Human-Transported Material Soils of Urbanizing Estuarine Landscapes

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Additions of human-transported materials (HTM) have significantly altered many coastal shorelines and wetlands. The hydrology and the ability of these anthropogenic soils to support ecologically important functions is poorly understood. In this study, we documented soil hydrologic patterns along disturbed estuarine shorelines and wetlands. Our goal was to determine if the soils had properties relative to the potential to support denitrification (i.e., labile C, saturation, and reducing conditions). Eleven anthropogenic sites, located in Rhode Island and 30 to >60 yr old, were studied. Auger transects were completed to characterize anthropogenic soils. Water table levels were monitored twice a month. Anthropogenic soils were described and sampled from pits at five representative locations. Soil organic C (SOC), permanganate-oxidizable C (POC), bulk density, and pH were measured. Deposits of HTM, comprised of dredge and fill materials, ranged in thickness from 26 to >285 cm, were predominantly sandy and often contained artifacts. In the thickest HTM deposits, water table levels rose as much as 2.5 m above the original buried soil surface. Redoximorphic features were identified within the range of water table activity in 16 of the 18 monitored anthropogenic soils, suggesting reducing conditions. Soil organic C ranged from 1.6 to 88.9 g kg^{-1}, was highest in surface horizons, and had an irregular distribution with depth. Labile C, estimated from POC measurements, followed the SOC distribution. Evidence of labile C, saturation, and reducing conditions in the majority of these soils suggest that most of the disturbed estuarine soils we studied have the capacity for denitrification.

Abbreviations: HTM, human-transported materials; POC, permanganate-oxidizable carbon; RMF, redoximorphic features; SOC, soil organic carbo

Estuarine landscapes (shorelines and adjacent wetlands) within urbanizing coastal watersheds are often drained or filled for development purposes (Tiner, 1984; Dahl, 2000). The materials that are used to fill these sites and constitute the parent materials of these altered (anthropogenic) soils are now called *human-transported materials* (Soil Survey Staff, 2006). Human-transported materials are common in urban and developing landscapes (Hernandez and Galbraith, 1997; Galbraith, 2006), and HTM deposits in coastal settings can be extensive (Galbraith, 2006).

Interest in HTM and human-altered 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 deposits (Pedersen et al., 1980; Ciolkosz et al., 1985; Potter et al., 1988; Stolt et al., 2001), classifying these soils (Schafer, 1979; Thurman and Sencindiver, 1986), and the problems associated with mapping these landscapes (Schafer, 1979; Indorante and Jansen, 1984; Haering et al., 2005). Similar studies have investigated the characteristics of HTM on military land (Evans et al., 2000), urban areas (Pouyat 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,b), and sand and gravel pits (Strain and Evans, 1994). Applied investigation of HTM properties as they relate to ecosystem services is needed, however.

One important ecosystem service performed by soils of estuarine landscapes is denitrification (Nowicki and Gold, 2008). Coastal waters are N limited, and the introduction of excess N to estuarine environments can result in significant ecological and management problems including eutrophication, hypoxia, and habitat disturbance (Valiela et al., 1990; Nixon, 1995). Estuarine soils with shallow water tables that interact with horizons containing labile C can remove groundwater N contamination through the process of microbial denitrification (Addy et al., 2005), and serve as a potential landscape sink for reducing N loads to estuaries (Nowicki and Gold, 2008). Given anthropogenic increases in N inputs to estuaries (Roman et al., 2000) and the extensive deposits of HTM in estuarine landscapes of urbanizing coastal watersheds, information regarding the properties of HTM relevant to the denitrification function would be useful.

Anthropogenic soils in estuarine landscapes have the potential to remove NO_3 if conditions support soil saturation and abundant electron donors (e.g., labile C) are present (Groffman and Crawford, 2003). Several studies have found that C distribution in anthropogenic soils is variable with depth (Ciolkosz et al., 1985; Short et al., 1986b; Thurman and Sencindiver, 1986; Buondonno et al., 1998), suggesting that the C required for

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microbial denitrification (Gold et al., 1998; Clough et al., 1999; Groffman and Crawford, 2003) may be present in the subsurface of disturbed estuarine landscapes 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.

In this study, we took a pedologic approach to determine if anthropogenic soils formed in HTM deposits over estuarine landscapes have properties that facilitate groundwater NO_3 removal through denitrification (subsurface layers with labile C, saturation, and reducing conditions). Field descriptions of deep soil pits and auger transects, water table measurements, and laboratory measurements of bulk density, pH, SOC and POC were used to assess these characteristics.

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 coverage available through RIGIS were initially referenced to identify estuarine landscapes that have been directly altered by additions of HTM. Soils mapped as Udorthents, urban land (anthropogenically disturbed soils), and native soil–urban land complexes along the estuarine shoreline were used as indicators of potential anthropogenic soils. Bulkhead, hardened shoreline, and degraded estuarine wetland coverages were also used as indicators of anthropogenic disturbance. Comparisons of historic and current site characteristics were made using 1939 aerial photographs and 1997 orthophotography. Estuarine landscapes identified as having the potential for HTM deposits were ground truthed by foot or canoe. Reconnaissance data were collected on the width of existing estuarine hydric soils, the type of shoreline disturbance, the distance to the estuarine shore or open water from the edge of the HTM deposits, HTM thickness, the distance to the closest building from the shoreline, land use, and the length and width of bulkheads or other constructed shoreline features. Soils were described from auger borings. The geomorphic setting of each disturbed site was noted as former fringing tidal marsh, tidal creek marsh, or unconsolidated shore based on predisturbance aerial photographs and field observations of adjacent undisturbed areas. In addition, related information such as the history of dredging operations or shoreline construction in the vicinity of the sites was obtained through discussions with municipal officials, residents, and property owners.

Eighty sites or shoreline segments with HTM additions were assessed during the reconnaissance visits. Based on the reconnaissance data, 11 sites representative of estuarine landscapes with anthropogenic soils were selected for study. The criteria for selecting study sites included geomorphic setting (whether the sites were formerly tidal creek marshes, fringing tidal marshes, or unconsolidated shore), HTM depth and characteristics, the nature and extent of the site disturbance, and accessibility. Historic aerial photographs and orthophotography for each decade between 1939 and 1998 were reviewed to determine when the HTM were deposited.

Field Sampling and Data Collection

Transect studies were completed across the 11 study sites to collect data on soil morphology and SOC distribution. Transects were orientated perpendicular to the shoreline at disturbed fringing marsh and unconsolidated shorelines or perpendicular to the tidal creek at disturbed tidal creek marshes, and were distributed across the study area while avoiding impediments such as buried utilities, structures, paved areas, and retaining walls. The number of transects was determined based on the length of shoreline or tidal creek within the study site area: two transects for <50 m, three transects for 50 to 150 m, and four transects for 150 to 250 m. Sampling intervals for the transects ranged from 4 to 28 m. Supplemental auger borings were completed at each site as needed. Fifty anthropogenic soil profiles formed in HTM deposits were described during the transect studies. Soil profiles were described from shallow pits (<50 cm deep) and bucket auger borings (<3 m deep) according to standard procedures (Soil Survey Staff, 1993; Schoeneberger et al., 2002). Soil organic C forms were described using the morphologic approach described by Blazejewski et al. (2005). Particular attention was paid to evidence of reducing conditions such as redoximorphic features.

Deep soil pits were also opened at five representative study site locations to make complete profile and SOC descriptions, resulting in a total of 55 soils formed in HTM deposits described during the field investigations. 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 the 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.

Each site was instrumented with wells constructed of 3.8-cm i.d. polyvinyl chloride slotted well screen with a pointed end cap and cover. Two wells were installed in a line perpendicular to the water's edge at each site. The distance between wells was dependent on the width of the HTM deposits, and varied from 6 to 27 m. Eighteen wells were installed in soils formed in HTM. Water tables were measured approximately once every 2 wk. 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).

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. Soil pH was measured on a 1:1 mixture of soil and water. After thoroughly mixing the fine-earth fraction of the bulk sample, approximately 2 g of soil from each bulk sample was ground and passed through a 0.25-mm mesh sieve. The ground samples were dried in an oven at 60°C for 24 h. 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 h 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 the soil horizons (Soil Survey Staff, 2004).

Permanganate-oxidizable C was measured from samples collected from the five deep soil pits to estimate the labile C content (Blair et al., 1995; Tirol-Padre and Ladha, 2004). We used 0.02 mol L^{-1} $KMnO_4$ to oxidize the active C fraction and light absorbance (550 nm) to quantify active C (Weil et al., 2003). Initially, a 5-g sample was used for the POC measurement. A smaller sample weight (<0.5 g) was used for samples from buried marsh horizons with a SOC content of >4%, an initial POC measurement >0.6 g C kg^{-1} soil, or a spectrophotometer absorbance reading of <0.1 (Donohue, 2007) because marshes and other wetlands tend to accumulate considerable SOC.

RESULTS AND DISCUSSION

Human-transported materials were added to fill seven of the study sites between 1939 and 1976. 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 before the addition of HTM. Land use at these sites now includes residential lawns and gardens, marinas, municipal parkland, and a filled area adjacent to a road crossing of a tidal creek marsh.

Two primary types of anthropogenic parent materials were identified in the 55 soils formed in HTM: dredged materials and nondredged materials. In addition, nondredged materials were frequently deposited over dredged materials. For the purposes of this discussion, three classes of anthropogenic soil parent materials are described and identified: dredge deposits, fill (any nondredged) materials, and fill-capped dredge deposits (Table 1). Fill-capped dredge deposits and fill materials were the most common type of anthropogenic soil parent materials (Table 2). In general, fill materials were the shallowest deposits, typically between 50 and 150 cm thick. Fill-capped dredge deposits ranged from 30 to >285 cm in thickness, with the fill material cap ranging in thickness from 20 to 100 cm. At one site, four soils were formed in dredge deposits without a cap and were on the order of 200 cm thick.

Physical Characteristics

Artifacts such as demolition debris, plastic, glass, and brick were present in 53% of the described anthropogenic soils (Table 2). Both fill materials and dredge deposits 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 >90% artifacts, one soil had horizons described as very artifactual (35–60%), and two soils had horizons described as extremely artifactual (60–90%). Two study sites had soils with buried asphalt pavement. Roots were observed below these layers, and thus they were not considered M horizons by strict definition because they were not root limiting (Soil Survey Staff, 2006).

The family particle size control section (PSC) of the anthropogenic soils is defined here as 25 to 100 cm (similar to the control section for Entisols; Soil Survey Staff, 2006), or 25 cm to the bottom of the anthropogenic materials if the HTM was <100 cm thick. Textures of HTM ranged from silt loam to extremely gravelly coarse sand, which corresponds to a range in PSC from coarse loamy to sandy skeletal (Table 3). Human-transported materials derived from fill materials were excavated from a variety of locations. Thus, fill material PSCs were more variable than dredge deposits, although sandy was still the most common PSC for fill materials.

The PSC of soils formed in fill-capped dredge deposits was sandy in 20 of 21 sites (Table 3). In contrast, at the one study site with just dredge deposits, the four soils that were described all had a coarse-loamy PSC (Table 3). Lenses and masses of silt and fine sand were stratified within sandy dredge deposits (Tables 1 and 4). Minimal amounts of coarse fragments were found in dredge deposits, but shell fragments and asphalt were sometimes present. Dredge deposits 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 predominantly sandy PSC for dredge deposits is consistent with those of recent soil survey mapping of anthropogenic soils in New York (Hernandez et al., 2006). Although sandy is typical, the four dredge deposits and one fill-capped dredge deposit with a coarse-loamy PSC demonstrate that variation in dredge deposits is possible as a result of where in the subaqueous environment the materials were dredged.

Undisturbed estuarine wetland soils have been found to have groundwater denitrifcation capacities, thereby reducing the risk of terrestrial NO_3 inputs to coastal waters (Addy et al., 2005). In order for disturbed estuarine soils to denitrify NO_3–enriched groundwater, the hydraulic conductivity of soils formed in HTM must be high enough to facilitate flow between the soils and coastal waters. Since coarser textured soils generally have higher hydraulic conductivity (Dingman, 2002), groundwater flow should not be impeded in sandy dredge deposits and fill materials of the estuarine landscape. Silty horizons and lenses, however, were identified in both dredge deposits and fill materials (Tables 1 and 4). Groundwater does not flow through these silty horizons as easily as coarser textured horizons.

Bulk density values for HTM ranged from 0.55 to 1.69 g cm^{-3} (Table 4). Surface horizons formed in HTM had the lowest bulk density, where roots were usually abundant and the soil was loosened through bioturbation. Sandy dredge deposits always had bulk density values near 1.6 g cm^{-3}, while a silty dredge deposit lens had a bulk density of 1.3 g cm^{-3} (Table 4). Subsurface horizons formed in fill materials had a wider range in bulk density values (1.09–1.69 g cm^{-3}) than dredge deposits, which may be related to greater variability in the texture and compaction of some fill materials during anthropogenic deposition. Most bulk density values, however, were similar to those predicted by Saxton et al. (1986) for respective natural soil materials having the same textures, suggesting 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 or serve as an aquitard, promoting the "perching" of infiltrated surface or tidal water. Bulk density values recorded in this investigation compare well to other dredge materials (Fanning and Fanning, 1989) and fill materials (Evans et al., 2000), but are lower than those reported by Short et al. (1986b) for fill materials of the Mall in Washington, DC.

Table 1. Representative profile descriptions of soils formed in the three most common types of human-transported material (HTM): fill materials, dredge deposits, and fill-capped dredge deposits.

Horizon	Depth	Description
	cm	
Potter Pond 1: residential lawn, fill materials, 1.7 m to open water; coarse-loamy, mesic Aeric Fluvaquent		
^Au	0–10	sandy loam; 5% gravel; 7.5YR 3/2; few very coarse pieces of plastic sheeting; horizon C†; many very fine and few fine roots
^C1	10–32	gravelly sandy loam; 15% gravel; 10YR 4/6 matrix with 7.5YR 3/2 C masses; 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 Fe concentrations and depletions; common very fine and few fine roots; few fine plant fragments; horizon C in the 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 Fe concentrations as pore linings; few very fine roots; few fine plant fragments; horizon C in 10YR 2/1 portion of matrix
Wilson Park: municipal park, fill-capped dredge deposits, 38.6 m to open water; sandy, mesic Oxyaquic Udifluvent		
^AC	0–29	sandy loam; 3% gravel; 10YR 3/3; common very fine and few fine roots; horizon C; fill materials
^C1	29–51	gravelly loamy sand; 15% gravel; 5Y 4/2; common distinct and prominent medium Fe concentrations associated with silt loam masses; common medium to coarse 5Y 3/1 silt loam C-enriched masses; fill materials
^2C2	51–60	sand; 1% gravel; 5Y 5/3; dredge deposits
^2Cg1	60–109	sand; 3% gravel; 5Y 5/3; common medium Fe concentrations and depletions, often associated with masses of finer textured sand present in soil matrix; dredge deposits
^2Cg2	109–129	sand; 5Y 4/1; common fine Fe concentrations and medium depletions; fine and medium 5Y 3/1 silt loam C-enriched masses common; dredge deposits
^2Cg3	129–139	silt loam; 5Y 3/1, interstratified with lenses of slightly grayer colors; very fine roots; horizon C; dredge deposits
^2Cg4	139–152	loamy sand; 10% gravel; 5Y 3/1; common medium Fe depletions and few fine and medium Fe concentrations, often associated with masses of very fine sand; hemic peat fragments, horizon C, and marsh plant stems present; dredge deposits
Bay Site: marina boatyard, dredge deposits, 7 m to toe of HTM/existing unfilled marsh; coarse-loamy, mesic Fluvaquentic Epiaquept		
^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 Fe concentrations and medium to coarse Fe 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 Fe 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, and 5Y 7/1; common fine to medium Fe 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 Fe concentrations present at interface of fine sand and silt loam textures
^Cg4	67–79	silt loam; 5Y 4/1; common fine Fe concentrations
^Cg5	79–109	silt loam (95%) and fine sand (5%); 5Y 4/1 and 5Y 6/2; common Fe concentrations; few 10YR 3/2 medium C masses; common N 2.5/0 and 10Y 3/1 C-enriched silt lenses 2–3 mm in thickness; materials interstratified with plate- or 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 Fe depletions; very few very fine and fine relict roots, common medium relict roots; common fine and medium N 2.5/0 C-enriched masses with a loamy fine sand texture; common N 2.5/0 loamy fine sand C-enriched lenses 1–3 mm in thickness; common fine and medium plant fragments; materials interstratified
^Cg7	134–210	loamy fine sand; 5Y 4/2; common medium and coarse Fe 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 C-enriched masses; materials interstratified with plate- or lens-like structure

† Horizon C: Organic fine and organo-mineral materials dispersed throughout the matrix (Blazejewski et al., 2005).

Table 2. Artifact occurrence in anthropogenic soils of the estuarine shoreline.

Soil type	Total soil profiles	Soil profiles with artifacts	Range in thickness	Type of artifacts present
	no.	no.	cm	
Fill materials	30	19	26–178	brick, asphalt, wood, glass, shingles, rubber, plastic, iron, charcoal
Dredge deposits	4	1	180–211	asphalt
Fill-capped dredge deposits	21	9	30 to >285	glass, concrete, asphalt, plastic, iron, brick

Water Table Fluctuations

Water table fluctuations within HTM were influenced by geomorphic setting, characteristics of the buried natural soils, tides, seasonal evapotranspiration, precipitation, or a combination of these factors (Fig. 1 and 2). Water tables rose as much as 2.5 m above buried marsh surfaces (Fig. 1), and were above the buried natural soil surface for all or most of the time in 16 of the 18 wells installed in HTM. Buried marsh surfaces may have been compacted during placement of the HTM as evidenced by the incorporation of mineral materials within the buried O horizons and Ab horizons dominated (by volume) with organic soil materials (Table 4). In some cases, water table levels were within 30 cm of the soil surface, suggesting that hydrologic criteria for wetlands were being met during some times of the year (Fig. 2).

Substantial differences between the measured water table level and the highest water table level between readings of the anthropogenic soils were observed in a repeating pattern at several sites through periods of little or no precipitation. For example, although precipitation was unusually low during March 2006 (1.83 cm), and between 15 and 31 March only trace amounts of precipitation were recorded, substantial differences were measured between the highest water table level and the preceding and current measured water table level for the Potter Pond 2 site (Fig. 2). This well was located in HTM deposits over a fringing tidal marsh. The rise in the water table during a period of virtually no precipitation suggests the influence of tidal activity on water table fluctuations at this site. Such water table patterns were common in many anthropogenic soils deposited over former fringing tidal marshes and unconsolidated shores, and persisted through periods of little precipitation. Since we only measured the water table levels bimonthly, we don't know if these fluctuations occurred daily or were the result of spring or storm tides. These apparent tidal effects were observed in wells <13 m away from open estuarine water. Although we expect well locations closest to open water, or those in areas that have the lowest elevation, to show the greatest tidal effect, our data could not confirm these relationships. Seasonal changes in water table levels were observed in some of the anthropogenic soils. For example, at the Cold Spring Beach site (Fig. 1), where fill-capped dredged deposits buried a tidal creek marsh, the water table level dropped from May 2005 through the summer and then quickly rose in the fall. During the winter, considerable water table fluctuation occurred between 10 and 104 cm before falling again in May of 2006. The seasonal water table pattern suggests that water table activity in anthropogenic soils of some disturbed estuarine shoreline settings is primarily controlled by precipitation inputs and growing-season evapotranspiration.

In settings where HTM was deposited directly over fringing or tidal creek marsh soils, water table levels were often well above the original soil surface (Fig. 1 and 2). The A and O horizons of these buried marshes have substantial organic soil materials (Table 4). Such horizons typically have low saturated hydraulic conductivity (Dingman, 2002), thereby limiting the rate of water movement. These horizons may have also been compacted during placement of the HTM. In addition, tidal marsh soils generally are saturated to the soil surface. Thus, the low hydraulic conductivity and saturated conditions of the natural soil horizons beneath anthropogenic deposits probably inhibits the drainage of water within the HTM. In contrast to the hydrology of HTM over tidal marsh, in soils where sandy textured unconsolidated shorelines were below the HTM, water table levels were usually near or below the original soil surface. Although water table levels often fluctuated into the anthropogenic materials, these materials were usually not saturated (Fig. 3). Therefore, the hydraulic conductivity and depth to saturation within natural soils beneath the HTM will dictate whether the overlying anthropogenic soils are continuously saturated.

Soil Morphologic Evidence of Reducing Conditions

Redoximorphic features (RMF) in the form of depletions, Fe concentrations, and gleyed horizons (^Cg) were present within the range of water table activity in 16 of 18 monitored anthropogenic soils (see Table 1 for representative examples). These features were distributed throughout the anthropogenic soil matrix. Some of the soils had a RMF distribution with depth following the sequence: Fe concentrations, depletions, and finally gleyed horizons. This sequence is indicative of an increasing duration of saturation with depth and is typically observed in natural soils (Morgan and Stolt, 2006). In a number of soils formed in dredge deposits, Fe concentrations with a diffuse boundary surrounded darker C-enriched silt loam lenses or finer textured depletions, indicating the importance of SOC in the formation of these features. Concentrations were also observed as pore linings and were clearly associated with roots, buried plant fragments, dark C-enriched masses, and coarse fragments in fill materials (Table 1). Redoximorphic features develop under reducing conditions in the soil when Fe coatings on soil particles are reduced,

Table 3. Summary of the anthropogenic materials family particle size class. The control section was defined as 25 to 100 cm, or 25 cm to the bottom of the anthropogenic materials if the human-transported material was <100 cm thick.

Soil type	Soil profiles	Sandy	Coarse-loamy	Sandy-skeletal	Loamy-skeletal
Fill materials†	30	15	9	4	1
Dredge deposits	4	0	4	0	0
Fill-capped dredge deposits	21	20	1	0	0

† One of the fill material soils was comprised of >90% artifact materials and the family particle size class was not recorded.

Table 4. Properties of selected anthropogenic soils described and sampled from deep pits.

Horizon	Depth	Texture†	Bulk density	Soil organic C	Permanganate-oxidizable C	pH
	cm		g cm^{-3}	——— g C kg^{-1} soil ———		
Ninigret Pond: 44 cm of fill materials over 23 cm of dredge deposits over estuarine deposits; sandy, mesic Aeric Fluvaquent						
^AC	0–13	sl	1.27	33.7	0.51	4.9
^C	13–15	s	–	–	–	–
^AC′	15–25	gr sl	1.38	25.1	0.46	5.0
^C′	25–44	gr s and sil	1.56	3.4	0.09	5.0
^2Cg1	44–55	s	1.63	1.6	0.00	4.2
^2Cg2	55–57	sil	–	7.0	0.22	3.9
^2Cg3	57–67	s	–	6.5	0.22	–
3Oeb	67–77	osm with sil and s lenses	0.32	135	3.25	4.7
Potter Pond 1: 81 cm of fill materials over estuarine deposits; coarse-loamy, mesic Fluventic Endoaquept						
^Au	0–3	fsl	0.55	88.9	2.71	4.9
^ACu	3–20	fsl and sil	0.96	40.9	0.84	4.8
^Cu1	20–33	sl	1.06	25.6	0.43	4.9
^Cu2	33–46	sl	1.19	35.5	0.53	5.1
^Cug1	46–58	gr sl	1.26	14.9	0.21	5.2
^Cug2	58–64	sl	–	41.0	0.63	4.9
^Cug3	64–81	sl	1.20	15.8	0.30	5.0
2Oeb	81–84	osm with vfs and sil	0.47	177	5.52	4.3
Potter Pond 2: 24 cm of fill materials over 29 cm of dredge deposits over estuarine deposits; sandy, mesic Typic Psammaquent						
^AC	0–6	sl	0.73	31.4	1.17	5.6
^Cg1	6–16	ls	1.55	8.1	0.15	5.9
^Cg2	16–20	ls	–	12.0	0.21	5.9
^Cg3	20–24	ls	1.55	15.7	0.32	5.9
^2Cg4	24–53	s	1.65	3.6	0.16	6.3
3Ab	53–62	s (primarily osm by volume)	0.34	65.1	2.29	3.6
Cold Spring Beach: 55 cm of fill materials over 97+ cm of dredge deposits; sandy, mesic Aquic Quartzipsamments						
^AC	0–5	gr ls	1.20	9.1	0.17	5.1
^C1	5–10	gr sl and gr ls	1.68	6.2	0.003	5.1
^C2	10–55	gr cos	1.60	5.3	0.00	5.6
^2Cug1	55–77	fs	1.59	2.5	0.00	5.7
^2Cug2	77–98	fs	1.61	4.4	0.00	5.3
^2Cug3	98–152+	fs	1.65	3.1	0.09	4.2
Wilson Park: 85 cm of fill materials over 67 cm of dredge deposits over estuarine deposits; coarse-loamy, mesic Aeric Fluvaquent						
^AC	0–12	gr sl	1.25	24.7	0.48	5.1
^Cu1	12–24	ls	1.37	3.4	0.00	5.0
^Cu2	24–55	gr sl	1.69	9.8	0.19	6.5
^Cg1	55–85	sl	1.32	8.6	0.21	–
^2Cg2	85–128	s, fs, and ls	1.67	4.5	0.13	3.8
^2Cg3	98–106	sil	1.30	10.9	0.48	3.3
^2Cg4	128–152	s	1.66	2.8	0.22	3.5
3Ab	152–180	ls and sil (primarily osm by volume)	–	67.2	3.52	–

† sl, sandy loam; s, sand; sil, silt loam; fsl, fine sandy loam; cos, coarse sand; vfsl, very fine sandy loam; osm, organic soil materials; lfs, loamy fine sand; si, silt; ls, loamy sand; gr, gravelly; xgr, extremely gravelly.

translocated, and segregated (Vepraskas, 1992). Anaerobic saturation is required to initiate this microbially mediated process (Vepraskas and Faulkner, 2001). Thus, RMF are often used as a field indicator of reducing conditions (Vepraskas, 1992; Veneman et al., 1998).

At six of the 18 soils where water tables were monitored, RMF were observed in near-surface horizons (<25 cm from the soil surface) that were only saturated for a few days as the result of endosaturation. What these features represent in regard to reducing conditions is unknown. Surface ponding was observed at some of these sites following heavy rain or snowmelt, suggesting that some of these RMF may have formed during periods of episaturation above compacted HTM horizons or finer textured HTM lenses. Another possibility is that the RMF formed in the original subaqueous or hydric soils that were the source of the HTM and are not currently indicative of reducing conditions. Dredge materials from marine environments often contain sulfides that after deposition may oxidize, resulting in a drastic drop in pH and development of color patterns as Fe is redistributed (Fanning and Fanning, 1989). To test if this could be the case, we measured the pH of the samples collected from the deep soil pits (Table 4). The Ninigret Pond, Cold Spring Beach, and Wilson Park sites all had dredge material horizons with pH values approaching 4 or less, indicative of sulfidic materials that have oxidized with time (Soil Survey Staff, 2006). These horizons, however, were well below the soil surface (>44 cm) and within the range of the fluctuating water table, suggesting that the observed RMF may have formed under reducing conditions. The potential for relict RMF, or those that form as a result of periodic episaturation or oxidation of sulfidic materials, suggest that caution should be exercised when interpreting RMF as evidence of reducing conditions in anthropogenic soils. One simple field test to address this issue could be the application of α-dipyridyl to the saturated or near-saturated soil materials (Childs, 1981; Faulkner et al., 1989). A positive reaction would suggest that the features were not relict. A negative reaction would still be inconclusive.

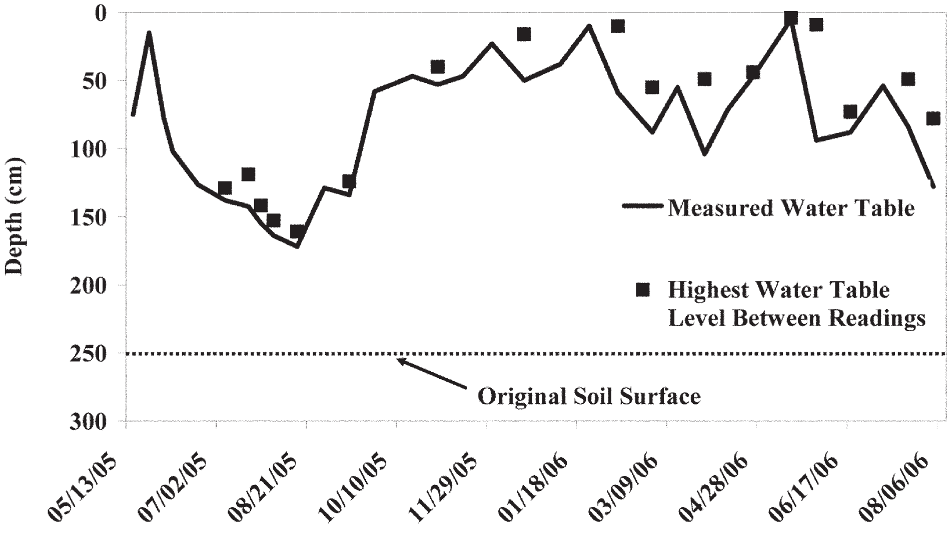

Fig. 1. Water table fluctuation in Well 2 at the Cold Spring Beach site (fill-capped dredge deposits over a tidal creek marsh). Water table patterns were driven primarily by precipitation and seasonal changes in evapotranspiration, rather than tidal influences. Where there is no measurement of the highest water table level between readings, the high water table device was either not yet installed or the device malfunctioned.

Soil Organic Carbon Content, Distribution, Form, and Lability

Recognizing SOC content, distribution, form, and lability below the water table is important because concentrations of C are potential denitrification “hotspots” (Jacinthe et al., 1998; Gold et al., 1998). Soil organic C content of the anthropogenic soils ranged from 1.6 to 88.9 g kg^{-1}, was highest in surface horizons, and had an irregular distribution with depth (Table 4). Numerous other studies of anthropogenic soils found considerable variability in SOC contents with depth depending on the type of materials (Ciolkosz et al., 1985; Thurman and Sencindiver, 1986; Short et al., 1986b; Fanning and Fanning, 1989; Evans et al., 2000; Pouyat et al., 2002). These studies, and our observations across a variety of HTM sources and settings, suggest that the subsurface C required for microbial processes is present, but highly variable, in HTM.

The SOC content of A and AC horizons developed in fill materials were similar to those of A and AC horizons in buried natural soils (Table 4). Root additions from vegetation that had become established at the sites, and subsequent humification of these organic matter inputs, are the probable source of the C in these surface and near-surface horizons. The higher subsurface C contents in the C and CA horizons of fill materials (Table 4) are probably a function of the C content of the HTM that were 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 deposits (Table 4), the majority of the dredge materials were sandy with relatively low C content. Thus, the overall mean C content of dredge deposit parent materials was not as high as that of fill materials.

Roots, root traces, masses, lenses, buried horizon C, and fragmental organic matter (FOM) were the C forms observed below the water table in anthropogenic soils (Tables 1 and 5). Roots were the most abundant C form, and were present in 84% of the described anthropogenic soil profiles (Table 5). In anthropogenic soils with good vegetative cover and surface horizons with an abundance of roots, humification of roots resulted in darkening of anthropogenic deposits and the creation of C-enriched ^A or ^AC horizons. This occurred in all but five of the anthropogenic soils. Some of the darkness in the surface horizon colors of anthropogenic soils may also have originated from C-rich HTM. Thirty-four of the 55 anthropogenic soils contained a C-rich buried horizon (Table 5). Masses, nonwoody FOM, and lenses were also common, while woody FOM and root traces were not as prevalent. These data show that a number of subsurface C forms were common below the water table in all three classes of HTM. These subsurface C forms explain the variation in SOC measurements with depth (Table 4). In all but two cases, natural soils buried beneath

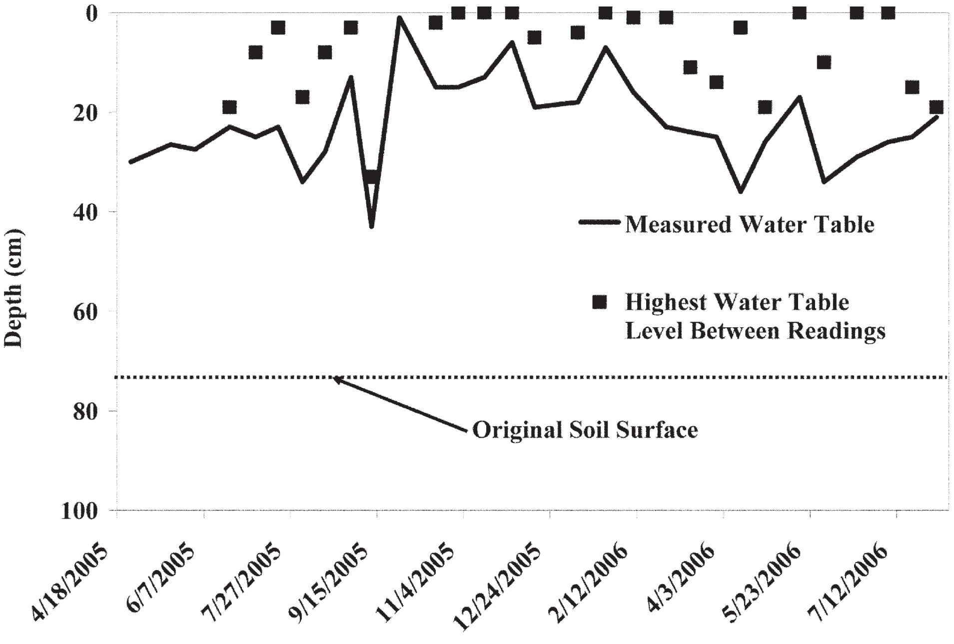

Fig. 2. Water table fluctuation in Well 2 at the Potter Pond 2 site(fill-capped dredge deposits over a fringing tidal marsh). Water table levels between readings were consistently higher than the measured water table, suggesting tidal influences on water table activity.

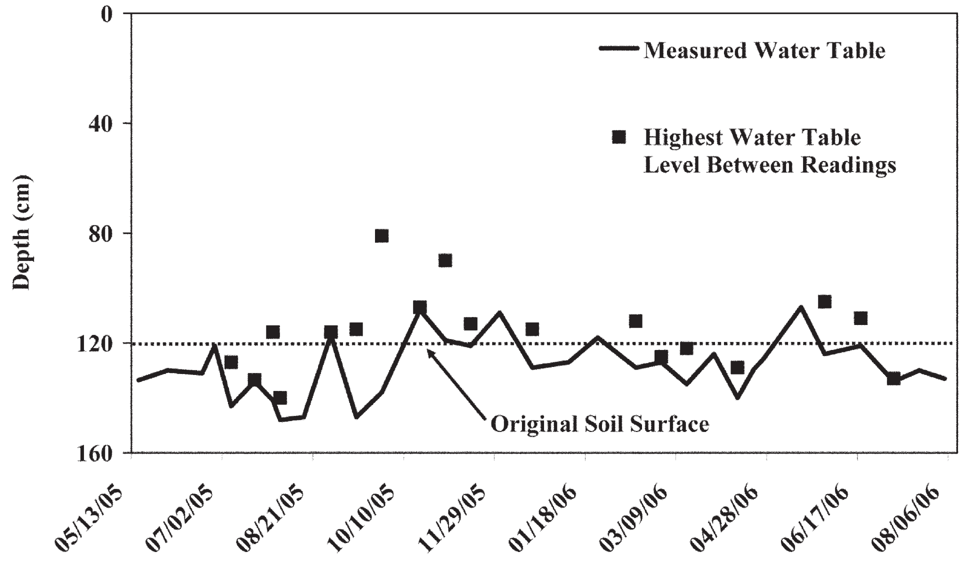

Fig. 3. Water table activity in Well 2 at the Boat Club site (fill materials over a sandy unconsolidated shore). Although water table levels often fluctuated into the fill materials, the fill materials were usually not saturated.

anthropogenic deposits were intact, indicating that the C forms that were present in the original tidal marsh or unconsolidated shore deposits were still present in the subsurface.

Carbon-rich silty lenses and masses were very common in dredge deposits (Tables 1 and 5). 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 10.7 and 7.0 g kg^{-1}. Sandy components of dredge deposits typically had SOC contents of <5.0 g kg^{-1} (Table 4). Although groundwater is more likely to flow through the sandy portions of dredge deposits, the point of contact between the silty and the sandy components provides a zone of concentrated C. The observation of RMF adjacent to these C masses suggested that these areas are “hotspots” of microbially driven oxidation–reduction reactions. Nonwoody FOM was also common in dredge deposits. The source of this FOM was probably eelgrass (*Zostera marina* L.), algal mats, and marsh plant detritus that were pumped in with mineral soil components during dredging operations.

Carbon-enriched soil materials were often mixed into fill materials during anthropogenic deposition. Occasionally lenses were observed in fill materials, apparently created when these materials were deposited and distributed to fill the area. Root traces buried in aggregates of silty-textured fill materials were infrequent. Woody and nonwoody FOM were also mixed into fill materials during anthropogenic deposition and buried in the subsurface.

Understanding the lability of subsurface C in anthropogenic soils of the estuarine landscape is important in determining the capacity of these soils to function in a denitrification capacity. The distribution of labile C with depth, estimated by measurements of POC, was similar to SOC (i.e., in general, when SOC increased with depth so did POC), and ranged from 0 to 2.71 g C kg^{-1} soil in HTM and 0 to 5.52 g C kg^{-1} soil in buried natural soils. Roots and plant FOM were abundant in the O, A, and AC horizons of buried tidal marsh soils. 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 C sources important to denitrification processes.

CONCLUSIONS AND IMPLICATIONS

In nearly every urbanizing coastal setting, alterations have been made to the landscape to accommodate multiple anthropogenic activities and uses. For example, using geographic information system databases, we identified 80 coastal areas in which to concentrate our reconnaissance efforts that had been altered enough that they could be recognized on aerial photographs as being human altered. These alterations typically involved the filling of tidal marshes that in the past provided a number of important ecosystem services. One of the more important functions of wetlands in these urbanizing landscapes is denitrification of NO_3 from terrestrial sources. Thus, we asked the question: do these anthropogenic soils still have the potential to function in the denitrification capacity? We defined the potential to function in the denitrification capacity as anthropogenic soils that have soil saturation within layers that have enough labile C to develop reducing conditions. Water table levels rose well within all of the 18 monitored soils formed in fill materials and dredge deposits, suggesting a direct link between the groundwater and these soils. Measurable labile C was found to be present in many of the HTM deposits, providing an active C source for microbially driven reduction of the NO_3 that often occurs in elevated concentrations in the groundwater of urbanizing areas. Evidence

Table 5. Number of anthropogenic soil profiles with C forms below the water table, stratified by soil type. The depth to the water table was estimated as the equivalent to the first horizon with redoximorphic features.

Soil type	Total soil profiles	Soil profiles with C forms present†						
		Roots	Root traces	Masses	Lenses	Buried horizon C	Nonwoody FOM‡	Woody FOM
		no.						
Fill materials	30	26	2	17	1	18	14	6
Dredge deposits	4	4	0	4	1	3	4	1
Fill-capped dredge deposits	21	16	0	17	9	13	17	1

† Carbon forms defined by Blazejewski et al. (2005).

‡ FOM, fragmental organic matter.

of reducing conditions was observed in the form of numerous Fe-related redoximorphic features such as depletions and concentrations. Since Fe is reduced at a lower potential than NO_3, the presence of Fe-related RMF suggests that NO_3 would also be reduced in these anthropogenic soils. Although our studies clearly show that these anthropogenic soils have the capacity for denitrification, additional studies are needed to differentiate relict from active Fe-related RMF, to elucidate groundwater flow paths within HTM, to measure microbial activity through tests such as denitrification enzyme activity, and to determine denitrification rates using in situ measurements. In addition, mapping of anthropogenic soils in urbanizing areas should be strongly encouraged. Recent urban soil survey projects have started correlating HTM soil to the series level of Soil Taxonomy instead of "urban land" as has been done in the past. Soil surveys with sufficient detail for making interpretations of denitrification potential in anthropogenic soils of disturbed estuarine landscapes would be a useful management tool in coastal watersheds.

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