AN OBSERVATIONAL, GEOSTATISTICAL, AND EXPERIMENTAL 
ASSESSMENT OF EDAPHIC PROPERTIES AND PROCESSES IN 
RESTORED AND NATURAL WETLANDS OF THE SOUTHEASTERN 
COASTAL PLAIN 

by 

Gregory Lee Bruland 

Department of the Environment 
Duke University 

Date: _____________________________ 

Approved: 

_______________________________ 
Curtis J. Richardson, Supervisor 

_______________________________ 
Mark M. Brinson 

_______________________________ 
Dean L. Urban 

_______________________________ 
Dharni Vasudevan 

Dissertation submitted in partial fulfillment of 
the requirements of the degree of Doctor 
of Philosophy in the Department of the 
Environment in the Graduate School 
of Duke University 

2004
ABSTRACT

(Environment – Applied Ecology)

AN OBSERVATIONAL, GEOSTATISTICAL, AND EXPERIMENTAL ASSESSMENT OF EDAPHIC PROPERTIES AND PROCESSES IN RESTORED AND NATURAL WETLANDS OF THE SOUTHEASTERN COASTAL PLAIN

by

Gregory Lee Bruland

Department of the Environment
Duke University

Date: _____________________________

Approved:

_______________________________
Curtis J. Richardson, Supervisor

_______________________________
Mark M. Brinson

_______________________________
Dean L. Urban

_______________________________
Dharni Vasudevan

An abstract of a dissertation submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy in the Department of the Environment in the Graduate School of Duke University

2004
ABSTRACT

Current monitoring of created (CW) and restored wetlands (RWs) does not require any assessment of soil properties. This is a cause for concern because soil forms the foundation of these developing ecosystems and inadequate soil properties can be detrimental to wetland function. In response to these concerns, my dissertation utilized observational, geostatistical, and experimental approaches to assess edaphic properties and processes in CW/RWs natural wetlands (NWs) of the southeastern Coastal Plain.

I hypothesized that the spatial variability of soil properties in CW/RWs would be less than that of paired NWs, as prior land-use and mitigation activities tend to homogenize wetland soils. Moran’s I analysis revealed that, for certain soil properties, significant fine-scale autocorrelation present in NWs was absent from CW/RWs. Frequency distributions, Cochran’s tests, and interpolated contour maps indicated that certain soil properties, such as nitrate, were considerably more homogeneous in CW/RW plots than NW plots across four hydrogeomorphic subclasses. For other properties, such as soil organic matter, there were no consistent differences in patterns of variability between CW/RW and NWs or across subclasses. I also illustrated how two natural riparian forested wetlands with similar vegetation and hydrology had considerably different phosphorus (P) sorption capacities and associated spatial distributions. At both sites, after accounting for autocorrelation, variability in P sorption was best explained by oxalate extractable aluminum. Uniform or random designs would have failed to capture these plots’ rich spatial structure.
As lack of organic matter and homogeneous edaphic conditions appear to be two main limitations of CWs/RWs, I concluded with an assessment of two strategies designed to ameliorate such conditions: organic amendments and microtopographic reestablishment. I determined the optimal range of organic amendments at a CW to be between 60 and 110 Mg compost ha⁻¹. Such amendments levels stimulated denitrification with only slight decreases in P sorption. By the third growing season after microtopographic reestablishment at a RW, inorganic nitrogen was highest in the hummocks, species richness was highest in flats, and aboveground biomass was highest in hollows. The ability to mimic the complexities of NW soils is arguably the next great challenge of wetland creation and restoration.
I would like to acknowledge my advisor, Dr. Curtis J. Richardson for his support of my dissertation research. He provided me great freedom to pursue my research interests; commented on countless drafts of proposals, abstracts, and manuscripts; and generously funded my attendance at numerous conferences and workshops. I would also like to thank my committee members Drs. Mark Brinson, Dean Urban, and Dharni Vasudevan. Dr. Brinson’s assessment of NCDOT mitigation wetlands in 2000 provided the impetus for much of this research. His knowledge of potential sites and suggestion of the paired site comparison approach was critical in the early stages of this project. Dr. Urban helped me develop the spatial sampling design used in three of the dissertation chapters and his Spatial Analysis in Ecology course inspired my interest in geostatistics. Dr. Vasudevan was always available with encouragement, advice, and helpful comments on the soil chemistry aspects of this research and academia in general. While they were not on my committee, I must also thank Dr. Steve Whalen of the University of North Carolina at Chapel Hill and Dr. W. Lee Daniels of the Virginia Polytechnic and State University. Dr. Whalen generously allowed me to use his equipment and instruments to conduct my denitrification research, and Dr. Daniels allowed me to sample his organic amendment experiment in southeastern Virginia.

This dissertation could not have been completed without the assistance of numerous other individuals. Dave Schiller, Leilani Paugh, Morris West, and Greg Lewis of the North Carolina Department of Transportation provided assistance with site selection, access, and hydrology data. Leo Snead, Steve Russell, and Pete Constanzer of
the Virginia Department of Transportation also helped with site selection and sampling. Rob Moul and Kim Williams of Land Management Inc., supplied me with various background information about the Rowel Branch site. Wes Willis, Julie Rice, and Paul Heine helped with the laboratory analysis at the Duke Wetland Center. Eric Fischer provided assistance with the denitrification measurements at UNC-Chapel Hill. Ryan Elting, Mike Osand, and Amani McHugh helped with field sampling efforts. Dr. Robert Wilbur of Duke University aided with plant identification. In addition to my committee members, Dr. Jim Pahl, Dr. P.V. Sundareshwar, Dr. Ryan King, Ariana Sutton, Wyatt Hartmann, and Kirsten Hofmockel provided valuable comments on earlier drafts of the dissertation.

Funding for this research was provided by a Graduate Research Fellowship from Center for Transportation and the Environment in Raleigh, North Carolina, from Duke University Wetland Center Case Studies Program, and from the Nicholas School of the Environment and Earth Sciences

Finally, I would like to recognize my family. My parents, Ken and Anne Bruland have provided encouragement at every point along the way. My father, who is a Professor of marine chemistry, has been a role model and mentor to me both as a scientist and as a human being. Warren and Gay Huff, my father- and mother-in-law, have also been very supportive. Most of all, my wife, Holly, has been a tremendous help. She assisted me in the field on numerous occasions, tirelessly and astutely edited dissertation chapters, critiqued oral presentations, and helped in countless other ways throughout the process. More importantly, at those times when I found it difficult to see the light at the
end of the Ph.D. tunnel, Holly listened, reassured, and provided a healthy dose of perspective. Without her support, I could not have completed this research.
# Table of Contents

ABSTRACT ........................................................................................................ iv
ACKNOWLEDGMENTS .................................................................................. vi
TABLE OF CONTENTS .................................................................................. ix
LIST OF TABLES .............................................................................................. xii
LIST OF FIGURES ........................................................................................... xiv
CHAPTER 1. INTRODUCTION ....................................................................... 1
   The Clean Water Act and Wetland Mitigation ................. 2
   Comparison of Created/Restored and Natural Wetland Soils ...... 3
   Spatial Variability of Soil Properties and Processes ............ 4
   Strategies to Improve Mitigation Success ...................... 10
   Objectives and Hypotheses ........................................ 12

CHAPTER 2. A COMPARISON OF SOIL ORGANIC MATTER IN PAIRED
   RESTORED AND NATURAL WETLANDS IN NORTH CAROLINA .... 17
   Introduction ......................................................................................... 18
   Methods ............................................................................................... 20
   Results ................................................................................................. 30
   Discussion ............................................................................................. 35

CHAPTER 3. SPATIAL VARIABILITY OF BASIC SOIL PROPERTIES IN
   PAIRED CREATED/RESTORED AND NATURAL WETLANDS ....... 41
   Introduction ......................................................................................... 42
   Methods ............................................................................................... 45
   Results ................................................................................................. 57
   Discussion ............................................................................................. 72
LIST OF TABLES

CHAPTER 2

2.1. Site characteristics of the 11 paired created/restored and natural wetland sites sampled in this study ................................................................. 21

2.2. Analysis of variance results testing for significance of wetland status, hydrogeomorphic subclass, the status by subclass interaction, the site within subclass effect, and the status by site within subclass effect for soil organic matter ................................................................. 32

CHAPTER 3

3.1. Plot means and ranges for the soil properties of the four paired sites sampled in this study ................................................................. 60

3.2. Comparison of the variances of the created/restored and natural wetland plots for bulk density, soil organic matter, pH, and sand content with the Cochran’s test ................................................................. 58

3.3. Significant regression coefficients and coefficients of determination for the four soil properties measured at the created/restored and natural wetland plots at Rowel Branch, Grimesland, ABC, and Dismal Swamp ............. 64

CHAPTER 4

4.1. Plot mean and ranges for the soil properties of the four paired sites sampled in this study ................................................................. 96

4.2. Comparison of the variances of the mitigation and natural reference wetland plots for soil moisture, pH, nitrate, ammonium, and soluble organic carbon with the Cochran’s test ................................................................. 93

4.3. Significant regression coefficients and coefficients of determination for the four soil properties measured at the created/restored and natural wetland plots at Rowel Branch, Grimesland, ABC, and Dismal Swamp ............. 102

4.4. Results for multiple stepwise regression analysis for the denitrification enzyme activity at the created/restored and natural wetland plots across all four sites ........................................................................ 115
CHAPTER 5

5.1. Comparison of the soil properties at Rowel Branch and Grindle Creek........ 142

5.2. Semivariogram characteristics for selected soil properties from Rowel
   Branch and Grindle Creek................................................................. 144

5.3. Results of Pearson, simple, partial, and pure-partial Mantel correlations
   among individual soil properties, space, and phosphorus sorption at the two
   sites................................................................................................. 148

CHAPTER 6

6.1. A Comparison of the mean values of the soil properties of the wetland prior
   to the establishment of the amendment experiment as well as of the compost
   used as the source of organic matter.................................................. 171

6.2. Analysis of variance results testing for significance of the amendment,
   wetness, and amendment by wetness interaction for bulk density, pH,
   microbial biomass carbon, the denitrification enzyme activity, and the
   phosphorus sorption index.................................................................. 173

CHAPTER 7

7.1. A Comparison of the mean values of the soil properties from the hummock,
   control, and hollow plots from the July 15th sampling date.................. 197

7.2. RAnalysis of variance results testing for the significance of the
   microtopography, time, and microtopography by time interaction for soil
   temperature, moisture, nitrate, and ammonium.................................... 198

7.3. Volunteer plant species observed in the hummock, control, and hollow
   sampling plots...................................................................................... 205

7.4. Summary of the hydrologic, edaphic, vegetative, and faunal responses
   observed in the three microtopographic zones reestablished at the site...... 215

CHAPTER 8

7.1. Guidelines for creation and restoration of wetland soil properties and
   processes............................................................................................. 225
LIST OF FIGURES

CHAPTER 1

1.1. Hypothetical differences in the mean, frequency distributions, and spatial
distribution for a soil property in a restored and natural wetland and
possible changes over time................................................................. 9

CHAPTER 2

2.1. Map of the locations of the eleven paired wetland study sites in the Coastal
Plain of North Carolina................................................................. 23

2.2. Comparison of soil organic matter in created/restored wetlands and natural
wetlands, across the four hydrogeomorphic subclasses, and across the
eleven paired created/restored and natural wetland sites...................... 34

CHAPTER 3

3.1. Map of the locations of the four paired study sites in the Coastal Plain of
North Carolina. ................................................................. 47

3.2. Example of the spatial sampling design used for this study showing the
four transects, the placement of the fixed centroids, and the locations of the
sampling points.............................................................................. 52

3.3. Histograms of the distributions of bulk density, soil organic matter, pH,
and sand content from the mitigation and natural wetland plots at the four
study sites. ......................................................................................... 59

3.4. Moran’s I correlograms for soil pH at the Rowel Branch restored and
natural wetland plots and for bulk density at the Dismal Swamp restored
and natural wetland plots................................................................. 67

3.5. Percent of significant values of Moran’s I by soil property and wetland
status................................................................................................. 70

3.6. Spatial distribution of sand content at the ABC restored and natural
wetland plots................................................................................... 121

3.7. Spatial distribution of soil organic matter at the Rowel Branch,
Grimesland, ABC, and Dismal Swamp created/restored and natural wetland plots…………………………………………………………………………………. 129

CHAPTER 4

4.1. Histograms of the distributions of soil moisture, nitrate, ammonium, and soluble organic carbon from the created/restored and natural wetland plots at the four study sites………………………………………………………. 95

4.2. Mean denitrification enzyme activity values by soil mass and by soil volume for the created/restored and natural wetland soils collected from the four study sites……………………………………………………………… 100

4.3. Moran’s I correlograms for ammonium at the Rowel Branch restored and natural wetland plots and for moisture at the Dismal Swamp restored and natural wetland plots………………………………………………………… 105

4.4. Percent of significant values of Moran’s I by soil property and wetland status………………………………………………………………………… 108

4.5. The spatial distribution of nitrate across the created/restored and natural wetland plots at the four study sites……………………………………. 111

4.6. The spatial distribution of ammonium across the mitigation and natural wetland plots at the four study sites…………………………………… 113

4.7. The spatial distribution of predicted denitrification enzyme activity across the created/restored and natural wetland plots at the four study sites……… 117

CHAPTER 5

5.1. Spatial distribution of percent clay, oxalate-extractable aluminum, and the phosphorus sorption index at the Rowel Branch and Grindle Creek sites…. 146

5.2. Path diagrams depicting the relationships among space, individual soil properties, and phosphorus sorption as estimated with Mantel tests for Rowel Branch and Grindle Creek……………………………………………… 150

CHAPTER 6

6.1. Map of the study site showing the location of the wet and dry blocks as well as the random locations of the amendment levels in each block……… 165
6.2. Mean values for bulk density, pH, microbial biomass carbon, denitrification enzyme activity, and phosphorus sorption index across the five amendment levels and two wetness blocks

CHAPTER 7
7.1. Map of the ABC wetland restoration site with the location of the hummock, flat, and hollow plots within the study area
7.2. Illustrated representation of the microtopographic features reestablished at the ABC site
7.3. Daily precipitation recorded in 2003 by an onsite rain gauge at the ABC site, and the mean water table depths in the flats and hollows
7.4. Mean soil temperature, moisture, nitrate, and ammonium in the hummock, flat, and hollow plots during the 2003 growing season
7.5. Mean microbial biomass carbon and denitrification enzyme activity values in the hummock, flat, and hollow plots sampled in July 2003
7.6. Mean species richness and aboveground standing biomass for the hummock, flat, and hollow plots sampled during October 2003

CHAPTER 8
7.1. Creation and restoration of wetland soil properties and processes flow chart
CHAPTER 1

INTRODUCTION
THE CLEAN WATER ACT AND WETLAND MITIGATION

The Clean Water Act (CWA) of 1972 mandates mitigation whenever natural wetlands are impacted by development. The Army Corps of Engineers (ACoE) has jurisdiction over this process and requires created and restored wetlands to meet specific vegetative and hydrologic criteria during a five-year monitoring period to be considered successful (Rheinhardt and Brinson 2000). Vegetative criteria require survival of a certain percentage of planted species per acre. Hydrologic criteria require that the water table be within 30 cm of the soil surface for a consecutive period of at least 12.5 % of the growing season. The current process does not require any monitoring of soil properties or processes (Rheinhardt and Brinson 2000). It is interesting that soil has been omitted from the mitigation process, as soil plays an integral part in the definition of a wetland as state din the the U.S. Fish and Wildlife Service Classification of Wetlands and Deepwater Habitats of the United States (Cowardin et al. 1979). Hydric soil, along with hydrophytic vegetation, and wetland hydrology are also the three criteria used to delineate jurisdictional wetlands as defined by the Army Corps of Engineers (Environmental Laboratory 1987). The lack of consideration of edaphic characteristics in the wetland mitigation process is a cause for concern for a number of reasons: (1) soil forms the foundation of these developing ecosystems (Stolt et al. 2000); (2) inadequate soil properties can be detrimental to vegetative survival and the establishment of wetland hydrology (Shaffer and Ernst 1999); and (3) soil is the medium for biogeochemical processes that transform and retain nutrients (Mitsch and Gosselink 2000). Without
suitable soil properties, created and restored wetlands may never replace the nutrient transformation and retention functions of the natural wetlands that were destroyed.

As few created or restored sites are assessed beyond what is needed to meet hydrologic and vegetative success criteria (Zedler 2000), the ability of these wetlands to replace natural wetland functions is a topic of considerable debate (Zedler and Calloway 1999, Stolt et al. 2000, Hunter and Faulkner 2001, Spencer et al. 2001). It has been stated that the definitive test of success for created and restored wetlands is how closely they function like natural wetlands (Galatowitsch and van der Valk 1994).

Unfortunately, only a few studies have attempted to determine whether wetland functions in created and restored wetlands are equivalent to those of natural wetlands (Hunter and Faulkner 2001). The assumption that wetland function follows wetland structure, which underlies the ACoE monitoring process, is also largely untested (Clewell and Lea 1990). In addition, the rates and trajectories at which both structural and functional equivalency are reached are surrounded by great uncertainty.

**COMPARISON OF CREATED/RESTORED AND NATURAL WETLAND SOILS**

Soil properties of created (CW) and restored wetlands (RWs) have almost always been shown to differ from natural wetlands (NWs) (Verhoeven et al. 2001). For example, CWs typically have higher sand and lower clay content than NWs (Bishel-Machung et al. 1996, Stolt et al. 2000, Campbell et al. 2002). This has important implications for wetland function, as coarse-textured soils typically have lower water-holding and nutrient-retention capacities than fine-textured soils (Sopher and Baird 1978,
Poach and Faulkner 1998). Created wetlands and RWs also usually have lower levels of organic matter and higher bulk densities than NWs (Bishel-Machung et al. 1996, Galatowisch and van der Valk 1996, Shaffer and Ernst 1999, Whittecar and Daniels 1999, Campbell et al. 2002). Such soil conditions can lead to low growth and survival of planted and colonizing species. Litter layers in CW/RWs are often poorly-developed or absent in comparison to that of NWs (Hunter and Faulkner 2001, Verhoeven et al. 2001). As a result of low organic matter and sparse litter, it has been speculated that the microbial communities in the soil of CWs are much less viable than those of NWs (Atkinson 1991, Duncan and Groffman 1994). Additionally, soil temperatures were reported to be significantly higher in CWs than in adjacent NWs as a result of a lack of shading of the soil surface by mature trees (Stolt et al. 2000). Furthermore, microtopography has been reported to be considerably lower in CW/RWs than in NWs (Whittecar and Daniels 1999, Stolt et al. 2000). While these studies have documented and described the differences between soils of NWs and those of CWs and RWs, there is a need for additional data on the development of soil properties and processes in CWs and RWs to indicate whether they are actually proceeding toward natural wetland ecosystems and whether they will be able replace the functions performed by the impacted wetlands (Spencer et al. 2001).

SPATIAL VARIABILITY OF SOIL PROPERTIES AND PROCESSES

Soil properties vary spatially and have been shown to exhibit strong fluctuations even over short distances (Goovaerts 1998). Beyond a locally random aspect, spatial
structure may be related to the combined action of physical, chemical, or biological processes that operate at different spatial scales (Goovaerts 1998). In natural forested wetlands, these processes might include overbank flooding, sediment deposition, groundwater inputs, surface runoff, erosion, fire, tree-throw, animal burrowing, litter production, and root activity. Thus it has been suggested that any study of heterogeneous wetland soils should attempt to quantify the spatial variability of the soil properties or processes under investigation (Stolt et al. 2001, Johnston et al. 2001). However, due to the combined difficulties of establishing spatially-explicit sampling designs at remote, wet, and densely-vegetated sites, as well as the collection and processing of the large number of samples needed for adequate spatial coverage, sampling designs that quantify spatial variability are seldom used in studies of wetland soils (Bridgham et al. 2001).

Currently, our understanding of the extent and scale of the spatial variability of soil properties in natural and managed ecosystems is quite limited (Robertson and Gross 1994). It has been shown to be difficult to quantify the spatial variability of relatively homogeneous ecosystems such as agricultural fields or upland forests (Robertson et al. 1997). However, with the development and use of geostatistical tools such as semivariance analysis and kriging, researchers have begun to quantify spatial heterogeneity in different ecosystem types (Schlesinger et al. 1996), along chronosequences (Boerner et al. 1998), across soil drainage catenas (Lyons et al. 1998), and among different land-uses (Robertson et al. 1993, Goovaerts 1998, Paz-Gonzales et al. 2000, Mummey et al. 2002).
Improving our understanding of the spatial variability of soil properties in wetlands is important because such variability is not only structural but also essentially functional in the soil ecosystem (Ettema et al. 1998). For example, a number of researchers have argued that environmental variability and species richness are positively correlated (Williams 1964, Jeltsh et al. 1998, Ettema and Wardle 2002). If the soils of CWs and RWs are less heterogeneous than those of NWs, CWs and RWs could be expected to have lower diversity of soil biota and vegetation. Spatial variability of edaphic properties is also important in terms of the nutrient transformation and retention functions that wetlands provide. For example, edaphic variability at the soil surface establishes a combination of aerobic and anaerobic soil zones that are needed in a wetland to ensure that ammonium can be nitrified to nitrate (NO$_3^-$) in aerobic zones, and then denitrified to nitrogen gas (N$_2$) in anaerobic zones (Reddy and Patrick 1984). A similar pattern of spatial variability was observed in a floodplain forest in Georgia. In this system, aluminum (Al) and iron (Fe) oxides showed a general decline with increasing distance from the river, and significantly different Al and Fe biogeochemical cycling in low versus high elevation microsites (Darke and Walbridge 2000). This research suggested that the patterns of variability in Al and Fe content may lead to a complex mosaic of areas of both low and high P sorption across the floodplain.

In contrast to NWs, CWs and RWs appear to have less variability in soil properties (Stolt et al. 2000). One explanation for this phenomenon is that wetland creation and restoration activities tend to homogenize wetland soils. For example, mitigation actives often involve excavation into subsoil and complete removal of topsoil.
In this process, soil surfaces are extensively cut and scraped with heavy machinery, leaving flat surfaces with little relief (Stolt et al. 2000). These uniform surfaces lack a litter layer and are underlain by compacted subsoils that are low in organic matter and extractable nutrients (Clewell and Lea 1990). In addition, restored wetlands are often located on former agricultural or silvicultural land. Long-term agricultural soil-use has a tendency to homogenize the topsoil, which is most evident for attributes such as organic matter, nitrogen, and cation exchange capacity (Whisenant et al. 1995, Paz-Gonzales et al. 2000). Over time, the combined activities of plants, animals, erosion, and deposition can be expected to increase the heterogeneity of the soils of created and restored wetlands. However, these processes occur over time scales of decades to millennia rather than over jurisdictional monitoring periods.

A number of studies have documented differences in the mean values of soil properties between CW/RWs and those of NWs. Figure 1.1a represents a comparison of the mean values of a soil property from a hypothetical RW and NW. In this example, there are significant differences both in the mean values in the variability of the soil property between the RW and NW. Figure 1.1b illustrates the differences in the frequency distributions of the values from the RW and NW. There is much less variability in the data from the RW than from the NW. Values from the RW only fall into three different classes in the frequency distribution, while values from the NW fall into eight different classes. Furthermore, there is no overlap between the two distributions. Figure 1.1c displays the differences in the spatial distributions of this soil
Figure 1.1. Differences in the mean values (a), the frequency distributions (b), and the spatial distributions of a hypothetical soil property in a restored (RW) and a natural wetland (NW). Possible changes that may occur in the mean values (d), the frequency distributions (e), and the spatial distributions (f) of this soil property in the RW and NW over time.
property in the RW and NW. Such differences in frequency and spatial distribution have important implications for wetland creation and restoration, as functional replacement of NWs involves not only the replacement of the mean values but also of the appropriate variability associated with those means. The question remains as to whether the mean values of the soil property will, over time, become more like those of the NW as shown in Figure 1.1d. The length of time required for this to occur in forested created/restored wetlands is uncertain. Furthermore, it is uncertain whether the frequency and spatial distributions of the soil property in the RW will become more like that of the NW as shown in Figures 1.1e and 1.1f. Finally, we need to investigate what mitigation practices can be taken to increase both the mean and variability of soil properties in RWs, causing them to resemble more closely those of NWs.

STRATEGIES TO IMPROVE CREATION/RESTORATION SUCCESS

The rapid development of the nutrient transformation and retention function has been identified as a priority in wetland mitigation (Noon 1996). However, minimal data exists on the length of time needed to develop adequate soil conditions for natural biogeochemical cycling. What little data is available suggests that key soil properties such as organic matter are not changing with time (Bishel Machung et al. 1996, Shaffer and Ernst 1999); or if changes do occur, they are slow and appear to be leveling off at values well below those of adjacent reference wetlands (Minello and Webb 1997, Zedler and Calloway 1999). Thus, it has been suggested that organic amendments may be the
best method for accelerating the development of wetland functions at created wetland sites (Stauffer and Brooks 1997).

Studies of natural freshwater wetlands have suggested that microtopography is a key factor in determining vegetative composition and diversity (Barry et al. 1996, Vivian-Smith 1997). While the exact causes of microtopographic heterogeneity in NWs are poorly understood, they are thought to be caused by a combination of factors such as sediment accumulation, erosion, tree fall, root growth, litterfall, animal burrowing, and animal tracks (Vivian-Smith 1997). Consequently, scales of microtopographic variability in NWs range from 0.01 m (as a result of sedimentation or animal tracks), to greater than one m (following tree throw) (Vivian-Smith 1997). In natural wetlands, microtopography creates a mosaic of soil patches with substrates that differ structurally, hydrologically, and chemically (Bledsoe and Sheer 2000).

It has even been suggested that the recreation of such microtopography is the key to successful wetland creation and restoration (Barry et al. 1996, Cantelmo and Ehrenfeld 1999). The fact that microtopography has been reported to be much less in CWs and RWs than in NWs (Barry et al. 1996, Whittecar and Daniels 1999, Stolt et al. 2000) is an alarming result of current mitigation practices. Furthermore, minimal data exist on the length of time needed for CWs and RWs to develop microtopography that is representative of NWs. Recreating surface microtopography during wetland restoration or creation may be an effective way to accelerate the development of wetland functions.
OBJECTIVES AND HYPOTHESES

The goal of this dissertation research was to utilize a variety of observational, geostatistical, and experimental approaches to compare soil properties and processes in created/restored and natural wetlands. Chapter 2 consisted of an observational assessment of soil organic matter (SOM) in paired CW/RW and NW across a range of four hydrogeomorphic (HGM) subclasses found in the southeastern Coastal Plain. Previous research has established that wetlands should be grouped by HGM setting when comparing ecosystems properties and functions (Brinson and Rheinhardt 1996, Rheinhardt et al. 1998, and Verhoevne et al. 2001). I used an Analysis of Variance (ANOVA) approach to determine differences in SOM content (1) between CW/RW and NWs, (2) across HGM subclasses, and (3) between CW/RWs and NWs within subclasses. This chapter paved a critical foundation for the rest of my dissertation.

The objective of chapter 3 was to compare the spatial variability of basic soil properties such as bulk density (BD), soil organic matter (SOM), pH, and sand content of CW/RWs to those of paired NWs across the four HGM subclasses. I tested two hypotheses: (1) that spatial variability of soil properties in riverine wetlands would be structured along gradient perpendicular to stream, while spatial variability of soil properties in nonriverine wetlands would be structured in discontinuous patches related to local factors (i.e. vegetation, microtopography); and (2) soil properties of CW/RWs would exhibit less spatial variability than soil properties of NWs as prior land-use (i.e. clearing, ditching, and agriculture) and mitigation activities (i.e. topsoil removal, excavation, and grading) tend to homogenize soil properties.
Chapter 4 built on the research of Chapter 3, but took a more narrow focus on denitrification and related soil properties in CW/RWs and NWs. In both chapters, variability was quantified by examining frequency distributions, summary statistics (mean standard deviation, range) and testing for the homogeneity of variances. Spatial variability was assessed with trend surface analysis (Gittens 1968, van den Pol-van Dasselaar 1998), the Moran’s Index of Autocorrelation (Moran 1950, Legendre and Fortin 1989), and interpolation of contour maps by inverse distance weighting (Issaks and Srivastava 1989). To my knowledge, these two chapters are the first studies to explicitly compare spatial variability soil properties of CW/RWs to those of paired NWs.

As we still have a very limited understanding of the spatial variability of soil properties and processes in natural wetlands, Chapter 5 focused on the data collected from the two natural riverine wetlands sampled in Chapters 3 and 4. The objectives of this chapter were twofold: (1) to quantify patterns of spatial variability of P sorption and related soil properties in the wetlands; and (2) to determine which soil properties best explained the variability in P sorption after accounting for the effects of spatial autocorrelation. This spatially-explicit sampling approach enabled me to use Mantel tests (Mantel 1967) to ascertain the importance of edaphic and spatial variables in controlling the P sorption capacity of soil cores collected from the two natural wetlands and to describe the spatial distributions of P sorption and related soil properties with semivariance analysis and kriging.

As I sampled sites in the field, analyzed data in the laboratory, and read the literature on soil properties in CW/RWs and NWs, I observed a reoccurring theme—a
lack of organic matter and microtopography in created and restored wetland soils. Thus, Chapters 6 and 7 evaluated organic amendments and microtopographic reestablishment at two experimental field sites. I wanted to determine whether these two strategies had the potential to improve mitigation success from both a jurisdictional and ecological standpoint. The objective of Chapter 6 was to examine the microbial and geochemical responses to different levels of organic amendments in a created wetland. This work was part of a larger study being conducted by researchers from the Virginia Polytechnic Institute that was designed to optimize OM amendments in created wetlands for the growth of planted tree seedlings. I hypothesized that: (1) microbial biomass carbon and denitrification enzyme activities (DEA) would increase with increasing organic amendment levels; and (2) that the phosphorus sorption index (PSI) would decrease with increasing organic amendment levels.

The goal of Chapter 7 was to assess the hydrologic, edaphic, and vegetative responses to microtopographic reestablishment in a restored wetland. To do this, I sampled a site that contained higher elevation hummocks and lower elevation hollows, as well as flats of intermediate elevation. The following hypotheses were tested: (1) low microtopographic elevation will cause hollows to be wetter and cooler than flats and hummocks; (2) inundated/saturated conditions in the hollows will result in higher denitrification in these zones than flats or hollows; and (3) species richness will be lower in zones experiencing moisture extremes (wetter hollows and drier hummocks) and higher in the zone with intermediate moisture (flats); and (4) growth of Typha and Scirpus will cause aboveground biomass to be highest in the hollows.
Finally in Chapter 8, I summarize the findings of Chapters 2-7 and discuss their implications for wetland ecology, mitigation, management, and policy. I also explore possibilities for future research, provide a list of recommendations for improving edaphic conditions at created/restored sites, and discuss the need to develop regional or national edaphic success criteria for created and restored wetlands.

Previous studies that have compared hydrology, vegetation, and soils of CW/RWs to those of NWs have been essential in increasing our understanding of the ecological properties and development of CW/RWs. However, these studies have only scratched the surface of the science of ecological restoration. Numerous studies have been fraught with inadequacies in experimental design such as comparing multiple CW/RWs to a single NW or grouping together CW/RWs and NWs of different HGM settings. Few, if any, studies have considered spatial autocorrelation. While a handful of studies have examined the effects of organic amendments on plant growth, none have applied organic matter at different amendment levels nor have they investigated the effects of organic amendments on soil processes that contribute to nutrient transformation and retention such as denitrification and P sorption. Likewise, while a number of studies have examined the effects of microtopography on species composition, soil properties, and ecosystem processes in natural wetlands or in small-scale experimental mesosystems, none have done so at the site-scale in a restored wetland.

In a recent review paper, Michener (1997) makes a plea for more innovate and robust experimental designs, statistical analyses, and better long-term monitoring of created/restored wetlands. My dissertation attempts to meet this call by explicitly
addressing previous inadequacies, by sampling multiple paired CW/RWs and NWs of similar soil type, by grouping CW/RWs and NWs according to HGM setting, by using spatial sampling designs and geostatistical tools for data analysis, and by experimentally addressing mitigation strategies at local field sites. This research is even more relevant due to the fact that in the period from 2001-2008, NCDOT alone will be required to mitigate for greater than 300 kilometers of stream impacts and approximately 2400 hectares of wetland impacts (D. Schiller, personal communication).