Classification, Mapping, and Interpretation of Subaqueous Soils.

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Introduction

Soil surveys have been made in the United States for over 100 years. For all but the last few years they have been conducted exclusively on the terrestrial parts of the landscape. This has included some areas covered by shallow water such as inland fresh water bogs and marshes or tidal marshes exposed at low tide bordering coastal estuaries, but deeper water areas have been mapped simply as “water”. The definition of ‘soil’ as used in the US Soil Survey has been somewhat vague in defining the transition from “soil” to “water”. The first edition of Soil Taxonomy (Soil Survey Staff, 1975, p. 2) recognized that while the top of the soil was generally marked by the interface with the air, it may also be the interface with “shallow water.” It went on to state that it is not soil if “water is deep enough that only floating plants are present.” The Soil Survey Manual (Soil Survey Division Staff, 1993, p. 7) instructed that “sediment below shallow water is soil if it can support bottom-rooted plants such as cattails or reeds”. While not explicitly stated, this was interpreted by some as indicating that emergent vegetation was required to meet the definition of soil, thereby excluding beds of submerged aquatic vegetation (SAV) such as eelgrass below the low tide elevation in estuarine ecosystems. The definition of soil as the object we classify was modified in the second edition of Soil Taxonomy (Soil Survey Staff, 1999, p.9) to say that it is not soil if “the surface is permanently covered by water too deep (typically more than 2.5 m) for the growth of rooted plants.” This modification was purposely made to allow for the recognition of soils in shallow water areas that support SAV and to open the way to classify and map them. The World Reference Base (FAO, 2006, p. 7-8) includes an expanded discussion for the object classified and now includes areas covered by 2 m of water (as measured at low tide) and explicitly includes a reference to “subaqueous soils.” So the concept of soil as used in soil survey and classification has expanded over the years to include permanently submerged sediments that are capable of supporting rooted vegetation, commonly called “subaqueous soils”.

Soil or Sediment?

To be considered soils and not simply sediment, there should be evidence that pedogenic processes are occurring. Simonson (1959) suggested that soil genesis consists of two overlapping steps, first the accumulation of parent material, and then the differentiation of horizons to form a soil profile. He attributed the development of horizons to the combined effect of four basic changes – additions, removals, transfers, and transformations, which encompass a wide array of processes. Do the substrates underlying shallow water in estuaries represent only accumulated parent material or have they undergone some degree of pedogenesis?

Demas and Rabenhorst (1999) studied 85 cores extracted from the shallow water estuarine environment of Sinepuxent Bay, Maryland, USA to see if they exhibited horizon differentiation that could be explained by the four basic changes described by Simonson. They concluded that there was evidence of pedogenesis based on the following observations.

Additions of biogenic calcium carbonate due to faunal remains (shells) from in-situ benthic organisms, as well as additions of organic matter from SAV roots and other plant parts. Organic matter concentrations were generally greatest in the surface few centimeters and often decreased with depth. In some instances a sequence of buried surfaces was observed, resulting in irregular carbon contents with depth in a manner similar to terrestrial alluvial soils.

Losses occurred primarily as a result of decomposition of organic matter, so that the inputs and losses achieve some balance reflecting environmental conditions. Where inputs exceed losses, organic soil materials may accumulate. Most soils in this study were found to have mineral horizons with between 0.25 and 3.45% organic carbon in the surface. Bacterial decomposition results in the eventual transfer of carbon and nutrients out of the system. Due to the permanently low hydraulic gradient, leaching is not an important process in these soils, which is in contrast with most terrestrial soils.

Transfers were observed to be the result of two processes. Bioturbation from burrowing benthic organisms (e.g. tubeworms, clams, etc.) which mixes material within the profile. Diffusion of oxygen across the soil/water interface is in response to a gradient between the higher dissolved O_2 concentration in the water column and the lower concentration in the water in the pore space of the soil due to respiring microorganisms that are decomposing organic matter. The combined result of the bioturbation and O_2 diffusion is reflected in a surface layer with higher chroma than the underlying low chroma layer. Bioturbation also has an affect on the gradual disruption of fine stratification (rock structure).

Transformations were observed in the form of lowered C:N ratios as fresh organic matter was decomposed and converted to other forms of humic substances, by redox reactions with iron, and also through the process of sulfidization. In this process, the combination of reduction of iron oxides in the surface to form ferrous iron and microbial decomposition of organic matter and reduction of sulfate from sea water to produce HS^-, results in the formation of iron-sulfide compounds, including pyrite. Sulfide production mostly occurs below the boundary separating the higher chroma (oxygenated) surface layer from the lower chroma (reduced) subsurface layers. Sulfidization is a very important process occurring in some subaqueous soils because it produces acid-sulfate materials.

A similar study examining the substrates under a mangrove forest in Brazil (Ferreira et.al., 2007) documented similar processes resulting in horizon differentiation. These researchers concluded that pedogenesis and diagenesis are occurring simultaneously, with pedogenesis dominant in the upper part of the profile.

Extension of the Soil-Landscape Paradigm

An important contributing factor to the success of soil survey is that trained soil scientists are able to delineate soil bodies on maps based on the soil-landscape paradigm (Hudson, 1992). Underlying the paradigm is the model which says that soils are the product of five factors of soil formation – climate, organisms, relief, parent material, and time (Jenny, 1941). Once the relationship of soils to the soil forming factors is learned for an area, soil scientists can map soils efficiently because the distribution of soils in the landscape is understood. This begs the question, “Can the soil-landscape paradigm be extended to soil bodies permanently submerged under water?” Demas and Rabenhorst (2001) proposed a revised model to explain the distribution of subaqueous soils.

$$Ss = f\,(C, O, B, F, P, T, W, E)$$

Where Ss = subaqueous soil, C is climatic temperature regime, O is organisms, B is bathymetry, F is flow regime, P is parent material, T is time, W is water column attributes, and E is catastrophic events. This equation is similar to Jenny's factors, but differes in that the climate factor is restricted to temperature, relief is replaced by the combination of bathymetry and flow regime, and two new factors are added - water column attributes and catastrophic events.

In their study of a 116 ha area within Ninigret Pond, a 667 ha coastal lagoon in southern Rhode Island, USA, Bradley and Stolt (2003) identified twelve submerged landscape units. These units were defined by factors such as slope, shape, water depth, and depositional environment. They concluded that landscape units could be used to model subaqueous soil distribution at the subgroup level of Soil Taxonomy. For example, the Lagoon Bottom was predominantly Typic Hydraquents. The Storm-surge Washover Fan Flat was predominantly Typic Sulfaquents. The Flood-tidal Delta was dominantly Typic Psammaquents, and the Mainland Cove was mostly Thapto-histic Hydraquents.

In a similar study, Osher and Flannagan (2007) investigated the relationship of soils to subtidal landforms in the 1,329 ha Taunton Bay estuary in southeast Maine, USA. They identified seven major landforms and found that there were relationships between soils and landforms. The Submerged Delta, Submerged Beach, and Shallow Coastal Cove landforms were predominantly Haplic Sulfaquents. The Submerged Marsh, Submerged Fluvial Stream, Fluvial Marine Terrace, and Deep Coastal Cove landforms were mostly Typic Sulfaquents. The Terrestrial Edge and Vegetated Channel Shoulder landforms were dominantly Typic Endoaquents. Based on the two studies cited here, as well as other work in the eastern and southern USA not cited here, it seems clear that soils are forming in these subtidal environments and soil-landscape relationships exist.

Logistical and Technical Considerations for Subaqueous Soil Survey.

Conducting soil survey in an aquatic environment presents unique challenges. An immediately obvious problem is that the subaqueous landforms are hidden beneath the water. A reliable topographic map at an appropriate scale is essential for relating soils to landforms. While existing maritime charts may be available, they often are at scales too small to be of practical use in soil survey. Soil scientists have created bathymetric maps by manually collecting data along transects utilizing GPS and an electronic transit to measure elevation, as well as distance and azimuth tied to a known fixed location. (Bradley and Stolt, 2002). This is similar to conducting an engineering survey on land, but with the added difficulty of wading in water. Faster methods utilizing acoustic soundings from a boat have been successfully utilized. These techniques have an advantage of speed, but also some disadvantages. First is the introduction of error due to wave action constantly changing the elevation of the acoustic sensor relative to the bottom. Also, the inability of the boat to operate in areas of very shallow water limits its use. Finally, the continuous effect of rising and falling water depth due to tidal flow must be compensated for~~.~~. The tidal elevation fluctuation can be corrected, but error due to wave action must simply be minimized by restricting data collection to calm conditions. Remote sensing tools such as side-scan radar could be used if available.

Sampling the soils is difficult. Hand tools such as augers and peat samplers have been used successfully, especially for relatively shallow borings. Retrieving successive samples over depth increments from the same hole can be very difficult, especially when standing on the deck of a boat. Simply relocating the hole can be nearly impossible. Forces of suction can prevent a person from removing an auger in some instances. An automated vibracore device mounted on the deck of a boat provides the best method of collecting samples. Aluminum tubes (7.6 cm diameter) are gradually inserted into the soil through the vibrating action of the device. A winch is used to extract the core. Cores are labeled and brought to shore where they can be stored if needed, and eventually cut open using a circular saw and described, using standard conventions.

Along with these technical challenges there are logistical challenges to be overcome. These include working from the deck of a small boat, wading in water, keeping paper and electronic equipment dry, limited space (on deck) for spreading out equipment and samples; and safety and health issues including safely operating a boat, working on water, and exposure to changing and potentially dangerous weather conditions.

Soil Interpretations

Soil surveys show the location of soils in the landscape. However, they are of limited value if they do not also provide information regarding the importance of the various soils to ecosystem function and their suitabilities and limitations for various forms of use and management. Some managers of estuarine resources have recognized the potential of soil survey as a tool that could help them to better understand and mange the ecosystems they are working with and they have entered into cooperative relationships with the National Cooperative Soil Survey. Perhaps one of the most impressive examples is the MapCoast partnership in Rhode Island, USA (see http://www.ci.uri.edu/projects/mapcoast/). They describe themselves as *"a consortium dedicated to multidisciplinary mapping of coastal underwater resources, including bathymetry, habitat, geology, soils/ sediment, and archeological resources in shallow waters"*. Following are some examples of interpretations that are needed with regard to subaqueous soil survey work.

Restoration of SAV including eelgrass beds. Bradley and Stolt (2006) found that the observed amount of eelgrass cover varied by soil-landscape units and was influenced by physical and chemical soil properties such as particle-size, salinity levels, and concentrations of acid volatile sulfides. They concluded that restoration efforts can benefit by targeting soil-landscape units having the best potential for establishing eelgrass.

Production and harvesting of bottom-dwelling shellfish such as clams, oysters and crabs is dependant upon healthy aquatic ecosystems and it is likely that information about subaquatic soils and landforms would be beneficial in managing and enhancing these resources.

Surabian (2007) used information such as texture and n-value of the upper parts of subaqueous soils to rate their suitability as a medium to hold moorings for boats. A mooring is a permanent anchor, not intended to be moved, and used to keep a boat in place. It is marked with a unique buoy so that it can be used repeatedly by the owner. Two types of moorings were rated. A mushroom anchor, shaped like an inverted mushroom, is designed to settle into soft bottom types where it sets a little below the surface and resists dragging due to a suction effect. Loamy or organic soil materials with high n-values are the best soils for this type of mooring. A deadweight anchor is a very heavy anchor designed to rest directly on the soil surface and resists dragging due to its great weight. Coarse textured soils with low n-values are best suited for this type of mooring. Surabian (2007) used a simple "not limited" or "very limited" rating to describe the suitability of each soil in the legend for each of the two mooring types. By helping to select the proper mooring type, this interpretation has the potential to provide significant economic benefit to boat owners and insurance companies alike by limiting losses in coastal communities after storm events.

Soil-landscape relationships can help in better understanding ecological processes and thereby improving our ability to manage these resources. Jesperen and Osher (2007) used observed carbon contents and soil-landscape relationships to estimate carbon storage in the upper 1 m of Taunton Bay Estuary, Maine, USA. They concluded there is about 136 Mg C ha^{-1} stored in the estuary, which they calculated as being 35 to 100 percent more than in nearby terrestrial soils.

Another important interpretive issue involves the placement of dredged subaqueous soil materials on the land surface as fill. Upon drying, those that contain sulfidic materials have the potential to generate high levels of sulfuric acid, thus damaging plant materials, waterways, concrete and other engineering structures that they are in proximity to the dredge materials.

Improvements to Soil Taxonomy

After about a decade of experience mapping and describing subaqueous soils at selected locations in the USA, soil scientists have proposed changes to Soil Taxonomy so that these soils will be mostly grouped together and recognized at a high level in the system. Two new suborders are proposed for the Entisols and Histosols – “Wassents” and “Wassists”. The formative element “wass” is from the German word for water, “wasser.” In each case, the criterion for identifying the suborder is a positive water pressure at the soil surface for at least 21 hours each day in all years. The 21 hour minimum is proposed to allow for short daily exposure of the soil surface in areas with large tidal fluctuations, such as northern Maine in the USA. The intent is for the inundation to be present every day, every year, with no exceptions for periodic short- or long-term drought cycles.

Within the Wassents, six Great Groups are proposed. The first, “Frasiwassents” uses a new formative element “frasi” from the German “fresh”. It is for Wassents with low electrical conductivity values (<2.0 dSm^{-1}). The remaining Great Groups; ‘Psammo-’, ‘Sulfi-’, ‘Hydro-’, ‘Fluvi-’, and ‘Haplo-’ are defined similarly to where these terms are used in other taxa.

A total of ten subgroup terms are used in various Great Groups of Wassents. They are Sulfic, Lithic, Thapto-histic, Aeric, Psammentic, Fluventic, Grossic, Haplic, and Typic. The Lithic criterion uses a depth of 100 cm (similar to the use of 125 cm in Oxisols). ‘Grossic’ is used for soils having thick layers with high n-value (> 0.7). The remaining terms are defined similarly to where they are used in other taxa.

Within the Wassists, three Great Groups are proposed. They are Frasi-, Sulfi-, and Haplowassists. The Frasiwassists have low electrical conductivity (<2.0 dSm^{-1}). Sulfiwassists have sulfidic materials within 50 cm. The Haplowassists are all other Wassists. Within each Great Group, the same three subgroups are proposed; Fibric, Sapric, and Typic, depending on the dominant type of organic materials present.

The World Reference Base (2006) has taxa similar to those proposed for Soil Taxonomy. WRB’s Subaquatic Fluvisols correlate to Wassents, and the Subaquatic Histosols correlate to Wassists.

Summary

In the last decade there has been increased interest in selected parts of the USA to include subaqueous estuarine coastal environments within our soil surveys so that resource managers have better information about the substrates supporting shellfish, vegetation, and other estuarine resources. Pedogenic processes have been identified as contributing to horizon development in the subaqueous environment. It has also been demonstrated that soil-landscape relationships exist, thus allowing soil scientists to extend the soil-landscape paradigm to this environment and make soil maps relatively efficiently. Mapping subaqueous soils presents significant technical and logistical challenges that are being solved. Techniques for developing bathymetric maps depicting the slope and shape of land forms have been established. Tools and techniques for sampling soils have been identified that work reasonably well.

To be useful, soil surveys must provide interpretive information about the soils mapped. Efforts are underway to develop interpretations to aid in restoring SAV, managing production of shellfish, identifying acid sulfate producing soil materials, rating suitability for mooring sites, and other uses. Revisions to Soil Taxonomy similar to recent additions to WRB are under development so that subaqueous soils can be recognized at a high level within the classification system.

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