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THE EFFECTS OF COASTAL URBANIZATION ON RIPARIAN HYDRIC SOILS

BY

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ABSTRACT

Coastal watersheds rely on hydric riparian soils to reduce groundwater nitrate pollution through microbial denitrification. The requirements for denitrification are the presence of labile carbon, soil saturation, and reducing conditions. Beginning with the colonial settlement period and continuing through recent urbanization, anthropogenic activities have altered riparian zones in southern New England. The effects of anthropogenic disturbance on the properties of estuarine and freshwater riparian soils are largely unknown. The objective of this research was to document and analyze characteristics of freshwater and estuarine riparian soils relevant to denitrification in anthropogenically disturbed landscapes of developing coastal watersheds. Twenty-one estuarine or stream-side riparian sites were investigated in Rhode Island to document the effects of urbanization and anthropogenic activities on riparian hydric soil properties. Historic aerial photographs from 1939 to 1997 were reviewed to assess anthropogenic disturbance. Soils were investigated along transects with an auger. At eleven selected locations soils were described and sampled from deep pits. Soil organic carbon (SOC), permanganate oxidizable carbon (POC), and bulk density were determined. Water tables were measured approximately twice a month at the estuarine sites.

Initial additions of human transported materials (HTM) to the estuarine sites occurred from before 1939 to 1976. Three classes of HTM, ranging in thickness from 26 to >285 cm were identified: dredge spoils, fill materials, and dredge spoils with a fill material cap. Artifacts were present in 53% of the anthropogenic soils. Family particle size class of HTM was predominantly sandy, and bulk density values ranged from 0.55-1.69 g cm^{-3}. The sandy nature and relatively low bulk density of the HTM in the estuarine riparian zone facilitated water movement in the HTM deposits. Water table fluctuations within HTM were influenced by tides, seasonal evapotranspiration, precipitation, geomorphic setting, characteristics of the buried natural soils, or a combination of these factors. In the thickest HTM deposits, water table levels rose as much as 2.5 meters above the original buried soil surface, and hydric conditions developed in some anthropogenic soils. Redoximorphic features, indicative of reducing conditions, were present within the range of water table activity in 16 of the 18 monitored anthropogenic soils. Soil organic carbon ranged from 0.16% to 8.89% and had an irregular distribution with depth. Labile carbon, estimated from measurements of POC, followed the distribution of SOC. Numerous carbon forms were distributed below the water table. These results demonstrate that the conditions necessary for denitrification (labile carbon, soil saturation, and reducing conditions) can develop in anthropogenic soils of the estuarine riparian zone.

The pollen record preserved in alluvial soils of six stream-side riparian zones was examined to identify deposits from pre-colonial, colonial agriculture, agriculture abandonment, and urbanization land use periods based on changes in plant communities. Radiocarbon analysis of plant fragments from selected alluvial horizons was used to establish timeframes of the various land use periods. In three alluvial soils of suburban-urban watersheds, modern artifacts were buried as deep as 28 cm, and were excellent markers of late 20th century deposition. Artifacts were not present in alluvial soils of agricultural-suburban watersheds. In two of the riparian zones numerous dark, thin lenses indicative of short term riparian surfaces developed during

periods of agricultural land use and urbanization. Buried surface horizons indicative of long periods of riparian stability prior to land use change were present in five of the six soils. Radiocarbon analysis indicated that increases in weed and grass pollen began during colonial settlement and agricultural land use c. 250 years B.P. Declines in weed and grass pollen were linked to agricultural abandonment during the late 1800's or changes in agricultural practices during the late 20th century. Forest regeneration subsequent to agricultural abandonment was identified by increases in the abundance of hardwood and conifer pollen. Depth to buried surface horizons and changes in soil morphology related well to changes in land use shown through the pollen record.

In thick alluvial deposits (>0.5 m), approximately one-third to nearly all of the sediments were deposited since colonial settlement. Radiocarbon analysis and interpretations of the pollen indicated that deposition rates were <0.01 cm yr^{-1}, 0.04 - 0.57 cm yr^{-1}, and 0.25 - 0.50 cm yr^{-1} during the pre-colonial, colonial agriculture, and urbanization periods, respectively. Artifacts, buried horizons, and organic rich lenses in stream channel sediments demonstrated that channel filling, migration, and re-establishment may partially offset gains in riparian zone elevation caused by accelerated alluvial deposition, thus helping to maintain hydric soil conditions. Organic horizons that were buried as a result of shifts to agriculture or urban land use had the highest mean SOC (22.5%) and POC (8.3 g C kg^{-1} soil), and were hotspots of carbon abundance buried in sandy alluvium. Combination horizons, such as C/O and C/A horizons, that developed during periods of watershed disturbance were interpreted to represent short periods of surface stability. These horizons had abundant carbon in the form of lenses, plant fragments, roots, and masses. In soils comprised primarily of A, AC, and CA horizons, SOC remained near 5% and POC near 1g C kg^{-1} soil through most of the alluvial deposits and the various land use periods. These soils with more uniform carbon distribution had coarse-loamy and coarse-silty textures. SOC:POC ratios were highly variable (2.2-187.5) and did not widen with an increase in horizon age or by dominant land use, demonstrating that land use shifts away from forests in the watershed do not necessarily result in a decrease in the abundance of labile carbon relative to SOC in riparian alluvium. My studies show that during periods of accelerated alluvial deposition caused by shifting land use and anthropogenic activity, elevated carbon contents and carbon hotspots that are important to denitrification can still develop in the riparian subsurface of lower order streams.

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PREFACE

This thesis was written and formatted following the guidelines presented by the University of Rhode Island Graduate School. There are three chapters: Human Transported Materials of the Estuarine Riparian Zone (Chapter 1), Use of Stratigraphic Markers to Establish Timeframes of Alluvial Deposition in Riparian Zones (Chapter 2), and Effects of Land Use Change on Sedimentation Rates, Soil Organic Carbon, and Permanganate Oxidizable Carbon in Hydric Riparian Soils (Chapter 3).

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INTRODUCTION

Nitrogen (N), in the form of nitrate, is a common pollutant to U. S. groundwater (USEPA, 1990). Coastal waters are N limited, and the introduction of excess N to estuarine environments from sources such as contaminated groundwater can result in significant ecological and management problems including eutrophication, hypoxia, and habitat disturbance (Valiela et al., 1990; Nixon, 1995). Concerns over N contamination have resulted in numerous studies of riparian soil environments and their ability to remove groundwater nitrate via microbial denitrification (Schipper et al., 1993; Jacinthe et al., 1998; Gold et al., 1998; Devito et al., 2000; Rosenblatt et al., 2001; Kellogg et al., 2005). Current research demonstrates that many riparian zones are effective at removing nitrate from groundwater (Hill, 1996; Gold et al., 2001; Addy et al., 2005), and that hydric soil conditions are important to this process (Simmons et al., 1992; Gold et al., 2001). Thus, coastal watersheds are dependent upon streamside and estuarine riparian hydric soils as ‘N sinks’ to reduce groundwater nitrate inputs to coastal waters.

Denitrifying bacteria are facultative, heterotrophic, aerobic organisms that only use nitrate as an electron acceptor when oxygen is unavailable (Hill, 1996). The denitrification process involves the reduction of nitrate to nitrite, and ultimately to gaseous forms of N including NO, N_2O, and N_2 that are lost to the atmosphere during microbial oxidation of labile carbon (Tiedje, 1982). Groundwater denitrification is therefore dependent on saturated anaerobic conditions, a reducing environment, and labile organic carbon (Starr and Gillham, 1993; Hill, 1996; Brady and Weil, 1996; Craft, 2001).

Numerous studies have found that soil organic carbon (SOC) is an important controlling property in the denitrification process (Gold et al., 1998; Jacinthe, P.A. et al., 1998; Clough et al., 1999; Davidsson and Stahl, 2000; Brettar and Hofle, 2002; Groffman and Crawford, 2003). The lack of SOC in the subsurface is often the primary limiting factor for nitrate removal when ambient groundwater nitrate levels are high (Starr and Gillham, 1993; Groffman et al., 1996). Patterns of denitrification have been found to follow C distribution in alluvial and outwash riparian settings (Kellogg et al., 2005). In these soils, 'patches' of C-rich subsurface material may serve as 'hotspots' of microbial denitrification activity (Jacinthe et al., 1998; Gold et al., 1998). Anaerobic laboratory assays by Smith and Tiedje (1979) found that denitrification activity was greater in the rhizosphere, and potential denitrifying activity decreased rapidly within just a few millimeters of roots. These effects were at least partially attributed to available organic matter. Such findings suggest that the abundance and distribution of SOC influences microbial denitrification in the soil environment.

Not all patches of SOC, however, have the same potential to aid in denitrification (Gold et al., 1998). Additions of plant materials are the primary source of organic matter (OM) to the soil, which include C as carbohydrates, fats, oils, and lignins (Tan, 2003). In the soil environment, OM is physically and chemically altered (humified) by microbial oxidation and other biochemical processes (Schnitzer, 1978; Craft, 2001). Alteration of plant derived OM sources yields humic (humin, humic acids, fulvic acids) and non-humic substances (Schnitzer, 1978; Tan, 2003). Plant derived OM and the SOC by-products of their alteration, have varying degrees of availability to soil microbes, which is referred to as lability (Tirol-Padre and Ladha, 2004). Labile SOC is considered active, while SOC not actively used by microbes is considered passive.

Several authors have discussed SOC lability in terms of active (light) and passive (heavy) fractions (Greenland and Ford, 1964; Sollins et al., 1984; Alvarez et al., 1998; Alvarez and Alvarez, 2000). The light fraction of SOC is primarily comprised of mineral free partially decomposed plant materials and non-humic substances that are easily utilized by microbes and turn over relatively quickly in the soil environment (Schnitzer, 1978; Sollins et al., 1984; Alvarez and Alvarez, 2000). The heavy humic fractions of SOC are inherently recalcitrant, sorbed on mineral surfaces, or found in organo-mineral aggregates (Sollins et al., 1984), and are not readily available to microbes (Brady and Weil, 1996; Alvarez and Alvarez, 2000; Tirol-Padre and Ladha, 2004). Thus, heavy SOC fractions are more stable in the soil environment, not as labile, and take longer periods of time to become mineralized by soil microbes relative to the light fraction (Schnitzer, 1978; Alvarez et al., 1998).

Until recently, little analysis of subsurface SOC with respect to morphology and genesis had been completed. Blazejewski et al. (2005) devised a method for describing and classifying subsurface SOC on a macro and micro-scale as an initial step in developing a method of assessing functional categories of SOC. These classes are: roots, root traces, lenses, infillings, fragmental organic matter (FOM), masses, and illuvial C. Mineral associated C with an enaulic/porphyric distribution in the soil matrix was also identified.

Although geomorphic setting can influence the abundance, form, and distribution of subsurface SOC in riparian zones (Blazejewski, 2003), roots (live and dead) are likely the most wide spread and important source of labile subsurface C (Megonigal and Day, 1988; Blazejewski, 2003) regardless of the setting. Root exudates also appear to be an important source of labile subsurface C (Woldendorp, 1962; O'Neill and Gordon, 1994; Ohtonen and Vare, 1998). Previous studies have shown that the distribution of roots in the soil can be influenced by numerous variables including: soil moisture (Kalisz et al., 1987), depth (Hackney and De La Cruz, 1986; Kalisz et al., 1987), SOC content (Sanju and Good, 1993), texture (Blazejewski, 2003), and vegetative cover (Gary, 1963; Sanju and Good, 1993). Additional information on the distribution, seasonal changes, and relationships between roots and water tables in riparian soils is needed to better assess their N sink function (Hill, 1996; Gold et al., 1998).

Anaerobic soil saturation and reducing conditions are also essential for denitrification (Vepraskas and Faulkner, 2001) to occur in riparian soils. Water table levels are a primary controller of redox state (Seybold et al., 2002), and soil morphology such as depth to redoximorphic features can be a useful indicator of water table activity (Genthner et al., 1998; Stolt et al., 1998; New England Hydric Soils Technical Committee, 2004). Most relatively undisturbed hydric soil environments exhibit anaerobic saturation and reducing conditions on a seasonal or permanent basis (Vepraskas and Faulkner, 2001), depending on the depth of the water table.

Although tidal marsh soils of the estuarine riparian zone are characterized by strongly reducing conditions and water tables near or above the soil surface most of the time (Rabenhorst, 2001; Seybold et al., 2002), the extent to which reducing conditions and soil saturation occurs within human transported materials (HTM) (ICOMANTH, 2006) that has been added to the marsh is not understood. In freshwater riparian zones, watershed urbanization affects stream geomorphic development by altering sediment supply and bankfull discharge (Paul and Meyer, 2001). Depending on the phase of stream geomorphic development and watershed disturbance, stream bed aggradation or incision may occur (Paul and Meyer, 2001). Where stream incision occurs riparian water tables can be lowered (Groffman et al., 2002; Schilling et al., 2004), resulting in a smaller zone for denitrification to occur within the soil. Conversely, where stream aggradation occurs or in areas upstream of undersized culverts an increase in the frequency and duration of riparian flooding would be anticipated, which could raise riparian water tables. Riparian water table responses to urbanization and soil disturbance are likely variable and related to the type of disturbance, and are in need of further study.

Although riparian soils are clearly important N sinks (Hill, 1996), helping to maintain the health of estuarine waters where coastal urbanization and wastewater inputs are increasing N loadings, there has been limited investigation of riparian zones in urbanizing areas (Groffman et al., 2002). There is a need to discern if urban riparian zones and other urban areas with similar potential functional importance have denitrification potential comparable to agricultural and forested landscapes (Groffman and Crawford, 2003). A thorough understanding of riparian soil properties that exert controlling influences on nitrate removal soil processes in urbanizing environments is critical to water quality management in coastal watersheds.

Little is known of the effects of urbanization on riparian zone characteristics essential for denitrification (Groffman and Crawford, 2003). Properties of urban soils are poorly understood (DeKimpe and Morel, 2000; Pouyat et al., 2002), and few studies have examined characteristics of riparian soils that have been affected by anthropogenic disturbance (Groffman and Crawford, 2003; Cavalcanti and Lockaby, 2005). Alluvial soil deposition and root growth can be altered by anthropogenic disturbance (Hupp and Bazemore, 1993; Kleiss, 1996; Cavalcanti and Locakaby 2005), which may affect soil properties relevant to N sink potential. In developing coastal areas estuarine riparian soils have often been drained, filled, and bulkheaded for development (Tiner, 1984; Dahl, 2000). Where riparian hydric soils have been directly altered by such additions of human transported materials (HTM) (ICOMANTH, 2006), there is significant uncertainty regarding how this anthropogenic disturbance has affected soil morphology and properties (New England Hydric Soils Technical Committee, 2004).

The objective of this investigation was to document characteristics of freshwater and estuarine riparian soils relevant to denitrification in anthropogenically disturbed landscapes of developing coastal watersheds. I completed this investigation by assessing soil morphology and characteristics, carbon distribution, and reducing conditions, and by monitoring riparian watertables in reference and disturbed riparian soils. Both freshwater and estuarine riparian landscapes were examined to explore the effects of urbanization on riparian hydric soils of different geomorphic settings. This thesis is comprised of three chapters. The first chapter examines the morphologies and characteristics of HTM in estuarine riparian zones. The second chapter establishes timeframes and land use periods of alluvial deposition in freshwater riparian zones using pollen preserved in freshwater alluvium, soil morphology, and radiocarbon dating techniques. The final chapter examines changes in properties and deposition rates of alluvium in freshwater riparian zones during the various land use periods.

CHAPTER 1:

HUMAN TRANSPORTED MATERIALS OF THE ESTUARINE RIPARIAN ZONE

ABSTRACT

Additions of human transported materials (HTM) to fill wetlands have significantly altered many coastal riparian zones. Data are needed to understand if the addition of HTM has affected the ability of these soils to support ecologically important functions such as denitrification. The objective of this chapter was to document anthropogenic soil characteristics in the estuarine riparian zone relative to the ability of such soils to function in the denitrification capacity. Seventy-seven soils were described from soil pits and auger borings among eleven disturbed coastal riparian sites and four reference sites in Rhode Island, USA. Auger transects were completed to characterize soils across disturbed and reference coastal riparian landscapes. At five representative locations with HTM deposits, pits were opened and the soils were described and sampled. Soil organic carbon (SOC), permanganate oxidizable carbon (POC), and bulk density were determined. Water table levels were monitored at each site twice a month. Historic aerial photography indicated HTM had been added 30 to > 60 years ago, depending on the site. Deposits of HTM ranged in thickness from 26 to >285 cm. Three classes of HTM were identified: dredge spoils, fill materials, and dredge spoils with a fill material cap. Family particle size class of HTM was predominantly sandy, and artifacts were present in 53% of the described anthropogenic soils. Bulk density values ranged from 0.55 to 1.69 g cm^{-3}. Water tables rose into HTM deposits at all sites. Fluctuations of the water table were influenced by tides, evapotranspiration, precipitation, geomorphic setting, and characteristics of the buried natural soils. In the thickest HTM deposits, water table levels rose as much as 2.5 meters above the original buried soil surface. Hydric soil conditions developed in some anthropogenic soils. Redoximorphic features were present within the range of water table activity in 16 of the 18 monitored anthropogenic soils, suggesting reducing conditions. Soil organic carbon ranged from 0.16% to 8.89%, was always highest in surface horizons, and had an irregular distribution with depth. Labile carbon, estimated from measurements of POC, followed the distribution of SOC. Numerous carbon forms were identified below the water table. My findings demonstrate that the necessary components for denitrification to occur (labile carbon, soil saturation, and reducing conditions), are present in anthropogenic soils of the estuarine riparian zone, indicating that these soils can function in this capacity.

INTRODUCTION

Estuarine riparian soils within urbanizing coastal watersheds are often drained, filled, and bulkheaded for development (Tiner, 1984; Dahl, 2000). The fill materials that constitute the parent materials of these anthropogenic soils are now termed human transported materials (HTM) (ICOMANTH, 2006; Soil Survey Staff, 2006). Human transported materials are common in urban and developing landscapes (Hernandez and Galbraith 1997; Galbraith 2006), and the extent of HTM in coastal environments can be substantial. For example, 22% (180 ha) of the soils within a 500 foot buffer zone of Potter Pond-Point Judith Pond in coastal Rhode Island are mapped as soils with anthropogenic disturbance and HTM deposits (Rector, 1981). A survey of the shoreline of Green Hill Pond in Rhode Island showed that 49% of the investigated area was disturbed by anthropogenic activity (Addy et al., 2005). In New York City, estuarine shorelines have been constructed through deposition of HTM over tidal marshes and open estuarine waters (Galbraith, 2006).

Interest in HTM and anthropogenically disturbed soils has grown in recent decades as the land area of anthropogenic soils increases and the use and management of these soils grows (Strain and Evans, 1994; Buondonno et al., 1998; Evans et al., 2000; DeKimpe and Morel, 2000). Most research on HTM has focused on the characterization of mine spoils (Pedersen et al., 1980; Ciolkosz et al., 1985; Potter et al., 1988; Stolt et al., 2001), and the problems associated with mapping (Schafer, 1979; Indorante and Jansen, 1984; Haering et al 2005) and classifying these soils (Schafer, 1979; Thurman and Sencindiver 1986). Similar studies have investigated the characteristics of HTM on military land (Evans et al., 2000), urban areas (Puyat et al., 2002; Langley-Turnbaugh et al., 2005; Hernandez et al., 2006), industrial lands (Buondonno et al., 1998), park land (Hernandez and Galbraith, 1997; Short et al., 1986a; Short et al., 1986b), and sand and gravel pits (Strain and Evans, 1994).

Soil surveys in urban areas have typically mapped landscapes with significant areas of HTM at the great group level (Udorthents), or as Urban Land and complexes of Urban Land and natural soil series (Smith, 1976; Rector 1981). Human transported materials often have unique properties (Short et al., 1986a; Buondonno et al., 1998), and these generalized mapping units do not provide information specific enough to communicate soil function and properties, or to make land use interpretations (Strain and Evans, 1994; Hernandez and Galbraith, 1997; Evans et al., 2000). Recently, however, the National Cooperative Soil Survey has completed mapping of HTM to the soil series level in urban areas of New York (Hernandez and Galbraith, 1997; Hernandez et al., 2006). To supplement such efforts, revisions to soil description and classification systems have been proposed (ICOMANTH, 2006) or adopted (IUSS Working Group WRB, 2006; Soil Survey Staff, 2006).

The functional capacity of an anthropogenic soil depends upon the properties of the soil. For example, anthropogenic riparian soils have the potential to remove nitrate if conditions support soil saturation and abundant organic matter is present (Groffman and Crawford, 2003). Several studies have found that carbon distribution in anthropogenic soils is variable with depth (Ciolkosz et al., 1985; Short et al., 1986a; Thurman and Sencindiver, 1986; Buondonno et al., 1998), suggesting that the carbon required for microbial denitrification (Gold et al., 1998; Clough et al., 1999; Groffman and Crawford, 2003) may be present in the subsurface of estuarine riparian zones comprised of HTM. Other work has identified redoximorphic features in anthropogenic soils (Evans et al., 2000), indicating that anaerobic saturation and microbially mediated oxidation-reduction reactions occur in some of these soils.

Although the extent of anthropogenic soils in coastal settings is well known, no investigations have specifically examined the properties and characteristics of anthropogenic soils relative to their ability to remove N. Considering this lack of information, the functional capacity of these soils remains unknown. Thus, through a pedologic approach, the objective of this chapter was to document and examine soil characteristics of HTM relevant to the N sink function in estuarine riparian settings.

MATERIALS AND METHODS

Site Selection

Study sites were selected through review of Rhode Island Geographic Information System (RIGIS) databases, field reconnaissance, and meetings with natural resources professionals and local residents. A digital version of the Soil Survey of Rhode Island (Rector, 1981) and estuarine shoreline coverages available through RIGIS were initially referenced to identify tidal marsh soils that have been directly altered by additions of HTM. Soils mapped as Udorthents (anthropogenically disturbed soils), urban land, and native soil-urban land complexes along the estuarine riparian zone were used as indicators of potential anthropogenic soils. Bulkhead, hardened shoreline, and degraded estuarine wetland coverages (available through RIGIS) were also employed as indicators of anthropogenic disturbance. Comparisons of historic and current site characteristics were made using 1939 aerial photographs and 1997 orthophotography. Estuarine areas identified as having the potential for

HTM were ground truthed by foot or canoe. Data were collected on width of existing estuarine hydric soils, type of shoreline disturbance, distance to the estuarine shore/open water from the edge of the anthropogenic deposits, HTM thickness, distance to the closest building from the shoreline, land use, and the length and width of bulkheads or other constructed shorelines. Soils were described from auger borings. The geomorphic setting of each site was noted as fringing marsh, tidal creek marsh, or unconsolidated shore. In addition, relational information such as history of dredging operations or shoreline construction in the vicinity of sites, obtained through discussions with municipal officials, residents, and property owners, was helpful in developing an understanding of the land use history of the sites.

Eighty sites or shoreline segments with HTM additions were assessed during the reconnaissance visits. Based on the information that was collected during the reconnaissance visits, 11 sites representative of estuarine riparian zones with anthropogenic soils were selected for study (Figure 1.1). Criteria for selecting study sites included geomorphic setting (tidal creek marshes, and fringing marshes in higher and lower energy environments), HTM depth and characteristics, nature and extent of the site disturbance, and accessibility. In addition, 4 reference tidal marsh sites without additions of HTM were selected for comparative purposes (Figure 1.1). Historic aerial photographs and orthophotography for each decade between 1939 and 1998 were reviewed to determine when HTM was deposited at each of the study sites.

Field Sampling and Data Collection

Transect studies were completed across the 11 study sites to collect data on soil morphology and SOC distribution. Soils were described from shallow pits (less than

50 cm deep) and bucket auger borings (up to 3 meters deep) according to standard procedures (Soil Survey Staff, 1993; Schoeneberger et al., 2002). Soil organic carbon forms were described using the morphological approach described by Blazejewski et al. (2005). Particular attention was paid to evidence of reducing conditions such as redoximorphic features. Sampling locations were distributed across the study area, while avoiding impediments such as buried utilities, structures, paved areas, and retaining walls. The number of sampling points per site was based on the size of the study area (Table 1.1). The number of transects was determined based on the length of shoreline or tidal creek within the study site area, as follows: two transects if less than 50 meters, three transects if 50 – 150 meters, four transects if 150 – 250 meters. Supplemental auger borings were completed at each site as needed. Transects were orientated perpendicular to the shore or the tidal creek. Sixty-four soils formed in natural or anthropogenic deposits were described during the transect studies. Eight additional natural soils were described when wells were installed at the four reference sites.

Deep soil pits were also opened at five representative study site locations to make complete profile and SOC descriptions, resulting in a total of 77 soils described during the course of field investigations (64 auger transect borings at study sites, 8 auger borings at reference sites, and 5 deep soil pits at study sites). The deep soil pits were excavated, described, and sampled to the bottom of the HTM, or as deep as site conditions allowed (86-144 cm). When necessary a gas powered pump was used to remove inflowing groundwater so that a description of soil and SOC morphology could be completed below the water table. Undisturbed and bulk samples were collected from each soil horizon for laboratory analyses. A bucket auger was used to sample and describe soil materials below the bottom of the soil pit. If the site was maintained as lawn, the vegetation coverage was recorded as such. When other vegetation was present, percent areal coverage of the species in each stratum was recorded within a specified radius of the soil pit. A 1.5 meter radius was used for herbs, a 4.5 meter radius for shrubs, sapling, and vines, and a 9 meter radius for trees. If a species was unidentifiable due to a lack of botanical features (such as inflorescence), or required the skills of a specialist (such as grasses), the percent cover of the species was recorded and a generic name was assigned (i.e. grass 1, grass 2).

Each of the 11 study sites and 4 reference sites were instrumented with wells constructed of 3.8 cm i.d. PVC slotted well screen with a pointed end cap and cover. Two wells were installed in line perpendicular to the water's edge at each site. A third well was installed at two of the sites. The distance between wells was dependent on the width of the HTM or hydric soils, and varied from 6 to 27 meters. Eighteen wells were installed in soils formed in HTM, and 14 wells were installed in natural soils. Water tables were measured approximately once every two weeks. The timing of the measurements was based on availability of equipment and personnel rather than tidal cycles. Each well contained a device comprised of a cork with a bored out center that slid freely along a steel rod, which pushed an internal magnet up the rod as the water table rose to record the highest water table level between readings (Morgan and Stolt, 2004). These devices were sometimes installed several weeks after the wells, so measurements of the highest water table level between readings were not always made for the earliest part of the monitoring period. In addition, there were several times when the maximum water table device malfunctioned.

Data Processing and Analyses

Bulk horizon samples from the five deep soil pits were air dried and passed through a 2 mm sieve to separate the fine earth fraction (particles < 2 mm in size) from the coarse fragments. Coarse fragments were further separated into coarse organic fragments and coarse inorganic fragments. The weight of all three soil components was recorded. Approximately 2 grams of soil from the fine earth fraction of each bulk sample was ground and passed through a number 60 (0.25 mm) mesh sieve. The ground samples were dried in an oven at 60°C for 24 hours. A 10 to 60 mg subsample (depending on horizon type) was analyzed for N and C content using a Carlo Erba NA 1500 Series 2 Nitrogen/Carbon Analyzer (Carlo Erba Instruments, Milan, Italy).

The fine earth fraction of undisturbed horizon samples from the five deep soil pits was oven dried at 105°C for 24 hours to obtain a dry soil weight. This weight was divided by the volume of the soil collected by the bulk density sampler and corrected for coarse fragment content to determine the bulk density of riparian soil horizons (Soil Survey Staff, 2004).

Permanganate oxidizable carbon (Tirol-Padre and Ladha, 2004) was measured from horizon samples from the five deep soil pits following the procedure described by Weil et al. (2003) to estimate labile carbon content. In this method 0.02 M $KMnO_4$ is used to oxidize the active carbon fraction and light absorbance (550 nm) is used to quantify active carbon (Weil et al., 2003). A 5 gram sample was used for the initial

POC measurement. A second POC measurement was completed using a smaller sample weight (<0.5 g) for samples with an initial POC measurement >0.6 g C kg^{-1} soil, SOC content of >4%, or a spectrophotometer absorbance reading of <0.1.

RESULTS AND DISCUSSION

Geomorphic setting, parent materials, and land use in disturbed estuarine riparian zones

Human transported materials were added to fill seven of the study sites between 1939 and 1976 (Table 1.2). Additions of HTM at four of the study sites predated 1939. Six of the sites were fringing marsh, three of the sites were tidal creek marsh, and two of the sites were fringing marsh-unconsolidated shore complexes prior to the addition of HTM. Land use at these sites now includes residential lawns and gardens, marinas, municipal parkland, and a road crossing (Table 1.2).

Profile descriptions of the 77 soils assessed during field investigations identified two primary types of anthropogenic parent materials: dredged fill and non-dredged fill. In addition, non-dredged fill was frequently deposited over dredged fill. For the purposes of this discussion, these three classes of anthropogenic soils are identified as dredge spoils, fill materials, and capped dredge spoil deposits, respectively. Soil texture, stratification, color, coarse fragment characteristics and carbon forms were key to distinguishing dredge spoil deposits from fill materials. Fill materials (Table 1.3) and dredge spoils capped with fill materials (Table 1.4) were the most common type of anthropogenic soil parent materials (Table 1.5). Dredge spoils without a cap were only present at the BAY site (Table 1.6). Fill materials were the shallowest deposits, typically between 50 to 150 cm. Capped dredged spoils ranged from 30 to >285 cm in thickness, and the thickness of the fill material cap ranged from 19 cm to 97 cm. Uncapped dredge spoils ranged from 180-211 cm in thickness. Soils derived from reworked HTM deposits (Table 1.7) were also present near the foot of anthropogenic landforms, and ranged from 22-80 cm in thickness. The reworked materials were deposited by natural forces, and are not HTM. These materials, however, are considered in this discussion since they are relevant to disturbed estuarine shorelines. Parent materials for the natural soils were estuarine deposits, organic soil materials (OSM), loess, and outwash (Tables 1.8 and Tables 1.9).

Physical characteristics of anthropogenic soils in the estuarine riparian zone

Artifacts such as demolition debris, plastic, glass, and brick were present in 53% of the described anthropogenic soils (Table 1.10). Both fill materials and dredge spoils contained artifacts, although artifacts were more common in fill materials. Artifacts were usually a small component of the soil matrix (<15%), however, one soil had horizons comprised of > 90% artifacts, one soil had horizons described as very artifactual (35 to 60%), and two soils had horizons described as extremely artifactual (60 to 90%). The Potter Pond 1 and Boat Club sites each had a soil with a manmade (M) horizon of buried asphalt pavement. Reworked HTM deposits and some reference soils located in tidal marshes adjacent to disturbed shorelines contained artifacts. Reference soils that were not directly adjacent to shoreline disturbance did not have artifacts.

Family particle size class (PSC) is a differentia for mineral soils used at the family level of Soil Taxonomy, and characterizes the mineral grain-size composition of the soil within a control section (Soil Survey Staff, 1999). The control section for the soils studied in this investigation was 25-100 cm, or 25 cm to the bottom of the anthropogenic deposits if they were shallower than 100 cm. Textures of horizons formed in HTM ranged from silt loam to extremely gravelly coarse sand, which corresponded to PSCs of sandy-skeletal to coarse-loamy (Table 1.11). Human transported materials derived from fill materials were excavated from other locations, bringing soil materials from a variety of geomorphic settings into the estuarine riparian zone (Table 1.3). Thus, PSC were more variable in fill materials, although sandy PSC was still the most common for fill materials. The range in PSC of anthropogenic soils was similar to that of natural soils in Rhode Island, with the exception of coarse-silty, which are occasionally encountered in natural soils.

In order for disturbed estuarine riparian zones to function in the denitrification capacity, hydraulic conductivity of soils formed in HTM must be high enough to permit groundwater flow through carbon enriched horizons. Since coarser textured soils generally have higher hydraulic conductivity, groundwater flow should not be impeded in sandy dredge spoils and fill materials of the estuarine riparian zone. Silty horizons and lenses identified in dredge spoils, however, may promote episaturation and areas of 'perched' water tables. In addition, groundwater may not move through finer textured fill materials as easily.

The PSC of soils formed in capped dredge spoils was sandy (Tables 1.4 and 1.11) in all but one case, while all four soils formed in uncapped dredge spoils at the BAY site had a coarse-loamy PSC (Table 1.6). Lenses and masses of silt and fine sand were stratified within sandy dredge spoils (Tables 1.4 and 1.6). Dredge spoil deposits had very little to no angular gravel, but did contain shell fragments and asphalt in some cases. Dredge spoils are often deposited over tidal marshes by constructing areas on the marsh enclosed by berms (Fanning and Fanning, 1989), creating a basin where dredged materials settle out in a subaqueous environment. This depositional environment usually results in stratification of finer and coarser textured materials. The predominately sandy PSC for dredge spoil deposits are consistent with those of recent soil survey mapping of anthropogenic soils in New York (Hernandez, 2006). The four uncapped dredge spoils and one capped dredge spoil with a coarse-loamy PSC, however, demonstrate that variation in dredge spoil textures will occur as a result of the local subaqueous soil characteristics from which the materials were dredged.

Reworked HTM deposits were predominately sandy (Tables 1.7 and 1.11). In one soil reworked sandy HTM occurred over silty and sandy loam textured tidal marsh A horizons within the control section, creating a sandy over loamy PSC. Reference tidal marsh soils comprised of mineral deposits had sandy over loamy PSC when estuarine sediments were deposited over loess or silty tidal deposits, and sandy or coarse loamy PSC when estuarine sediments were deposited over glacial outwash (Tables 1.9 and 1.11).

Bulk density values for HTM ranged from 0.55 to 1.69 g cm^{-3} (Table 1.12). One-way ANOVA showed no significant differences ($p < 0.05$) in bulk density among subsurface horizons from fill materials, dredge spoils, or buried natural soils. Surface horizons formed in HTM had the lowest bulk density (Figure 1.2), where roots were usually abundant and the soil loosened through bioturbation. Sandy dredge spoils always had bulk density values near 1.6 g cm^{-3}, while a silty dredge spoil lens had a bulk density of 1.3 g cm^{-3} (Table 1.13). Subsurface horizons formed in fill materials had a wider range in bulk density values (1.09 to 1.69 g cm^{-3}) (Table 1.13), which may be related to greater variability in texture and horizons that were compacted during anthropogenic deposition. Most of the horizons formed in either HTM or the natural soils buried beneath anthropogenic deposits had bulk density values that were within a typical range for the corresponding soil texture (Table 1.13) (Saxton et al., 1986). These findings suggest that the majority of the horizons formed in HTM were not compacted during anthropogenic deposition. This is important because compacted subsurface soils might impede groundwater movement. Occasional high bulk density values from horizons formed in fill materials, however, did suggest that some fill materials were compacted during deposition and may serve as an aquitard or promote 'perching' of infiltrated surface or tidal water. The bulk density values measured in this investigation compare well to other dredge materials (Fanning and Fanning, 1989) and fill materials (Evans, 2000), but are lower than those measured by Short et al. (1986a) in fill materials of the Mall at Washington D.C.

Water table activity in anthropogenic soils of the estuarine riparian zone

In order for anthropogenic soils of the estuarine riparian zone to function in the denitrification capacity, water tables must rise into the HTM. Water tables rose as much as 2.5 meters above buried marsh surfaces (Figure 1.3), and were above the buried natural soil surface for all or most of the time in 16 of the wells installed in HTM. In some cases hydric conditions developed (Figure 1.4). Water table fluctuations within HTM of the estuarine riparian zone were influenced by tides, seasonal evapotranspiration, precipitation, geomorphic setting, characteristics of the buried natural soils, or a combination of these factors.

Substantial differences between the measured water table level and the highest water table level between readings of riparian estuarine anthropogenic soils were observed in a repeating pattern at several sites. This pattern persisted through periods of little or no precipitation. For example, precipitation was unusually low during March 2006, with a monthly total of only 1.83 cm (Appendix A). Between March 15 and March 31 only trace amounts of precipitation were recorded (March 25). Although precipitation was minimal between March 15 and March 30 substantial differences were measured between the highest water table level and the preceding and current measured water table level at Well 2 of the Potter Pond 2 site (Figure 1.4). This well was located in HTM deposits over a fringing tidal marsh. On March 15 the measured water table was 24 cm below grade. By March 30 the highest water table level had risen to 14 cm below grade, but the measured water table had dropped to 25 cm below grade. The 10 cm rise in the water table identified by the highest water table level during a period of virtually no precipitation demonstrates the influence of tidal activity on water table fluctuations at this site. Such water table patterns were common in many anthropogenic soils of fringing estuarine riparian settings and unconsolidated shores, and persisted through periods of little precipitation. Wells installed in HTM over fringing marshes and unconsolidated shores ranged from 1.5 to 23 meters to open estuarine water (Table 1.14) and 1.4 to 18 meters to the edge of the HTM. These observations suggest that tidal influences on water table activity can extend laterally into HTM of estuarine shores for considerable distances.

Water table levels were governed, in part, by seasonal effects related to evapotranspiration in some of the anthropogenic soils (Figure 1.3). At the Cold Spring Beach site, the water table level dropped from May 2005 through the summer as the result of evapotranspiration. The water table quickly rose in the fall, and during the winter considerable water table fluctuation occurred between 10 and 104 cm. In May 2006 the water table dropped again as evapotranspiration increased. A similar pattern was observed at the BAY site (Figure 1.5). Human transported materials were deposited over a tidal creek marsh at the Cold Spring Beach site. At the BAY site HTM were deposited over a tidal creek marsh-freshwater marsh complex. The wells at these sites were located further from a tidal creek channel or open estuarine water (38 to 83 m) than any of the wells installed in HTM over fringing tidal marsh or unconsolidated shore. The entire tidal creek and surrounding marsh were filled with HTM at the Cold Spring Beach site, effectively cutting off the source of tidal water. Well 2 was 83 m from the open water of Narragansett Bay. At the Bay site Well 2 was 6 m to *Phragmites australis* dominated marsh at the toe of the anthropogenic soil fill extension, and 38 m from the existing tidal creek. The peat beneath the HTM was characteristic of freshwater peat, indicating that the portion of the marsh that was filled never had strong tidal influences. The seasonal water table pattern, lack of tidally influenced water table fluctuations, and landscape setting for these soils suggests that when the edge of HTM deposits are not directly exposed to tidal waters, water table activity in anthropogenic soils of the estuarine riparian zone is primarily controlled by precipitation inputs and growing season evapotranspiration. The tidally influenced Brushneck Cove site also showed higher water tables during winter months

(Figure 1.6), suggesting both seasonal and tidal influences on water table activity can occur in HTM at certain locations.

The type of soil material at the base of the HTM affected water table dynamics. Where marsh soils were filled the measured water table level and the highest water table level between readings were often well above the original soil surface (Figures 1.3 and 1.4). Buried marshes had substantial organic soil materials in the former surface horizons. Such soils typically have low saturated hydraulic conductivity, thereby limiting the chance of water movement. Thus, low hydraulic conductivity in buried natural soil horizons beneath anthropogenic deposits may prohibit drainage and affect water table fluctuations within the HTM by restricting downward movement of infiltrated tidal water and precipitation.

In the two locations where sandy textured unconsolidated shorelines were below HTM, measured water table levels were usually near or below the original soil surface, but the highest water table level between readings often rose into the HTM (Figure 1.7). These data indicate the presence of endosaturation.

Soil morphology as evidence of reducing conditions in anthropogenic soils

Redoximorphic features (RMF's) were present within the range of water table activity in 16 of 18 monitored anthropogenic soils (Table 1.14). These features were distributed throughout the anthropogenic soil matrix in many soils, and sometimes followed a sequence of vertical distribution relative to longer periods of saturation with depth (Figure 1.8). At some sites with dredge spoil deposits, Fe concentrations with a diffuse boundary surrounded darker carbon enriched silt loam lenses or finer textured depletions (Figure 1.9). Concentrations were also observed as pore linings and were clearly associated with roots, buried plant fragments, dark carbon enriched masses, and coarse fragments in fill materials (Table 1.3). Redoximorphic features develop under reducing conditions in the soil when Fe coatings on soil particles are reduced, translocated, and segregated (Vepraskas, 1992). Anaerobic saturation is required to initiate this microbially mediated process (Vepraskas and Faulkner, 2001). Thus, RMF's are often used as a field indicator of microbially mediated oxidation-reduction reactions that occur under reducing conditions (Vepraskas, 1992; Veneman et al., 1998) and suggest that microbially mediated oxidiation-reduction reactions are active in HTM of the estuarine riparian zone. This is important, because Fe is reduced at a lower potential than nitrate (Patrick and Jugsujinda, 1992). If Fe is reduced in these systems by microbial activity, then N would be as well.

RMF's were not present in the soil at Potter Pond 1 Well 2 or Point Avenue Well 2. At Potter Pond 1 Well 2, 14 of the 34 measured water table levels were within the anthropogenic horizons (Figure 1.10). Eight of these 14 measurements occurred between late October 2005 and late February 2006, when soil temperatures may have been low enough to effectively inhibit microbial activity. The soil at Point Avenue Well 2 had highly variable parent material color and a very high artifact content that made field assessment of RMF's impractical. Well 1 at the Point Avenue site was located only 9.7 m away, however, and did exhibit RMF's within the range of water table activity suggesting that reducing conditions were present within the anthropogenic deposits at the Point Avenue site. Thus, the timing and duration of saturation, and site-specific characteristics of the anthropogenic deposits can account for the absence of RMF's in the anthropogenic soils that lacked RMF's within the range of water table activity.

Redoximorphic features indicative of considerable periods of reduction such as Fe depletions or depleted matrices were sometimes present in horizons that were usually not saturated during the monitoring period (Figure 1.11). In such cases, these features may have formed at another location before the soil materials were brought to the site as HTM (i.e. developed under reducing conditions in the subaqueous environment from which the HTM were derived). Another possibility is that some RMF's formed in dredge spoils when the materials were pumped into the site under saturated conditions. A third possibility is that compacted HTM resulted in the development of a perched water table (episaturation) and the duration of saturation was sufficient for RMF's to form. Areas of ponded surface water were often observed at sites subsequent to heavy rains, suggesting poor infiltration and episaturation above anthropogenic soil horizons. Thus, the potential for RMF's that are relict or the result of episaturation demonstrates that caution must be exercised when interpreting RMF's in anthropogenic soils.

Soil organic carbon content and distribution

Soil organic carbon content was always highest in surface horizons of anthropogenic soils, ranged from 0.16% to 8.89%, and had an irregular distribution with depth (Figure 1.12, Tables 1.12 and 1.13). Ciolkosz et al. (1985) and Thurman and Sencindiver (1986) observed a similar range in organic carbon content in minespoils and also identified irregular carbon distributions. Short et al. (1986a) and Evans et al. (2000) found that soil organic matter (SOM) was highest in surface horizons of fill materials and varied with depth. Assuming that 50% of the SOM measured in those studies (Short et al., 1986a; Evans et al., 2000) was carbon, the SOC I measured in fill materials was higher. Fanning and Fanning (1989) reported SOC contents of 3.1-4.0% in four-year-old sulfidic dredge spoils in Maryland. Puyat et al. (2002) found carbon densities in four old dredge spoils of New York to have approximately 1/6th the carbon density of the Maryland dredge spoils. My measurements of SOC in dredge spoils were also lower than the Maryland dredge deposits, with a maximum value of 1.09% in a silt loam lens. The distribution of carbon with depth across a variety of HTM sources and settings suggests that subsurface carbon required for microbial processes is present in HTM.

Root additions from vegetation that had become established at the sites, and subsequent humification of these organic matter inputs, increased carbon content in surface horizons of anthropogenic soils (Tables 1.12 and 1.13). Soil organic carbon content of A and AC horizons developed in fill materials were similar to those of A and AC horizons in natural soils. One-way ANOVA showed SOC content of subsurface horizons (C or CA horizons) was higher in fill materials than in dredge spoils or buried natural soils ($p < 0.01$) (Table 1.12). Thus, soil horizons formed in HTM of the estuarine riparian zone had carbon contents that were comparable to, or exceed, natural estuarine riparian mineral soils. The higher subsurface carbon contents in the C and CA horizon of fill materials (Table 1.12) is likely a function of the carbon content of the HTM that was deposited at the study sites. Although the silty lenses and masses in the Wilson Park and Ninigret Pond soils had the highest SOC content of dredge spoils (Table 1.13); the majority of the dredge materials were sandy with relatively low carbon content. Thus, overall mean carbon content of dredge spoil parent materials was not as high as that of fill materials.

Forms of subsurface soil organic carbon

Soils formed in HTM of the estuarine riparian zone contained both pedogenic and anthropogenic forms of carbon (Tables 1.15 and 1.16). Recognizing carbon forms below the water table is important because concentrations of carbon are potential denitrification 'hotspots' (Jacinthe et al., 1998; Gold et al., 1998). Carbon added to the subsurface by pedogenic processes once the HTM is in place, such as roots, is newer and may be more labile, although both anthropogenic and pedogenic carbon may be important to denitrification processes.

Roots, root traces, masses, lenses, buried horizon carbon, and fragmental organic matter (FOM) were the carbon forms observed below the water table in both anthropogenic soils and natural soils (Table 1.15). Roots were the most abundant carbon form, and were present in 84% of the described anthropogenic soils. In surface horizons where roots were most prevalent, humification of root additions resulted in darkening of anthropogenic deposits, and the creation of new carbon enriched A or AC horizons in all but five of the anthropogenic soils. Vegetation was lacking or sparse at the five soils without A or AC horizons. Some of the darkness in the surface horizon colors of anthropogenic soils may also have originated from carbon rich HTM. Thirty-four of the 55 anthropogenic soils contained a carbon rich buried horizon (Table 1.15). Masses, non-woody FOM, and lenses were also common, while woody FOM and root traces were not as prevalent. These data (Table 1.15) show that a number of subsurface carbon forms were common below the water table in all three classes of HTM. These subsurface carbon forms explain the variation in SOC measurements with depth (Figure 1.12; Table 1.13). In all but two cases, natural soils buried beneath anthropogenic deposits were intact, indicating that the carbon forms that were present in the original tidal marsh or unconsolidated shore deposits are still present in the riparian subsurface.

Silty lenses and masses that were rich in carbon were very common in dredge spoil deposits (Table 1.16). These silty components were often dark gray (5Y 4/1) to very dark gray (5Y 3/1) in color. Two samples of these materials were analyzed and had SOC contents of 1.07% and 0.7%. Sandy components of dredge deposits typically had SOC contents of <0.5% (Table 1.13). Although groundwater is more likely to flow through the sandy portions of dredge spoils, the point of contact between the silty and the sandy components provides a zone of concentrated carbon. RMF's adjacent to these carbon masses suggested these areas are 'hotspots' of microbially driven oxidation-reduction reactions (Figure 1.9) Non-woody FOM was also common in dredge spoil deposits (Table 1.16). The source of this FOM was probably eelgrass, algal mats, and marsh plant detritus that were pumped in with mineral soil components during dredging operations.

Masses of carbon enriched soil materials were often mixed into fill materials during anthropogenic deposition (Table 1.16). Occasionally lenses were observed in fill materials, apparently created when these materials were deposited and distributed to fill the area (Table 1.16). Root traces buried in aggregates of silty textured fill materials were infrequent (Tables 1.15 and 1.16). Woody and non-woody FOM were also mixed into fill materials during anthropogenic deposition and buried in the subsurface (Tables 1.15 and 1.16).

Roots, masses, horizon carbon, and non-woody FOM were the most prevalent carbon forms in reworked HTM and reference tidal marsh soils (Tables 1.7., 1.8, 1.9, and 1.15). Woody FOM was rarely observed, and root traces were observed in only two reference pedons. These observations suggest that carbon was added to the subsurface primarily by root additions from tidal marsh vegetation. Root decomposition usually resulted in a darkened A or transitional (AC or CA) horizon directly under the surface layer of the peat. Below the darkened subsurface horizons, masses and decomposing root clusters ringed by darkened carbon masses were noted. These roots, and masses associated with their decay, may be important 'hotspots' for denitrification processes in the subsurface of undisturbed riparian soils and in buried riparian soils. One reference soil located in a tidal creek marsh had a horizon of freshwater peat 183-208 cm below the surface, which had developed prior to coastal submergence and burial by estuarine deposits. Where they are present in the estuarine riparian zone, these deep buried deposits of freshwater organic soil materials provide a substantial source of subsurface carbon.

Carbon lability in anthropogenic soils of the estuarine riparian zone

Understanding the lability of subsurface carbon in anthropogenic soils of the estuarine riparian zone is important to determining the capacity of these soils to function in the denitrification capacity. The distribution of labile carbon with depth, estimated by measurements of POC, was similar to SOC (Figures 1.12 and 1.13, Table 1.13), and ranged from 0-2.71 g C kg^{-1} soil in HTM and 0-7.62 g C kg^{-1} soil in natural soils. Permanganate oxidizable carbon was highest in former surface and near-surface horizons of buried tidal marsh soils (Table 1.12). Roots and plant FOM were abundant in O, A, and AC horizons of tidal marsh soils (Table 1.15). Surface horizons of HTM also had higher POC contents than subsurface HTM horizons. Roots from grass and other vegetation were most abundant in surface horizons of HTM. These data suggest that roots (buried and those established after HTM additions) and buried plant fragments are labile carbon sources important to denitrification processes.

Permanganate oxidizable carbon content of subsurface horizons formed in HTM and buried natural soils were similar (Table 1.12). The anthropogenic materials had a wider and slightly higher range of values. Fourteen percent of the subsurface fill material horizons, and 30% of subsurface dredge spoil horizons had no POC, compared to 21% of the subsurface horizons of buried natural soils (Table 1.13). These data suggest that although carbon contents may be elevated in subsurface soils of disturbed estuarine riparian zones, occasionally not all of the carbon will be labile enough to fuel microbial processes such as denitrification.

The POC approach was developed as a rapid method to measure carbon lability for assessing soil quality in agricultural settings (Blair et al., 1995). The effectiveness of the POC method for measuring carbon lability has been debated (Tirol-Padre and Ladha, 2004). Weil et al. (2003) modified the approach of Blair et al. (1995) by using a more dilute $KMnO_4$ solution to provide a more accurate measurement of carbon lability. My POC results suggest that some additional adjustment to the approach developed by Weil et al. (2003) is required for estimating labile carbon in riparian soils. Initial measurements of POC using 5.0 g soil sample aliquots revealed that POC content reached a maximum value of approximately 0.7 g C kg^{-1} soil, and had a very small range in soils with high SOC content. These results indicated that samples with higher carbon contents were consuming the entire permanganate reagent. High carbon samples were reanalyzed using a smaller soil sample (<0.5 g). Weil et al. (2003) recommend re-analyzing samples using a smaller sample weight when spectrophotometer absorbance is < 0.01. However, my second analysis showed that all samples with an initial absorbance value of < 0.1 exhibited an increase in POC. Six of 9 samples with an initial absorbance value of 0.1-0.16 showed an increase in POC content. This suggests that a 0.01 absorbance threshold for reanalyzing riparian samples with higher carbon contents is too low, and that a value of 0.1 to 0.15 may be more appropriate to ensure that the entire permanganate reagent is not consumed.

SUMMARY AND CONCLUSIONS

The goal of this investigation was to document and examine characteristics of anthropogenic soils in the estuarine riparian zone relevant to their ability to function in the denitrification capacity. These characteristics include the presence of labile carbon, soil saturation, and a reducing soil environment. I collected data on physical properties, morphology, water table activity, and carbon of anthropogenic soils to assess the characteristics required to support microbial denitrification processes.

Three classes of HTM deposits were identified in the estuarine riparian zone: dredge spoils, fill materials, and capped dredge spoil deposits. Estuarine deposits derived from reworked HTM were also present near the foot of anthropogenic landforms. Textures of horizons formed in HTM ranged from silt loam to extremely gravelly coarse sand, which corresponded to family particle size classes (PSC) of sandy-skeletal to coarse-loamy, although sandy was the most common PSC. Reworked HTM deposits were also predominately sandy. Artifacts were present in many anthropogenic soils and reworked HTM deposits. Bulk densities of subsurface anthropogenic soil horizons were similar to buried natural soils, but occasional high values were measured. The predominately coarse soil textures and normal bulk density values suggested that groundwater movement should not be impeded by soil compaction or low hydraulic conductivity in most anthropogenic deposits of disturbed estuarine riparian settings. Occasional high bulk density values and finer textured lenses, however, indicate that some horizons may serve as an aquitard and promote perching of infiltrated surface or tidal water.

Water tables rose into HTM deposits at all sites. Water table fluctuations within HTM of the estuarine riparian zone were influenced by tides, seasonal evapotranspiration, precipitation, geomorphic setting, characteristics of the buried natural soils, or a combination of these factors. Tidal influences on water table fluctuations were most evident at sites where anthropogenic soils were deposited over 'fringing' riparian marshes or unconsolidated shorelines, and had direct exposure to tidal water. Tidal influences on water table activity in anthropogenic soils extended laterally into anthropogenic deposits for considerable distances. Where tidal waters were effectively cut off by site disturbance, or where the HTM deposits were not directly exposed to tidal waters, water tables were primarily governed by seasonal effects related to evapotranspiration and precipitation.

Redoximorphic features (RMF's) were frequently identified in anthropogenic soils of the estuarine riparian zone, and were present within the range of water table activity in the majority of monitored soils. The coincidence of water table activity and RMF’s suggests that microbially mediated oxidiation-reduction reactions are active in HTM of the estuarine riparian zone. The timing and duration of saturation, or site-specific characteristics of the anthropogenic deposits explained the absence of RMF's in the few anthropogenic soils that lacked RMF's within the range of water table activity. Recognizing RMF's in anthropogenic soils is useful for predicting water table depth and the potential for denitrification. If redox potential is low enough to result in the formation of RMF's, then nitrate in the soil-groundwater system will also be reduced through the denitrification process. Some caution should be exercised in interpreting RMF's of anthropogenic soils because some features could be relict. This is particularly important in dredge spoils or other HTM that were derived from or deposited under saturated conditions.

Soils formed in HTM contained both pedogenic and anthropogenic forms of carbon. Surface horizons of HTM deposits were darkened by humification processes, and numerous carbon forms were observed below the water table in all three classes of HTM, buried natural soils, and reworked HTM. The abundance of carbon forms corresponded well to measurements of SOC, which were always highest in surface horizons and had an irregular distribution with depth. Horizons formed in HTM of the estuarine riparian zone had SOC contents that were comparable to or exceeded natural estuarine riparian mineral soils. The distribution of labile carbon, estimated by measurements of POC, generally followed that of SOC. Understanding carbon form, distribution, and lability below the water table of anthropogenic soils in estuarine riparian zones is important because denitrification in riparian areas is often carbon limited, and subsurface carbon concentrations are potential denitrification 'hotspots'.

My studies demonstrate that anthropogenic soils in estuarine riparian settings can have the characteristics required to function in the denitrification capacity. Urban soil survey projects have recently started correlating HTM to the soil series level of Soil Taxonomy. Soil surveys with sufficient detail for making interpretations of denitrification potential in anthropogenic soils of disturbed estuarine riparian zones would be a useful management tool in coastal watersheds. To further develop understanding of the denitrification potential of anthropogenic soils in the estuarine riparian zone additional studies are needed to elucidate relationships between soil morphology, water tables, and redox potential in HTM deposits, determine hydrologic flowpaths within HTM, measure microbial activity through tests such as denitrification enzyme activity, and determine denitrification rates using in-situ measurements.

Table 1.1. Sampling approach used to determine the number of sampling locations to describe the soils of an area that had been disturbed with additions of anthropogenic soils. The site area was calculated using Geographical Information System polygon coverages.

Site Area (m^2)	**Number of Sampling Points**
< 1000	4
1,000 – 3,000	6
3,000 – 5,000	8
5,000 – 7,000	10

Table 1.2. Geomorphic setting and land use of study and reference sites.

Site Name	Site Code	Initial HTM Deposition*	Current Land Use	Geomorphic Setting Prior To HTM Addition	Type of HTM
Study Sites:					
Ninigret Pond	NP	1939 - 1952	Marina	Fringing Marsh	Capped Dredge Spoils + Offsite Materials
Potter Pond # 1	PP-1	1952-1962	Residential	Fringing Marsh and Non-Tidal Riparian Wetland	Offsite Materials
Potter Pond # 2	PP-2	1962-1976	Residential	Fringing Marsh	Capped Dredge Spoils + Offsite Materials
Cold Spring Beach	CSB	1952-1962	Municipal Parkland	Tidal Creek Marsh	Capped Dredge Spoils
Wickford Harbor South	WHS	Predates 1939	Residential	Fringing Marsh	Offsite Materials
Wilson Park	WP	1962-1976	Municipal Parkland	Fringing Marsh	Capped Dredge Spoils
Brushneck Cove	BC	Predates 1939	Municipal Parkland	Fringing Marsh	Offsite Materials

*The exact year of deposition is unknown, but aerial photographs indicate deposition occurred between the indicated years.

Table 1.2. Geomorphic setting and land use of study and reference sites (continued).

Site Name	Site Code	Initial HTM Deposition*	Current Land Use	Geomorphic Setting Prior To HTM Addition	Type of HTM
Study Sites:					
Boat Club	LRBC	1939-1952	Marina	Fringing Marsh and Unconsolidated Shore	Offsite Materials
Bay Site	BAY	1962-1976	Marina	Tidal Creek Marsh and Freshwater Tidal Marsh	Dredge Spoils
Old Mill Cove	OMC	Predates 1939	Residential	Fringing Marsh and Unconsolidated Shore	Offsite Materials
Point Ave	PA	Predates 1939	Road Crossing	Tidal Creek Marsh	Offsite Materials
Reference					
Wilson Park Reference	WP-REF	-	Fringing Marsh	Fringing Marsh	-
Wickford Point	WP-REF	-	Fringing Marsh	Fringing Marsh and Unconsolidated Shore	-
Warwick City Park	WCP-REF	-	Tidal Creek Marsh	Tidal Creek Marsh	-
Tidewater	TW-REF	-	Tidal Creek Marsh	Tidal Creek Marsh	-

*The exact year of deposition is unknown, but aerial photographs indicate deposition occurred between the indicated years.

Table 1.3. Soil description for the Potter Pond 1 site, HA-2-A. The soil was formed in fill materials.

Horizon	**Depth (cm)**	**Description**
^Au	0-10	Sandy loam; 5% gravel; 7.5YR 3/2; many very fine and few fine roots; horizon carbon present; few very coarse pieces of plastic sheeting.
^C1	10-32	Gravelly sandy loam; 15% gravel; 10YR 4/6 with 7.5YR 3/2 masses of darker material; common very fine and few fine and coarse roots; few fine plant and wood fragments.
^C2	32-46	Gravelly sandy loam; 15% gravel; 2.5Y 5/4 (90%), 10YR 2/1 (5%), and 10YR 4/3 (5%); common fine concentrations and depletions; common very fine and few fine roots; few fine plant fragments; horizon carbon present in 10YR 2/1 portion of matrix.
^Cg	46-70	Silt loam; 2% gravel; 10YR 2/1 (90%) and 2.5Y 5/4 (10%); common fine concentrations as pore linings; few very fine roots; few fine plant fragments; horizon carbon present in 10YR 2/1 portion of matrix.

Described By: Sean Donohue
Location: 1.7 meters to toe of HTM and open water
Landform: Brackish fringing marsh covered with HTM derived from fill materials
Land Use: Residential lawn
Depth to water table: 32 cm
Classification: Coarse-loamy, mesic Aeric Fluvaquent

Table 1.4. Soil description for the Wilson Park site, HA-3-B. The soil was formed in dredge spoil with a fill material cap.

Horizon	**Depth (cm)**	**Description**
^AC	0-29	Sandy loam; 3% gravel; 10YR 3/3; common very fine and few fine roots; horizon carbon present; fill materials.
^C1	29-51	Gravelly loamy sand; 15% gravel; 5Y 4/2; common distinct and prominent medium concentrations associated with silt loam masses; common medium to coarse 5Y 3/1 silt loam masses; fill materials.
^2C2	51-60	Sand; 1% gravel; 5Y 5/3; dredge spoil.
^2Cg1	60-109	Sand; 3% gravel; 5Y 5/3; common medium concentrations and depletions, often associated with masses of finer textured sand present in soil matrix; dredge spoil.
^2Cg2	109-129	Sand; 5Y 4/1; common fine concentrations and medium depletions; fine and medium 5Y 3/1 silt loam masses common; dredge spoil.
^2Cg3	129-139	Silt loam; 5Y 3/1, interstratified with lenses of slightly grayer colors; very fine roots; horizon carbon present; dredge spoil.
^2Cg4	139-152	Loamy sand; 10% gravel; 5Y 3/1; common medium depletions and few fine and medium concentrations, often associated with masses of very fine sand; hemic peat fragments, horizon carbon, and marsh plant stems are present; dredge spoil.

Described By: Sean Donohue
Location: 38.6 meters to toe of HTM and open water along Transect 3
Landform: Fringing marsh covered with dredge spoil deposits capped with fill materials
Land Use: Lawn of municipal park
Depth to water table: 60 cm
Classification: Sandy, mesic Oxyaquic Udifluvents

Table 1.5. Mean and range in thickness of soils formed in anthropogenic and reworked anthropogenic parent materials.*

Soil Type	Number of Soils	Mean (cm)	Range (cm)	Number of Soils Within Each Depth Class 0 - <50 cm	50 - <100 cm	100 - <150 cm	150 - <200 cm	>200 cm
Fill Materials	30	95	(26-178)	2	14	11	3	0
Dredge Spoils	4	200	(180-211)	0	0	0	2	2
Capped Dredge Spoils	21	126	(30->285)	1	7	1	5	7
Reworked HTM	6	49	(22-80)	3	3	0	0	0
All Soils	61	106	(22-270)	6	24	12	10	9

*For soils where the thickness of HTM could not be determined due to refusal, these locations were not included in calculations of the mean.

Table 1.6. Soil description for the Bay site, HA-2-A. The soil was formed in dredge spoil.

Horizon	Depth (cm)	Description
^C1	0-8	Loamy fine sand (60%) and silt loam (40%); 2.5Y 5/2 and 2.5Y 4/2; very few very fine roots; very few fine and medium plant fragments.
^C2	8-33	Silt loam; 5Y 4/2; common fine to medium concentrations and medium to coarse depletions.
^Cg1	33-47	Silt loam (95%) with fine masses of fine sand (5%); 5Y 4/2 and 5Y 6/2; common fine to medium concentrations, often as lenses at interface of plate like structure of silt loam; few fine and very fine relict roots.
^Cg2	47-61	Silt loam (90%) and fine sand (10%); < 2% gravel; 5Y 5/1, 5Y 4/1, 5Y 7/1; common fine to medium concentrations; few fine and medium relict roots; few fine and medium plant fragments.
^Cg3	61-67	Fine sand (60%) and silt loam (40%); 5Y 5/2 and 5Y 4/2; common fine to medium concentrations present at interface of fine sand and silt loam textures.
^Cg4	67-79	Silt loam; 5Y 4/1; common fine concentrations.
^Cg5	79-109	Silt loam (95%) and fine sand (5%); 5Y 4/1 and 5Y 6/2; common concentrations; few 10YR 3/2 medium masses; common N 2.5/0 and 10Y 3/1 silt lenses 2-3 mm in thickness; materials interstratified with plate/lens like structure.
^Cg6	109-134	Loamy fine sand (60%) and silt loam (40%); 5Y 3/1 and 5Y 3/2; common fine and medium depletions; very few very fine and fine relict roots, common medium relict roots; common fine and medium N 2.5/0 masses with a loamy fine sand texture; common N 2.5/0 loamy fine sand lenses 1-3 mm in thickness; common fine and medium plant fragments; materials interstratified.

Table 1.6. Soil description for the Bay site, HA-2-A, continued. The soil was formed in dredge spoil.

Horizon	Depth (cm)	Description
^Cg7	134-210	Loamy fine sand; 5Y 4/2; common medium and coarse depletions, often as lenses 2-3 mm thick; few very fine, fine, and medium roots; common N 2.5/0 and 10YR 2/1 fine, medium, and coarse masses; materials interstratified with plate/lens like structure.

Described By: Sean Donohue
Location: 7 meters to toe of HTM/existing marsh; 6.5 meters to well 2
Landform: Tidal creek marsh covered with dredge spoil deposits
Land Use: Marina boatyard
Depth to water table: 8 cm
Classification: Coarse-loamy, mesic Fluvaquentic Epiaquepts

Table 1.7. Soil description for the Wilson Park site, HA-4-A. The soil was formed in reworked HTM over tidal marsh.

Horizon	**Depth (cm)**	**Description**
^ACg	0-12	Loamy sand; 2% gravel; 2.5Y 3/2 and 5Y 4/2; common fine and medium concentrations and depletions; many very fine and fine roots, common medium roots; common 2.5Y 3/3 medium and coarse masses common; common plant fragments; reworked HTM.
^Cg	12-36	Sand; 2% gravel; 5Y 4/2; common fine and medium depletions; many very fine roots, common fine and medium roots; common 5Y 3/2 fine and medium masses; many plant fragments; reworked HTM.
2Ab	36-48	Loamy sand, primarily organic materials by volume; 5Y 2.5/1; many very fine and common fine and medium roots; many plant fragments; estuarine deposits.
3CA	48-73	Gravelly sand; 20% gravel; 5Y 4/1; many very fine, common fine, and few medium roots; horizon carbon present; outwash.
3Cg	73-80	Gravelly sand; 15% gravel; 5Y 5/2; outwash.
3C	80-100	Gravelly coarse sand; 20% gravel; 2.5Y 5/4; outwash.

Described By: Sean Donohue
Location: 6.4 meters to open water/edge of vegetated marsh
Landform: Fringing tidal marsh along toe of HTM embankment
Land Use: Municipal park
Depth to water table: 0+ cm
Classification: Sandy, mesic Haplic Sulfaquent
Note: The presence of sulfidic materials was not verified by laboratory measurements. Sulfidic materials were presumed to be present based on a sulfidic odor and the salt marsh landscape location.

Table 1.8. Soil description from the Warwick City Park reference site, HA-1-A. The soil was formed in organic soil materials, estuarine deposits, and outwash.

Horizon	**Depth (cm)**	**Description**
Oe	0-10	2.5Y 3/2; many very fine and common fine and medium roots; common fine plant fragments; organic soil materials.
Oi1	10-38	2.5Y 3/1; many very fine and common fine and medium roots; many fine plant fragments; organic soil materials.
Oi2	38-50	5Y 3/2; many very fine and common fine and medium roots; common fine plant fragments; organic soil materials.
O'e	50-86	Many very fine and common fine and medium roots; few fine plant fragments; organic soil materials.
A	86-145	Fine sand, mostly organic soil materials by volume; 5Y 3/2; many very fine and few fine and medium roots; few fine plant fragments; estuarine deposits.
Cg	145-185	Fine sand; 5Y 5/2; common fine and medium concentrations and depletions; common very fine, few fine, and very few medium roots, often in clusters; few 5Y 3/2 medium and coarse masses; very few fine plant fragments.

Described By: Sean Donohue
Location: 4.5 meters to tidal creek channel
Landform: Tidal creek marsh
Land Use: Municipal park
Depth to water table: 0+ cm
Classification: Mesic Typic Sulfihemists
Note: The presence of sulfidic materials was not verified by laboratory measurements. Sulfidic materials were presumed to be present based on a sulfidic odor and the salt marsh landscape location.

Table 1.9. Soil description for the Wilson Park Reference site, Well 3. The soil was formed in estuarine deposits and outwash.

Horizon	**Depth (cm)**	**Description**
A1	0-7	Silt loam, primarily organic soil materials by volume; 2.5Y 3/2; many very fine, fine, and medium roots; common fine plant fragments; horizon carbon present; estuarine deposits.
A2	7-34	Loamy sand; 3% gravel; 5Y 3/2; many very fine and medium, common fine roots; few fine plant fragments; horizon carbon present; estuarine deposits.
AC	34-56	Loamy sand; 5% gravel; 5Y 3/2; few medium depletions; common very fine and fine, few medium roots; common 5Y 4/3 medium and coarse masses of decomposing roots; very few fine plant fragments; horizon carbon; estuarine deposits.
C1	56-74	Loamy sand; 5% gravel; 5Y 3/2; few medium depletions; common very fine and few fine roots; few 5Y 4/3 medium and coarse masses; very few fine plant fragments; estuarine deposits.
2C2	74-100	Loamy sand; 1% gravel; 5Y 3/2; common medium and coarse depletions; few very fine; few 5Y 2.5/1 fine and medium masses; outwash.

Described By: Sean Donohue
Location: 10.5 meters to water/edge of vegetated marsh
Landform: Fringing tidal marsh
Land Use: Municipal park
Depth to water table: 0+ cm
Classification: Sandy, mesic Typic Endoaquoll

Table 1.10. Artifact occurrence in anthropogenic and natural soils of the estuarine riparian zone.

Soil Type	**Total Number of Soils**	**Number of Soils With Artifacts**	**Type of Artifacts Present**
Fill Materials	30	19	Brick, Asphalt, Wood, Glass, Shingles, Rubber, Plastic, Iron, Charcoal
Dredge Spoils	4	1	Asphalt
Capped Dredge Spoils	21	9	Glass, Concrete, Asphalt, Plastic, Iron, Brick
Reworked HTM	6	3	Plastic, Asphalt, Brick, Ceramic
Natural Soils	16	3	Glass, Ceramic

Table 1.11. Family particle size class of anthropogenic and natural soils of the estuarine riparian zone. The control section was 25-100 cm, or 25 cm to the bottom of the anthropogenic parent materials if less than 100 cm thick.

Soil Type	**Number of Soils**	**Sandy**	**Coarse Loamy**	**Sandy Skeletal**	**Loamy Skeletal**	**Sandy Over Loamy**
Fill Materials*	30	15	9	4	1	0
Dredge Spoils	4	0	4	0	0	0
Capped Dredge Spoils	21	20	1	0	0	0
Reworked HTM	6	5	0	0	0	1
Natural Soils***	16	9	2	0	0	2

* One soil was comprised of > 90% artifactual materials, so a family particle size class using Soil Taxonomy was unable to be determined. Three additional soils had > 35% artifacts, but did not meet Soil Taxonomy requirements for a skeletal family particle size class.

*** Three pedons of organic soil materials were present, so a particle size family class was not determined.

Table 1.12. Summary of properties of fill materials, dredge spoils, and natural soils.

Horizon Type	**Fill Materials**		**Dredge Spoils**		**Natural Soils**	
	Mean (n)	**Range**	**Mean (n)**	**Range**	**Mean (n)**	**Range**
			Soil Organic Carbon (%)			
O	-	-	-	-	15.4 (3)	13.48-17.71
A and AC	3.6 (7)	0.91-8.89	-	-	5.4 (5)	1.99-7.95
C and CA	1.5 (14)	0.34-3.55	0.5 (10)	0.16-1.09	0.5 (14)	0.13-1.07
			Permanganate Oxidizable Carbon (g C kg^{-1} soil)			
O	-	-	-	-	5.5 (3)	3.25-7.62
A and AC	0.9 (7)	0.17-2.71	-	-	2.1 (5)	0.88-3.52
C and CA	0.2 (14)	0-0.63	0.2 (10)	0-0.48	0.1 (14)	0-0.35
			Bulk Density (g cm^{-3})			
O	-	-	-	-	0.35 (3)	0.27-0.47
A and AC	1.05 (7)	0.55-1.38	-	-	0.74 (3)	0.34-1.19
C and CA	1.42 (12)	1.06-1.69	1.60 (8)	1.30-1.67	1.47 (4)	1.15-1.67