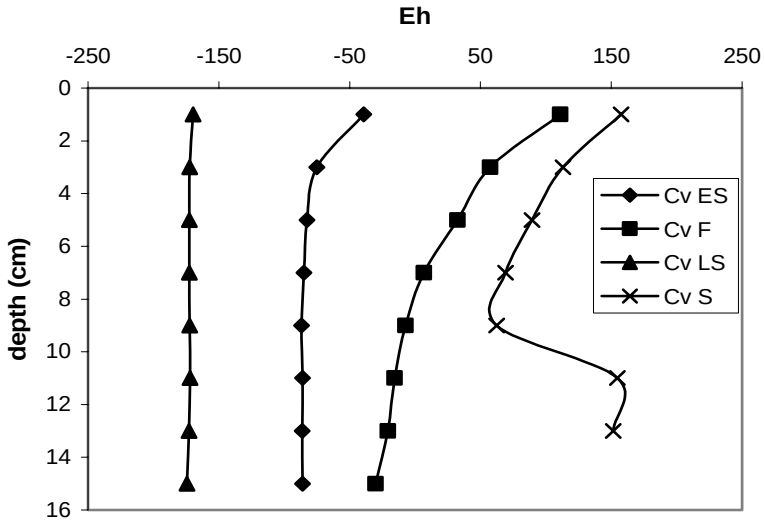

Figure A.6. Wickford Harbor, Cove (WK72 & WK69). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

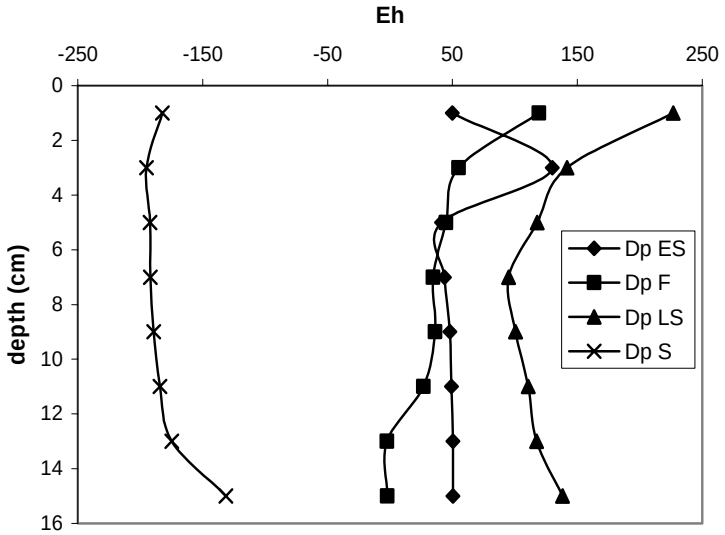

Figure A.7. Wickford Harbor, Depositional Beach (WK74 & WK76). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

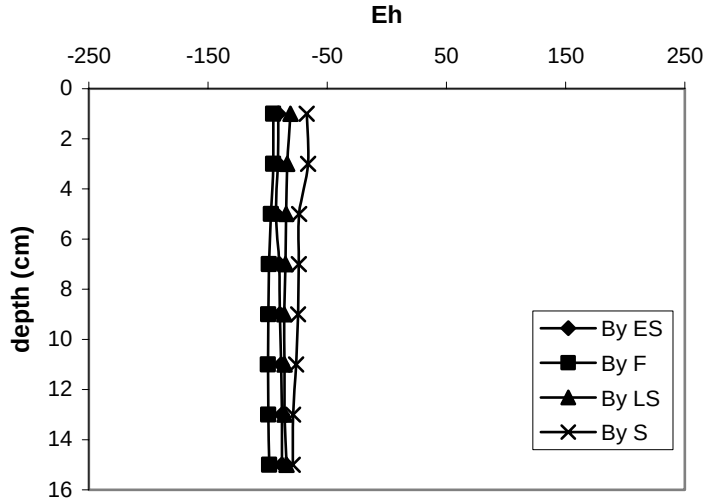

Figure A.8. Little Narragansett Bay, Bayfloor (LN05 & LN06). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

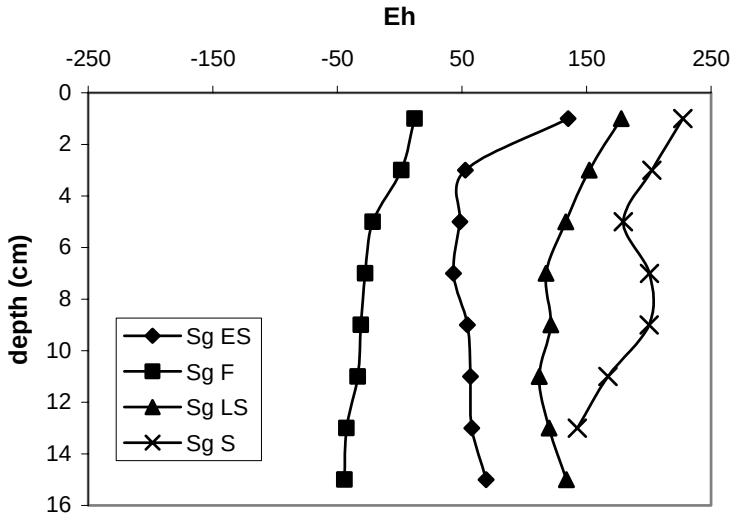

Figure A.9. Little Narragansett Bay, Shoal (LN07 & LN08). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

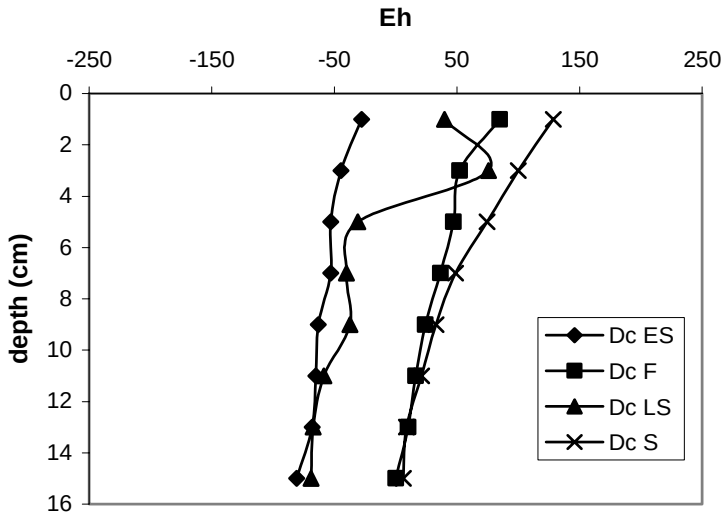

Figure A.10. Little Narragansett Bay, Drowned River Channel (LN11 & LN12). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

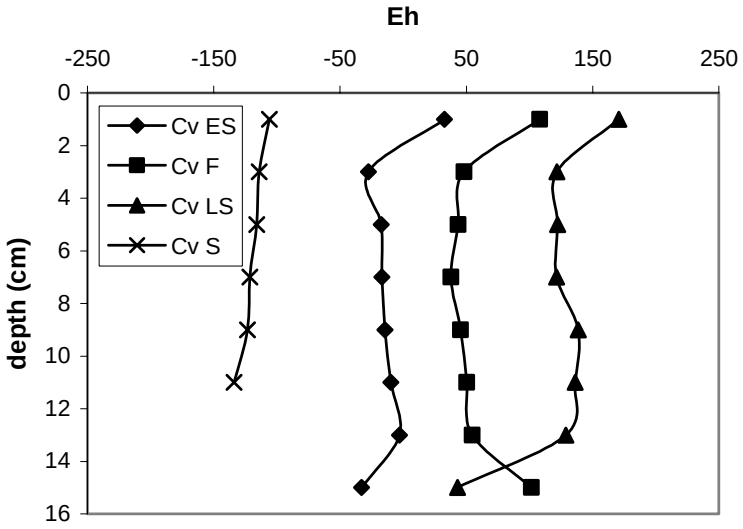

Figure A.11. Little Narragansett Bay, Cove (LN03 & LN04). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

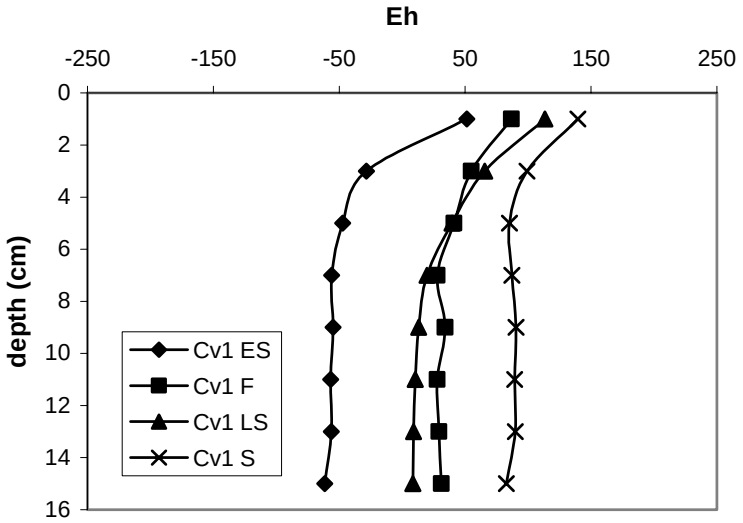

Figure A.12. Little Narragansett Bay, Cove (LN01 & LN02). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

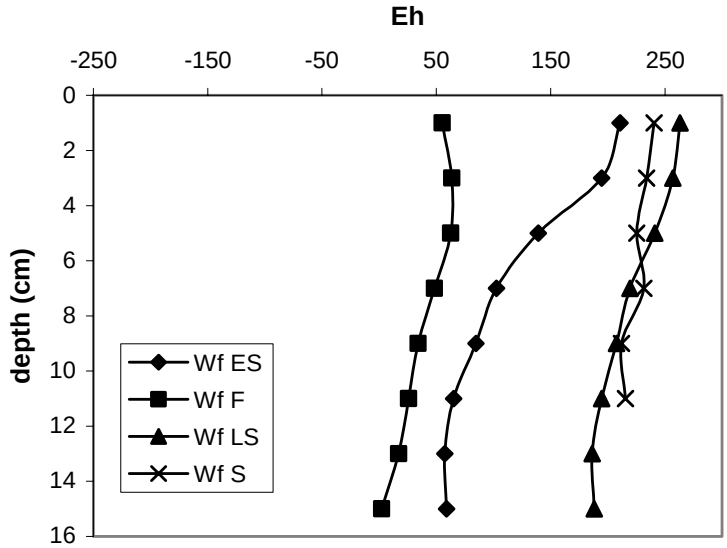

Figure A.13. Little Narragansett Bay, Washover Fan Flat (LN09 & LN10). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

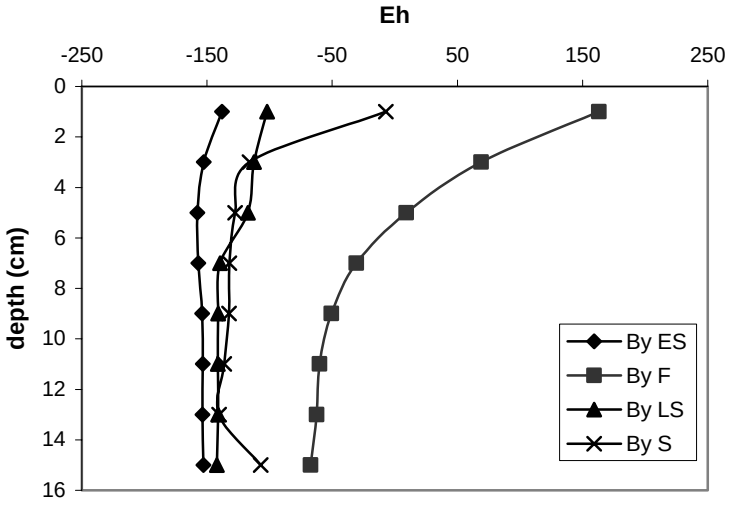

Figure A.14. Greenwich Bay, Bayfloor (GR05 & GR08). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

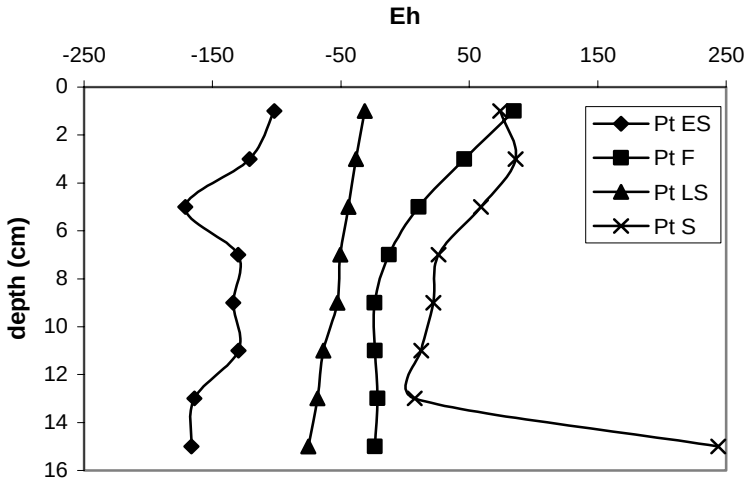

Figure A.15. Greenwich Bay, Platform (GR06 & GR13). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

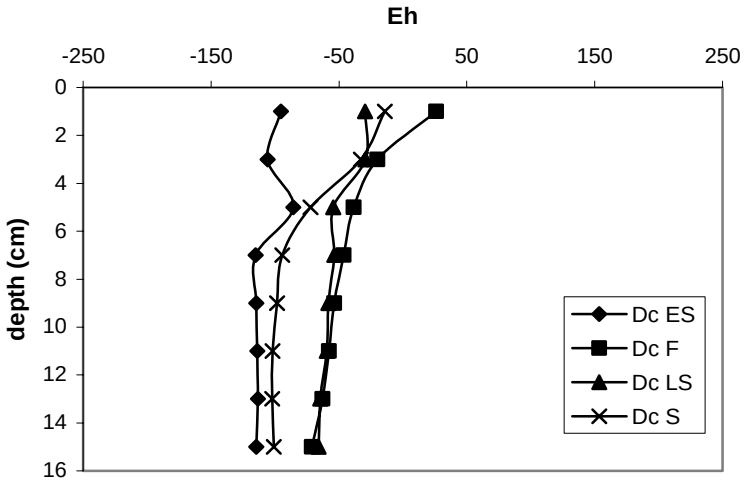

Figure A.16. Greenwich Bay, Drowned River Channel (GR03 & GR04). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

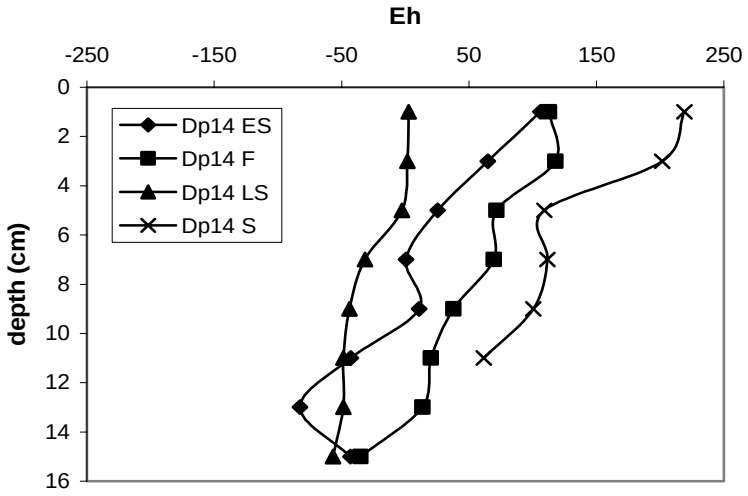

Figure A.17. Greenwich Bay, Depositional Beach (GR14 & GR15). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

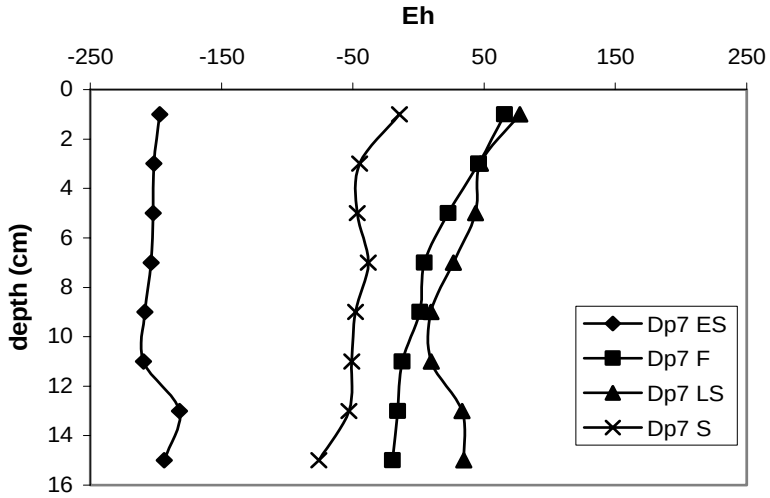

Figure A.18. Greenwich Bay, Depositional Beach (GR07 & GR16). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

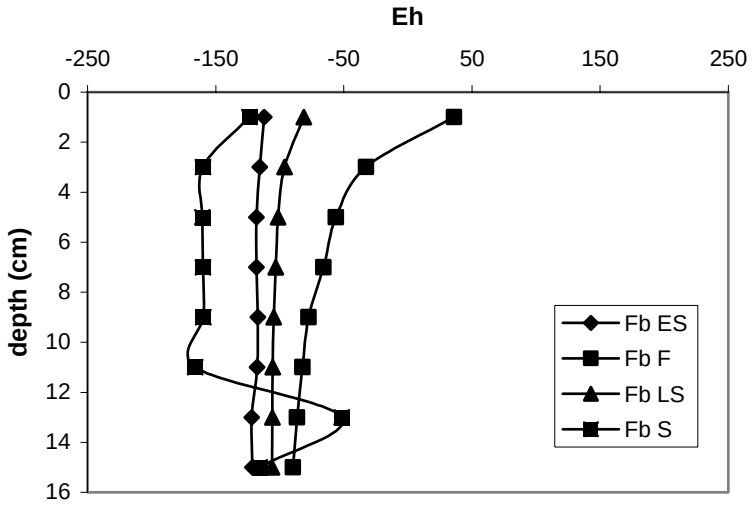

Figure A.19. Greenwich Bay, Fluviomarine Bottom (GR11 & GR12). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

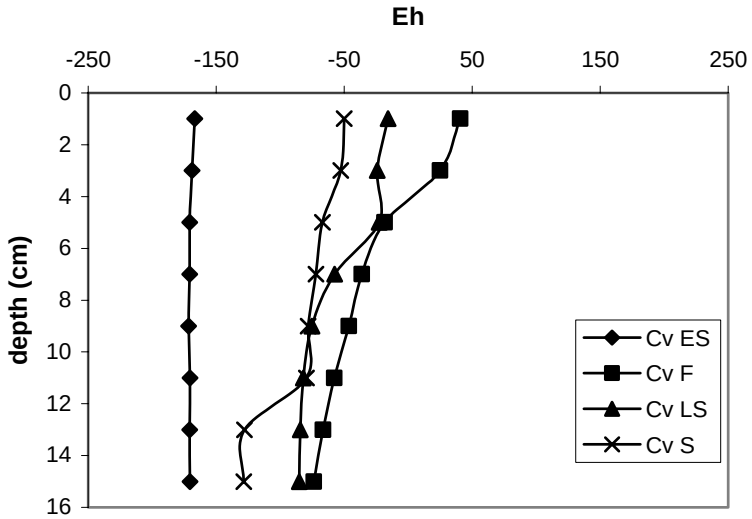

Figure A.20. Greenwich Bay, Cove (GR09 & GR10). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 4: SEASONAL REDOX POTENTIAL PROFILES

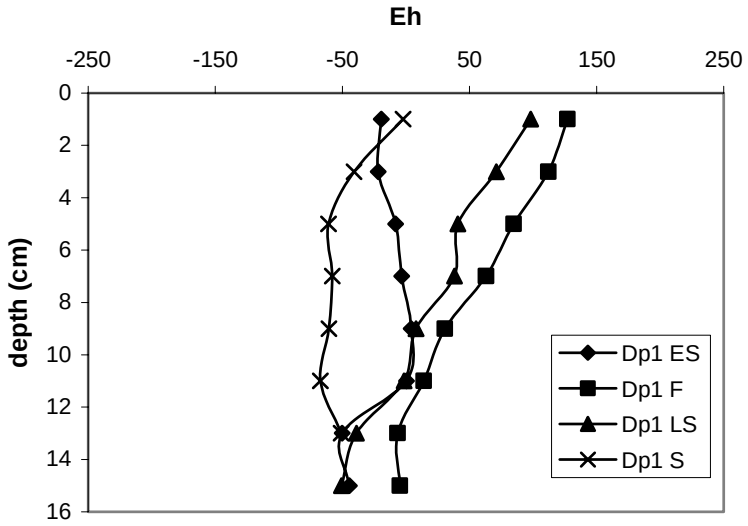

Figure A.21. Greenwich Cove, Depositional Beach (GR01 & GR02). Monitoring periods: S = Spring; ES = Early Summer; LS = Late Summer; F = Fall.

APPENDIX 5: SULFIDE ANALYSIS DATA.

Sample ID	Bay	Landscape Unit	AVS (ug/g)†	CRS (ug/g)	TS (ug/g)	% SOC	%CaCO3
Core2_3C	Little Narragansett	Dc	1.12	435	436	0.60	0.59
Core2_3Cg2	Little Narragansett	Dc	0.22	779	779	0.96	0.93
Core2_3Cg3	Little Narragansett	Dc	0.84	1050	1051	0.77	0.86
Core2_A	Little Narragansett	Dc	0.21	1193	1193	6.65	4.87
Core2_AC	Little Narragansett	Dc	14.31	4292	4306	5.39	3.41
Core4_2Ab	Little Narragansett	Dc	0.33	2447	2448	3.26	1.38
Core4_2AC2	Little Narragansett	Dc	0.96	1229	1230	1.25	0.75
Core4_3C	Little Narragansett	Dc	0.66	1640	1640	0.74	0.52
Core4_A	Little Narragansett	Dc	0.14	2019	2019	6.68	4.75
Core4_AC	Little Narragansett	Dc	26.94	5772	5799	6.29	3.83
Drc1 2C2	Wickford	Dc	0.00	20	20	0.90	0.17
Drc1 C2	Wickford	Dc	0.00	3967	3967	2.63	1.54
Fb2 2C1	Wickford	Fb	0.00	1318	1318	1.83	0.66
Fb2 2C2	Wickford	Fb	0.00	672	672	1.06	0.38
Fb2 Ab	Wickford	Fb	0.00	5854	5854	1.89	0.50
GR04_C1	Greenwich	Dc	1.54	6579	6580	5.24	4.43
GR04_C2	Greenwich	Dc	5.33	7839	7845	4.24	2.62
GR04_C3	Greenwich	Dc	1.48	7519	7521	4.68	4.36
GR04_C4	Greenwich	Dc	0.09	7794	7794	4.45	4.09
GR12_A	Greenwich	Fb	210.05	3501	3711	5.84	4.00
GR12_C1	Greenwich	Fb	7.02	3510	3517	3.35	2.10
GR12_C2	Greenwich	Fb	0.80	3583	3584	3.12	1.79
Mc3 AC	Wickford	Cv	16.25	6250	6266	4.68	3.36

†AVS=acid volatile sulfides, CRS=chromium reducible sulfur, TS=total sulfides, SOC=soil organic carbon,

APPENDIX 5: SULFIDE ANALYSIS DATA.

Sample ID	Bay	Landscape Unit	AVS (ug/g)	CRS (ug/g)	TS (ug/g)	% SOC	%CaCO3
Mc3 C2	Wickford	Cv	0.46	1697	1697	2.63	1.27
RI003-2006-003-GR_C	Greenwich	Dp	0.00	33	33	0.26	0.28
RI003-2006-003-GR_CA1	Greenwich	Dp	0.04	212	212	0.26	0.21
RI003-2006-003-GR_CA2	Greenwich	Dp	0.00	447	447	0.39	0.27
RI003-2006-003-GR_Cg1	Greenwich	Dp	0.00	42	42	0.23	0.09
RI003-2006-004-GR_C/A	Greenwich	Pt	0.05	2659	2659	0.53	0.37
RI003-2006-004-GR_C1	Greenwich	Pt	1.02	215	216	0.32	0.22
RI003-2006-008-GR_Cg2	Greenwich	Cv	12.12	3728	3741	2.23	1.59
S06CT011008_A1	Little Narragansett	Bs	22.58	890	912	0.89	0.85
S06CT011008_A2	Little Narragansett	Bs	5.24	859	864	1.35	0.95
S06CT011008_C3	Little Narragansett	Bs	1.59	915	916	0.89	0.66
S06CT011009_A2	Little Narragansett	Cv	0.47	4451	4451	5.05	3.75
S06CT011009_Cg2	Little Narragansett	Cv	0.23	897	897	0.40	0.41
S06RI009001_A2	Little Narragansett	Cv	11.12	8490	8501	7.50	6.64
S06RI009001_C1	Little Narragansett	Cv	2.21	8058	8060	8.20	6.67
S06RI009001_C2	Little Narragansett	Cv	0.22	10770	10770	8.62	6.14
S06RI009001_C3	Little Narragansett	Cv	1.16	11591	11592	8.71	6.79
Sb4 2C1	Wickford	Dp	0.78	915	916	1.21	0.42
Sb4 2C2	Wickford	Dp	0.28	1005	1005	0.81	0.35
Sb4 3C	Wickford	Dp	0.19	661	661	0.76	0.29
Sb4 C1	Wickford	Dp	0.80	283	284	0.53	0.13
Wick266_^Cg2	Wickford	Sg	0.33	2051	2052	0.71	0.28
Wick267_2C1	Wickford	By	0.90	962	962	1.00	0.63
Wick267_AC	Wickford	By	10.74	4175	4186	4.15	2.80
Wick267_C1	Wickford	By	0.37	3331	3331	3.75	2.75
Wick268_Cg1	Wickford	Pt	0.13	427	427	0.68	0.37
Wick268_Cg3	Wickford	Pt	0.37	346	346	0.52	0.37
Wick268_Cg4	Wickford	Pt	0.88	917	918	0.88	0.57

APPENDIX 5: SULFIDE ANALYSIS DATA.

Sample ID	sand (%)	silt (%)	clay (%)	salinity change*	salt (ppt)	incubation pH	pH change (2 wk)
Core2_3C	72	25	3	-13	1.93	3.35	-0.84
Core2_3Cg2	69	28	3	-32	1.11	4.24	-0.62
Core2_3Cg3	70	26	4	-18	0.89	3.92	-0.71
Core2_A	37	48	15	62	7.37	3.21	-2.77
Core2_AC	30	55	14	15	14.59	3.06	-3.38
Core4_2Ab	65	33	2	1	3.66	3	-2.30
Core4_2AC2	67	31	2	-15	2.18	3.86	-1.48
Core4_3C	81	17	1	-5	2.42	3.22	-2.29
Core4_A	28	72	0	54	6.85	4.73	-1.97
Core4_AC	37	63	0	14	6.19	4.29	-2.71
Drc1 2C2	80	18	3	3	nd	3.99	-2.63
Drc1 C2	62	30	8	47	nd	3.28	-3.16
Fb2 2C1	80	20	0	20	nd	3.7	-2.69
Fb2 2C2	92	8	0	9	nd	3.82	-2.51
Fb2 Ab	79	21	0	69	nd	2.96	-2.46
GR04_C1	23	63	15	0	10.85	4.53	-0.54
GR04_C2	17	55	29	15	11.36	4.41	-0.36
GR04_C3	6	58	36	14	8.03	3.75	-2.31
GR04_C4	9	57	34	6	10.11	3.72	-2.91
GR12_A	41	46	14	24	6.63	4.08	-2.74
GR12_C1	32	48	20	34	3.56	4.93	-1.91
GR12_C2	38	42	20	23	3.91	3.85	-3.48
Mc3 AC	9	79	13	26	nd	3.46	-1.77
Mc3 C2	75	24	0	13	nd	3.14	-2.62
RI003-2006-003-GR_C	53	46	1	-18	1.36	7.15	-1.17

*salinity change=difference between initial saturated paste salinity and salinity after peroxide oxidation, salt (ppt)=dry weight of salts in ppt soil, incubation pH=pH after 8 weeks moist incubation, pH change (2 wk)=change in pH after 2 weeks moist incubation.

APPENDIX 5: SULFIDE ANALYSIS DATA.

Sample ID	sand (%)	silt (%)	clay (%)	salinity change	salt (ppt)	incubation pH	pH change (2 wk)
RI003-2006-003-GR_CA1	96	3	1	-6	0.61	8.08	-0.17
RI003-2006-003-GR_CA2	94	4	1	-6	1.53	4.63	-1.94
RI003-2006-003-GR_Cg1	97	3	0	0	0.29	5.35	-1.86
RI003-2006-004-GR_C/A	47	52	2	-5	1.89	4.41	-0.84
RI003-2006-004-GR_C1	99	1	0	-8	1.47	5.45	-0.51
RI003-2006-008-GR_A2	16	63	21	5	10.03	5.63	-2.06
RI003-2006-008-GR_Cg2	35	60	5	4	3.02	4.97	-1.03
S06CT011008_A1	78	22	0	-7	0.44	5.34	-0.74
S06CT011008_A2	83	17	1	4	2.69	4.46	-1.88
S06CT011008_C3	79	18	3	7	1.30	4.36	-1.21
S06CT011009_A2	64	36	0	-3	9.63	4.6	-1.72
S06CT011009_Cg2	77	23	0	-5	1.46	3.35	-3.39
S06RI009002_A2	8	63	29	57	16.17	3.93	-2.49
S06RI009002_C1	12	72	17	39	10.69	3.7	-2.99
S06RI009002_C2	5	76	19	33	10.62	3.71	-2.69
S06RI009002_C3	4	71	25	29	14.45	3.72	-2.77
Sb4 2C1	66	34	0	5	nd	3.98	-1.24
Sb4 2C2	49	51	0	2	nd	4.67	-0.57
Sb4 3C	46	54	0	8	nd	2.99	-2.14
Sb4 C1	93	7	0	2	nd	5.38	-1.18
Wick266_^Cg2	90	8	2	-8	1.04	5.26	-1.20
Wick267_2C1	97	3	0	7	1.62	4.21	-2.46
Wick267_AC	32	49	19	20	7.31	4.16	-2.76
Wick267_C1	40	44	16	33	5.43	3.98	-2.31
Wick268_Cg1	95	4	1	-19	1.77	5.52	-1.13
Wick268_Cg3	93	6	1	-20	1.79	3.65	-3.42
Wick268_Cg4	86	11	2	-6	1.86	3.95	-3.29

BIBLIOGRAPHY

Addy, K., and L. Green. 1996. *Algae in aquatic ecosystems*. Natural Resources Facts, University of Rhode Island, College of Resource Development, Department of Natural Resources Science Cooperative Extension. Fact sheet no. 96-4.

Bailey, J.S., R.J. Stevens, and D.J. Kilpatrick. 1989. A rapid method for predicting the lime requirement of acidic temperate soils with widely varying organic matter contents. *Journal of Soil Science* 40:807-847.

Baldwin, D.S., K.C. Hall, G.N. Rees, and A.J. Richardson. 2007. Development of a protocol for recognizing sulfidic sediments (potential acid sulfate soils) in freshwater wetlands. *Ecological Management and Restoration* 8:56-60.

Berner, R.A. 1970. Sedimentary pyrite formation. *American Journal of Science* 268:1-23.

Biggs, R.B. 1967. The sediments of Chesapeake Bay. p. 239-260. *In* Lauff, G.H. (eds.). *Estuaries*. American Association for the Advancement of Science, Washington, D.C.

Bohn, H.L. 1971. Redox potentials. *Soil Science* 112:39-45.

Bohn, H.L., B. McNeal, and G.O. O'Conner. 1979. *Soil Chemistry*. John Wiley and Sons, New York, NY.

Boothman, W.S. 1998. *Determination of degree of pyritization (DOP) in sediments*. Environmnetal Protection Agency, National Health and Ecological Effects Research Laboratory, Atlantic Ecology Division, Narragansett, RI.

Boothroyd, J.C., N.E. Friedrich, and S.R. McGinn. 1985. Geology of microtidal coastal lagoons: Rhode Island. *Marine Geology* 63:35-76.

Bortone, S.A. 2005. The quest for the "perfect" estuarine indicator: an introduction. p. 1-3. *In* Bortone, S.A. (eds.). *Estuarine Indicators*. CRC Press, Washington, D.C.

Brady, N.C., and R.R. Weil. 2002. *The nature and property of soils*. Prentice Hall, Upper Saddle River, NJ.

Bradley, M.P. 2001. *Subaqueous soils and subtidal wetlands in Rhode Island*. M.S. Thesis Department of Natural Resources Science. University of Rhode Island, Kingston, RI.

Bradley, M.P., and M.H. Stolt. 2002. Evaluating methods to create a base map for subaqueous soil inventory. *Soil Science* 167:222-228.

Bradley, M.P., and M.H. Stolt. 2003. Subaqueous soil-landscape relationships in a Rhode Island estuary. *Soil Science Society of America Journal* 67:1487-1495.

Bradley, M.P., and M.H. Stolt. 2006. Landscape-level seagrass-sediment relations in a coastal lagoon. *Aquatic Botany* 84:121-128.

Brouwer, H., and T.P. Murphy. 1994. Diffusion method for the determination of acid-volatile sulfides (AVS) in sediment. *Environmental Toxicology and Chemistry* 13:1273–1275.

Brown, C.W. 1939. Hurricanes and shore-line changes in Rhode Island. *Geographical Review* 29:416-430.

Bush, G.W. 2004. *U.S. ocean action plan*. United States Government Publication, Washington, D.C.

Cicchetti, G., J.S. Latimer, S.A. Rego, W.G. Nelson, B.J. Bergen, and L.L. Coiro. 2006. Relationships between near-bottom dissolved oxygen and sediment profile camera measures. *Journal of Marine Systems* 62:124-141.

Clesceri, L.S., A.E. Greenberg, and A.D. Eaton (eds.). 1998. *Standard methods for the examination of water and wastewater 20th ed*. American Public Health Association, Washington, D.C.

Compton, J.E., R.D. Boone, G. Motzkin, and D.R. Foster. 1998. Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: Role of vegetation and land-use history. *Oecologia* 116:536-542.

Cooper, S.R., and G.S. Brush. 1993. A 2,500-year history of anoxia and eutrophication in the Chesapeake Bay. *Estuaries* 16:617-626.

Coppock, C., and M.C. Rabenhorst. 2003. *Subaqueous soils of Rehoboth Bay, Delaware: Soil mapping in a coastal lagoon*. ASA-CSSA-SSSA symposium poster, Denver, CO.

Curtin, D., C.A. Campbell, and D. Messer. 1996. Prediction of titratable acidity and soil sensitivity to pH change. *Journal of Environmental Quality* 25:1280-1284.

D'Avanzo, C.D., and J.N. Kremer. 1994. Diel oxygen dynamics and anoxic events in an eutrophic estuary of Waquoit Bay, Massachusetts. *Estuaries* 17:131-139.

Davis, A.A., M.H. Stolt, and J.E. Compton. 2004. Spatial distribution of soil carbon in southern New England hardwood forest landscapes. *Soil Science Society of America Journal* 68:895-903.

Day, J.W. Jr., C.A.S. Hall, W.M. Kemp, and A. Yáñez-Arancibia. 1989. *Estuarine Ecology*. John Wiley & Sons, New York, NY.

Demas, G.P. 1998. *Subaqueous soils of Sinepuxent Bay, MD*. PhD Dissertation. University of Maryland, College Park, MD.

Demas, G.P., and M.C. Rabenhorst. 1999. Subaqueous soils: pedogenesis in a submersed environment. *Soil Science Society of America Journal* 63:1250-1257.

Demas, G.P., and M.C. Rabenhorst. 2001. Factors of subaqueous soil formation; a system of qualitative pedology for submersed environments. *Geoderma* 102:189-204.

Demas, S.Y., A.M. Hall, D.S. Fanning, M.C. Rabenhorst, and E.K. Dzantor. 2004. Acid sulfate soils in dredged materials from tidal Pocomoke Sound in Somerset County, MD, USA. *Australian Journal of Soil Research* 42:537-545.

Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation - habitat requirements as barometers of Chesapeake Bay health. *BioScience* 43:86-94.

Desbonnet, A. 1999. *Pawcatuck watershed water resources: a management issues profile.* Rhode Island Sea Grant Program Coastal Resources Center. University of Rhode Island, Narragansett, RI.

Dillingham, T.P., R. Abrams, A. Desbonnet, and J.M. Willis. 1993. *The Pawcatuck River estuary and Little Narragansett Bay: an interstate management plan*. Rhode Island Coastal Resources Management Council and Connecticut Department of Environmental Protection.

Dobson, R.L., R.L. Gabrielson, A.S. Baker, and L. Bennett. 1983. Effects of lime particle size and distribution and fertilizer formulation on clubroot caused by Plasmodiophora brassicae. *Plant Disease* 67:50-52.

Dryer, K.R. (eds.). 1979. *Estuarine Hydrography and Sedimentation*. Cambridge University Press, Cambridge, U.K.

Erikson, L.H. 1998. *Flushing times of Greenwich Bay, RI: Estimates based on freshwater inputs*. M.S. Thesis Department of Ocean Engineering. University of Rhode Island, Kingston, RI.

Fanning, D.S., and M.C.B. Fanning. 1989. *Soil morphology, genesis, and classification*. John Wiley and Sons, New York, NY.

Fischler, K.C., L.R. Ellis, T.J. Saunders, and M.E. Collins. 2005. *New latitudes: Subaqueous soil research in Florida*. Abstracts of the ASA-CSSA-SSSA international meeting, Salt Lake City, UT.

Fitzgerald, D.M., I.V. Buynevich, R.S. Davis Jr., and M.S. Fenster. 2002. New England tidal inlets with special reference to riverine associated inlet systems. *Geomorphology* 48:179-208.

Flannagan, C., and L.J. Osher. 2003. *Subaqueous soil survey of Taunton Bay, Maine: Techniques and Applications*. Abstracts of the Estuarine Research Federation Biennial Conference, Seattle, WA.

Fossing, H., and B.B. Jorgensen. 1989. Measurement of bacterial sulfate reduction in sediments: evaluation of a single-step chromium reduction method. *Biogeochemistry* 8:205-222.

Frithsen, J.B. 1989. *Marine eutrophication: nutrient loading, nutrient effects, and the federal response*. University of Rhode Island Graduate School of Oceanography, Narragansett, RI.

Fulweiler, R.W., and S.W. Nixon. 2005. Export of nitrogen, phosphorus, and suspended solids from a southern New England watershed to Little Narragansett Bay. *Biogeochemistry* 76:567-593.

Germano, J., and D. Rhoads.1988. *Narragansett Bay sediment quality survey*. Rhode Island State publication NBP-89-23. Rhode Island Department of Environmental Management, Providence, RI.

Germano, J.D., D.C. Rhoads, L.F. Boyer, C.A. Menzie, and J. Ryther. 1989. REMOTS Imaging and side-scan sonar: Efficient tools for mapping seafloor topography, sediment type, bedforms, and benthic biology. *Oceanic processes in marine pollution* 4:39-48.

Glasgow, H.B. Jr., and J.M. Burkholder. 2000. Water quality trends and management implications from a five-year study of a eutrophic estuary. *Ecological Applications* 10:1024-1046.

Goodman, J.L., K.A. Moore, and W.C. Dennison. 1995. Photosynthetic response of eelgrass (*Zostera marina* L.) to light and sediment sulfide in a shallow barrier island lagoon. *Aquatic Botany* 50:37-47.

Granger, S., M. Brush, B. Buckley, M. Traber, M. Richardson, and S. Nixon. 2000. *Restoring water quality in Greenwich Bay: An assessment of eutrophication in*

Greenwich Bay. Graduate School of Oceanography, University of Rhode Island, Kingston, RI.

Griffin, T.M., M.C. Rabenhorst, and D.S. Fanning. 1989. Iron and trace metals in some tidal marsh soils of the Chesapeake Bay. *Soil Science Society of America Journal* 53:1010-1019.

Gustavson, T.C., and J.C. Boothroyd. 1987. A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: A modern analog of the southeastern margin of the Laurentide Ice Sheet. *Geological Society of America Bulletin* 99:187-200.

Heiri, O., A.F. Lotter, and G. Lemeke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25:101-110.

Hennessee, E.L., P.J. Blakeslee, and J.M. Hill. 1986. The distributions of organic carbon and sulfur in surficial sediments of the Maryland portion of Chesapeake Bay. *Journal of Sedimentary Petrology* 56:674-683.

Hinchey, E.K., and L.C. Schaffner. 2005. An evaluation of electrode insertion techniques for measurement of redox potential in estuarine sediments. *Chemosphere* 59:703-710.

Holmer, M., and S.L. Nielsen. 1997. Sediment sulfur dynamics related to biomass-density patterns in *Zostera marina* (eelgrass) beds. *Marine Ecological Progress Series* 146:163-171.

Hudson, B.D. 1990. Concepts of soil mapping and interpretation. *Soil Survey Horizons* 31:63-73.

Hudson, B.D. 1992. *The soil survey as a paradigm-based science*. USDA-SCS National Soil Survey Center, Lincoln, NE.

Jenny, Hans. 1941. *Factors of soil formation*. McGraw Hill Book Co. Inc., New York, NY.

Jespersen, J.L., and L.J. Osher. 2007. Carbon storage in the soils of a mesotidal gulf of Maine estuary. *Soil Science Society of America Journal* 71:372-379.

Jorgensen, B.B. 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). *Limnology and Oceanography* 22:814-831.

Joubert, L., and J. Lucht. 2000. *Wickford Harbor watershed assessment*. URI Cooperative Extension, Kingston, RI.

Keller, A.A., C.A. Oviatt, H.A. Walker, and J.D. Hawk. 1999. Predicted impacts of elevated temperature on the magnitude of the winter-spring phytoplankton bloom in temperate coastal waters: a mesocosm study. *Limnology and Oceanography* 44:344-356.

Kennedy, S., and V. Lee. 2003. *Greenwich Bay: An Ecological History*. Rhode Island Sea Grant Communications Office, Narragansett, RI.

Knox, G.A. 1986. *Estuarine ecosystems: a systems approach*. vol. 1. CRC Press, Inc. Boca Raton, FL.

Lasorsa, B., and A. Casas. 1996. A comparison of sample handling techniques and analytical methods for determination of acid volatile sulfides in sediment. *Marine Chemistry* 52:211-220.

Leonard, E.N., V.R. Mattson, D.A. Benoit, R.A. Hoke, and G.T. Ankley. 1993. Seasonal variation of acid volatile sulfide concentration in sediment cores from three northeastern Minnesota lakes. *Hydrobiologia* 271:87-95.

Light, T.S. 1973. Standard solution for redox potential measurements. *Analytical Chemistry* 44:1038-1039.

MapCoast. 2007. *MapCoast subaqueous soils and sediment user conference report.* <http://www.ci.uri.edu/projects/mapcoast/> Accessed 4/10/2007.

McMaster, R.L. 1960. Sediments of the Narragansett Bay System and Rhode Island Sound, Rhode Island. *Journal of Sedimentary Petrology* 30:249-274.

McMaster, R.L. 1984. Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, USA. *Sedimentology* 31:777-792.

Meijer, L.E., and Y. Avnimelech. 1999. On the use of micro-electrodes in fish pond sediments. *Aquacultural Engineering* 21:71-83.

Microsoft. 2003. *Microsoft Excel XP*, Microsoft Corporation, Redmond, WA.

Midwood, A.J., and T. W. Boutton. 1998. Soil carbonate decomposition by acid has little effect on 13C of organic matter. *Soil Biology and Biochemistry* 30:1301-1307.

Moshiri, G.A. and W.G. Crumpton. 1978. Some aspects of redox trends in the bottom muds of a mesotrophic bayou estuary. *Hydrobiologia* 57:155-158.

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon and organic matter. p. 961-1010. *In* Sparks, D.L., A.L. Page, P.A. Helmke, R.H. Loeppert, P.N. Soltanpour, M.A. Tabatabai, C.T. Johnston, and M.E. Sumner (eds.).

Methods of soil analysis part 3; Chemical methods, book series 5, Soil Science Society of America, Madison, WI.

Oakley, B.A., and J.C. Boothroyd. 2006. *Benthic geologic habitats of Greenwich Bay, Rhode Island*. Department of Geosciences, University of Rhode Island. Unpublished report.

Odum, W.E. 1970. Insidious alteration of the estuarine environment. *Transactions of the American Fisheries Society* 99:836-847.

Oviatt, C., A. Keller, and L. Reed. 2002. Annual primary production in Narragansett Bay with no bay-wide winter-spring phytoplankton bloom. *Estuarine, Coastal and Shelf Science* 54:1013-1026.

Pearson, T.H., and S.O. Stanley. 1979. Comparative measurement of the redox potential of marine sediments as a rapid means of assessing the effect of organic pollution. *Marine Biology* 53:371-379.

Preisendorfer, R.W. 1986. Secchi disk science: visual optics of natural waters. *Limnology and Oceanography* 31:909-926.

Prell, W., D. Murray, and C. Deacutis. 2006. *Summer-season survey of dissolved oxygen in upper Narragansett Bay beginning in 2005*. <http://www.geo.brown.edu/georesearch/insomniacs> Accessed 1/28/07.

Pritchard, D.W. 1967. What is and estuary: physical viewpoint. p.3-5. *In* Lauff, G.H. (eds.). *Estuaries*. American Association for the Advancement of Science, Washington, D.C.

Reuter, R.J., and J.C. Bell. 2003. Hillslope hydrology and soil morphology for a wetland basin in south-central Minnesota. *Soil Science Society of America Journal* 67:365-372.

Richardson, M.J. 2006. *Process-based and landscape-level measures of soil organic carbon sequestration and fluxes in southern New England forests*. M.S. Thesis Department of Natural Resources Science. University of Rhode Island, Kingston, RI.

Rhode Island Coastal Resources Management Council (RICRMC). 2005. *Greenwich Bay Special Area Management Plan*. RI Coastal Resources Management Council, Wakefield, RI.

Rhode Island Department of Environmental Management (RIDEM). 2003. *The Greenwich Bay fish kill- August 2003: Causes, impacts, and responses*. Division of Water Resources, Providence, RI.

Rhode Island Geographic Information System (RIGIS). 2004. *Rhode Island Geographic Information System digital orthophotography*. <http://www.edc.uri.edu/rigis/> Accessed 3/2/2006.

Ryther, J.H. 1969. Photosynthesis and fish production in the sea. *Science* 166: 72-76.

SAS. 2003. *JMP IN 5.1*, SAS Institute, Inc., Cary, NC.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson (eds.). 2002. *Field book for describing and sampling soils, Version 2.0*. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Scott, B.J., M.K. Conyers, R. Fisher, and W. Lill. 1992. Particle size determines the efficiency of calcitic limestone in amending acidic soil. *Australian Journal of Agricultural Research* 43: 1175-1185.

Smith, S.V. 1981. Marine macrophytes as a global carbon sink. *Science* 211:838-840.

Soil Survey Staff. 1993. *Soil survey manual*. Agricultural Handbook No. 18, USDA-NRCS, U.S. Government Printing Office, Washington, D.C.

Soil Survey Staff. 1990. *Keys to soil taxonomy, fourth edition*. SMSS technical monograph no. 6., Blacksburg, VA.

Soil Survey Staff. 1992. *Keys to soil taxonomy, fifth edition*. SMSS technical monograph no. 19., Pocahontas Press, Inc., Blacksburg, VA.

Soil Survey Staff. 2006. *Keys to soil taxonomy, tenth edition*. United States Department of Agriculture Natural Resources Conservation Service, Government Printing Office, Washington, D.C.

Soil Survey Laboratory Staff. 2004. *Soil survey laboratory methods manual*. Soil survey investigation report no. 42 version 4.0. Unites States Department of Agriculture, Government Printing Office, Washington, D.C.

Stevenson, J.C., L.W. Staver, and K.W. Staver. 1993. Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. *Estuaries* 16:234-361.

Stolt, M.H. 2007. *Proposed amendments to soil taxonomy to accommodate subaqueous soils*. <http://www.nesoil.com/sas/Subaqueoustaxonomy.htm> Accessed 5/4/2007.

Taft, J.L., W.R. Taylor, E.O Hartwig, and R. Loftus. 1980. Seasonal oxygen depletion in Chesapeake Bay. *Estuaries* 3:242-247.

Teasdale, P.R., A.I. Minett, K. Dixon, T.W. Lewis, and G.E. Batley. 1998. Practical improvements for redox potential (E_H) measurements and the application of a multiple-electrode redox probe (MERP) for characterizing sediment in situ. *Analytica Chimica Acta* 367:201-213.

Thermo-electron. 2003. *Orion Silver/Sulfide Electrode Instruction Manual*. Thermo-Electron Corporation, Beverly, MA, USA.

Thompson, J.A., J.C. Bell, and C.A. Butler. 1997. Quantitative soil-landscape modeling for estimating the areal extent of hydromorphic soils. *Soil Science Society of America Journal* 61:971-980.

Tomaszek, J.A. 1995. Relationship between denitrification and redox potential in two sediment-water systems. *Marine Freshwater Research* 46:27-32.

Trenhaile, A.S. 1997. *Coastal Dynamics and Landforms*. Clarendon Press, Oxford, U.K.

Ulrich, G.A., L.R. Krumholz, and J.M. Sulfita. 1997. A rapid and simple method for estimating sulfate reduction activity and quantifying inorganic sulfides. *Applied and Environmental Microbiology* 63:1627-1630.

United States Department of Agriculture - Natural Resources Conservation Service (USDA-NRCS). 2006. *Field indicators of hydric soils in the United States, Version 6.0*. Hurt, G.W. and L.M. Vasilas (eds.). USDA-NRCS, in cooperation with the National Technical Committee for Hydric Soils.

United States Department of Agriculture - Natural Resources Conservation Service (USDA-NRCS). 2007. *Use of reaction (pH) in soil taxonomy*. <http://soils.usda.gov/technical/technotes/note8.html> Accessed 4/25/2007.

Valente, R., D.C. Rhoads, J.D Germano, and V. Cabelli. 1992. Mapping of benthic patterns in Narragansett Bay, RI. *Estuaries* 15:1-17.

Vepraskas, M.J., and S.P. Faulkner. 2001. Redox chemistry of hydric soils. p. 85-97. *In* Richardson, J.L and M.J. Vepraskas (eds.). *Wetland Soils: Genesis, hydrology, landscapes and classification*. Lewis Publishers, Washington, D.C.

Wafer, C.C., J.B. Richards, and D.L. Osmond. 2004. Construction of platinum-tipped redox probes for determining soil redox potential. *Journal of Environmental Quality* 33:2375-2379.

Weaver, A.R., D.E. Kissel, F. Chen, L.T. West, W. Adkins, D. Rickman, and J.C. Luvall. 2004. Mapping soil pH buffering capacity of selected fields in the coastal plain. *Soil Science Society of America Journal* 68:662-668.

Westrich, J.T., and R.A. Berner. 1984. The role of sedimentary organic matter in bacterial sulfate reduction: the *G* model tested. *Limnology and Oceanography* 29:236-249.

Winkler, L.W. 1888. Die Bestimmung des im Wasser gelösten Sauerstoffes. *Chemische Berichte* 1: 2843-2855.