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REVIEW ARTICLE

Subaqueous soils: their genesis and importance in ecosystem management

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Abstract

Research by soil scientists examining estuarine aquatic substrates has identified pedogenic processes, resulting in the reclassification of these aquatic substrates (sediments) as subaqueous soils (SASs). Pedogenic processes in SASs are similar in concept to those occurring in subaerial soils, and thus SASs can be described and mapped based on pedogenic similarities using Jenny's soil forming factors for interpreting soil genesis. The occurrence of SASs in estuarine and freshwater ecosystems places them at the centre of many ecosystem-dependent processes supporting food webs linked directly to the human population and its economy. Early research on SASs has been driven by addressing fishery habitat support questions for US subaquatic vegetation populations (SAV), and for estimating the carbon sequestration potential of soils with SAV. New land use interpretations for SASs include bottom type, presence of sulphidic materials, potential for submerged aquatic vegetation restoration, limitations for moorings and species lists for plants and algae common to tidal areas. Subaquatic soils are a viable, exciting frontier of soil science research that will surely foster multi-disciplinary collaborations. While their genesis is only beginning to be understood, it is clear that their importance in human-dependent land management issues such as soil and water quality, food supply and human survival is great. However, the fragility of such soils for providing vital functions to support life on Earth suggests that they need to be investigated and monitored.

Keywords: Subaqueous, soil, management, aquatic

A perspective of sediments as subaqueous soils

Research by soil scientists examining estuarine aquatic substrates has identified pedogenic processes, resulting in the reclassification of these aquatic substrates (sediments) as subaqueous soils (SASs) (Demas, 1993; Demas *et al.*, 1996; Demas & Rabenhorst, 1999) (Figure 1). Aquatic substrates are commonly defined in marine, lacustrine and estuarine fields as sediment (Folger, 1972; Kerhin, 1980). Sediment is a generalized term that characterizes deposits from air, water or ice, on earth's surface (Krumbein & Sloss, 1963), while soil has the potential to support plants (Soil Survey Staff, 1999), and exhibits pedogenesis (Simonson, 1959; Soil Survey Staff, 1999). Although some scientists have previously proposed the concept of sediments as soils (Kubiëna, 1953; Goldschmidt, 1958; Muckenhausen,1965), the idea was never widely accepted until efforts begun by the late Dr. George Demas (a soil scientist working for the US Department of Agriculture, National Cooperative Soil Survey Program who later researched SASs during a dissertation with Dr. Marty Rabenhorst at the University of Maryland) (see Demas, 1993, 1998; Demas & Rabenhorst, 1998 for early papers on SASs).

Recognizing aquatic substrates as SASs enables them to be consistently described and mapped, and allows for use and management interpretations to be built based on observable and measurable physical and chemical processes in a similar manner to subaerial soils (Demas & Rabenhorst, 1999, 2001). Pedogenic processes in SASs are observed to be similar in concept to those occurring in subaerial soils (Bradley & Stolt, 2003; Demas & Rabenhorst, 1998, 1999, 2001; Osher & Flannagan, 2007). This observation resulted in the evolution of the definition of soil in *Soil Taxonomy* (Soil Survey Staff, 1999), to include soils permanently submersed in up to 2.5 m of water. Demas & Rabenhorst (2001) suggest SAS

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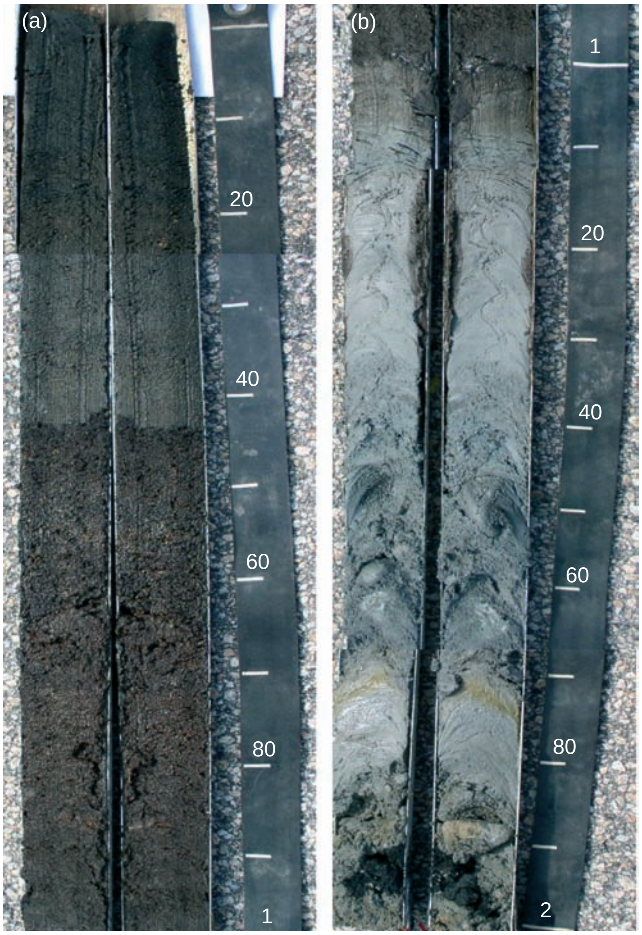

Figure 1 Estuarine subaqueous soil from Pt. Judith Pond, Rhode Island. Billington (proposed soil series; Thapto-Histic Sulfaquent or Thapto-Histic Sulfiwassent (Soil Survey Staff, 1999)) silt loam with a buried cedar swamp horizon (42 cm) (a) top half of core. (b) bottom half of core. White bars on black tape are 10 cm intervals.

development follows the soil genesis model of Jenny's state factor equation (S = f(Cl, O, R, P, T)) with Simonson's (1959) resultant processes of additions, losses, transformations and translocations (Demas & Rabenhorst, 2001) leading to pedogenesis and horizon formation (Simonson, 1959). For example, in a coastal estuary, Demas & Rabenhorst (1999) found pedogenic processes to include additions of biogenic calcium carbonate (example, Figure 1, white flecks between 60 and 80 cm) and organic matter, losses of organic matter and metals, translocation of oxygen via diffusion and bioturbation and transformations of humic substances and sulphides. Some of these same pedogenic processes occur in freshwater SASs (Erich *et al*., 2009).

In a similar manner to subaerial soils, SASs can be described and mapped based on pedogenic similarities and then use of Jenny's soil forming factors assists with interpreting soil genesis. Examples of such factors can be observed across landscapes where SAS soil develops (Bradley & Stolt, 2003). Since the work of Demas & Rabenhorst (1998, 2001) and Demas *et al*. (1996), several SAS mapping efforts have been conducted in the northeastern US, resulting in a greater understanding of SAS genesis. This work has established clear relationships between SAS development and the underwater landscapes on which the soil occurs. Bradley & Stolt (2003) examined SAS distribution within a coastal lagoon, and identified topographic relationships between SASs and landscape position. Osher & Flannagan (2007) classified SASs of a Maine estuary and identified pedogenic relationships unique to landscape positions. Vaughan *et al*. (2008) characterized and examined the morphology of ditch soils, identifying and describing subaqueous matrix materials in agricultural ditches as soil undergoing pedogenesis with distinct physical and chemical soil properties. Vaughan *et al*. (2008) noted that prior descriptions of organic and mineral ditch materials as sediments rather than soils, indicated the source of material, but ignored observable functions specific to soils.

As research continues on SASs, USDA Soil Taxonomic classifications are being developed so that soils can be accurately classified and described (Demas & Rabenhorst, 1999; Bradley & Stolt, 2003; Osher & Flannagan, 2007). Recently, the National Cooperative Soil Survey (NCSS), *Subaqueous Soils Committee* proposed a new suborder 'Wassents' for soils that are permanently saturated by water (Osher & Flannagan, 2007). Osher & Flannagan (2007) used subgroup and great group classes of Wassents (sulfic, haplic, typic, psammentic) developed to classify estuarine SAS. Further development of taxonomic classes also resulted in the capability to express the importance of soil texture in estuarine soil management (Osher & Flannagan, 2007). The NCSS has also added new subaqueous landscape, landform and related material terms to the National Soil Survey Handbook. Historically, in soil surveys these underwater features were included in the map unit 'water'.

SAS sampling

Sampling of SAS can be done using traditional sediment sampling equipment such as dredge grab samplers and vibracore (Figure 2a). Additionally, pedologists use hand augers such as bucket, dutch-mud and side-filling peat augers. Each tool has an appropriate application, which depends on the objectives of the sampling and description. For landform mapping, bathymetric surveys can be completed using basic fish finder technology or advanced marine sonar equipment. SAS surveying can be enhanced with the use of ground penetrating radar (GPR) to determine depths of specific layers (Figure 2b) and supplemented with hand measurements in shallow areas. For example, in Pennsylvania, USA, GPR is being used to determine the depth of a new freshwater SAS forming over a flooded, former subaerial soil, in an effort to determine over time

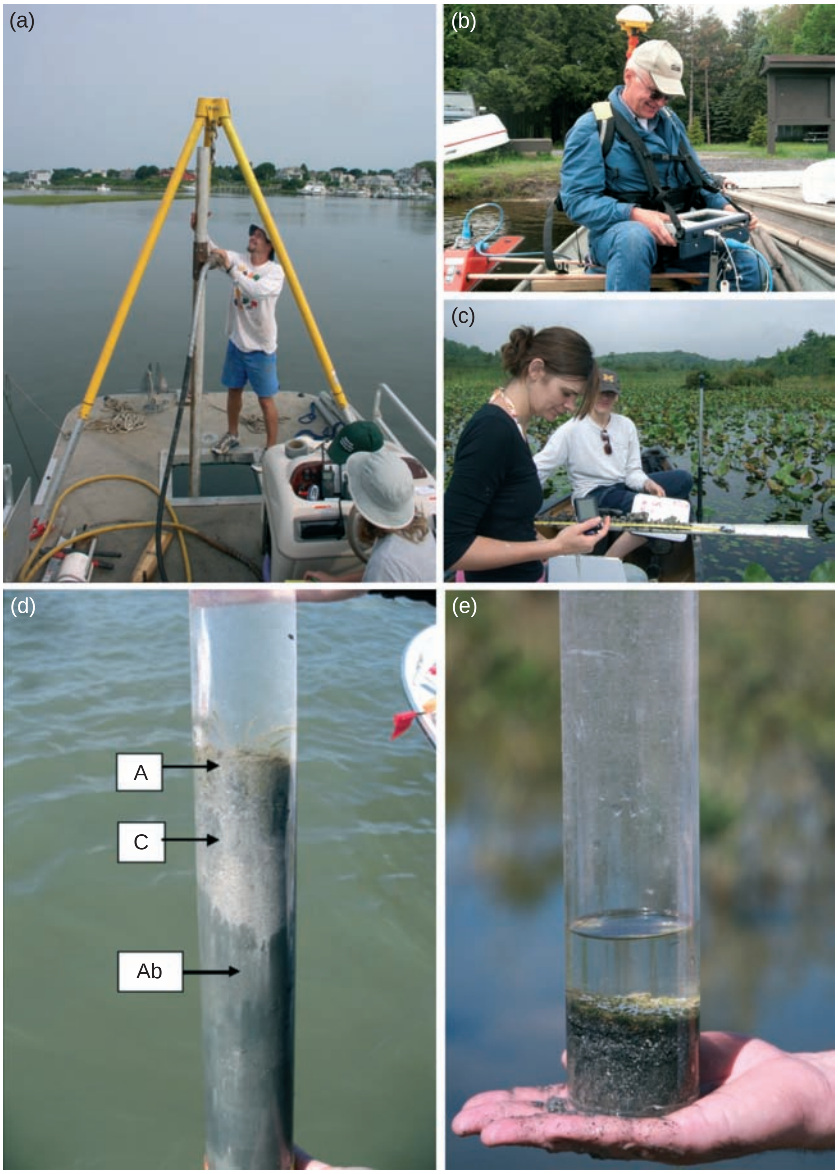

Figure 2 (a) Core vibracore rig on a pontoon boat in Rhode Island, USA. (b) Global positioning system and ground penetrating radar survey on canoe to determine depth of new SAS over flooded subaerial soil. (c) Hand augering and profile description by canoe in Pennsylvania, USA. As the soil is augered, it is placed in the half-section of white plastic pipe braced across the canoe. (d) Florida soil core extracted from a landform supporting *Halophila johnsonii*, a threatened species of seagrass. *H. johnsonii* is visibly rooted in the soil core and the A horizon resulting from vegetative colonization is apparent. Below is the C horizon (dredge spoil) which buried a seagrass bed, thereby creating an Ab horizon. The photograph was taken in 2006, 10 months after the spoil deposition. (e) Upper 10 cm of a recently formed SAS in a mangrove mitigation site near Fort Pierce, Florida. The site was constructed from dredge spoil, consisting mainly of calcium carbonate and quartz sand particles. This sample was taken approximately 2 year after the site was constructed. Note the formation of an A horizon. The green surface layer with bubbles is an algal mat that colonized the soil surface. Also note the ease with which undisturbed horizons can be observed through the clear polycarbonate tube walls. This core was inserted and retrieved by hand.

carbon sequestration and mercury concentration (Erich *et al.*, 2009); GPR will not work in salt water for this particular application because of solute interference.

For pedon descriptions, vibracore sampling provides the best results (Figure 2a). The disturbance to the soil during sampling is minimal, preserving thin, delicate layers that can often occur in a sedimentary environment (Figure 1). Vibracoring can be resource intensive, requiring a motor to provide vibrations and a tripod and winch/hoist to remove the core (Figure 2a). This is often conducted from a boat. Additionally, the core tubes must be cut to reveal the pedon sampled (Figure 1). For a quicker, less intensive view of the soil, hand augers are used (Figure 2c). This method of sampling is similar to the use of hand augers in the subaerial environment. Advantages of hand sampling include lower cost and the ability to view soil morphological properties immediately after removal from the bottom.

Hand augers are less precise because material can be leaked from the auger or mixed during retrieval. While these problems can occur in subaerial soils, the aquatic environment in which SASs occur amplifies this possibility. A compromise between vibracoring and hand auguring is hand coring using polycarbonate tubes (Figure 2d,e). The tubes are pushed into the soil by hand, capped with a rubber stopper, and then extracted from the soil. This allows for precise sampling of many shallow, thin horizons that can occur near the surface. The clear sides of the tubes allow for visual confirmation that the desired horizons were sampled. Other coring devices that use polycarbonate tubes employ a piston fixed to a tripod that slides upward in the core when sampling (Hopkins, 1964). The vacuum suction provided by the piston core prohibits compression of soil horizons. Piston cores employ the same approach, but a piston fixed to a tripod slides in the core tube when sampling to provide vacuum pressure needed to prohibit compression of more fluid horizons (high *n* value [Soil Survey Staff, 1999] horizons).

SAS development and subsequent pedogenesis

Pedogenesis in a submerged environment can develop in recently deposited sediment over pre-existing subaerial soils, in a recently flooded soil or a soil that has been continuously flooded (as in an estuarine environment). The term 'subaqueous' is typically used for soils that have formed under a continuous water column, while 'submerged' is used for soils, once subaerial, but now formed under water because of sea level rise, flood events or elevated water tables (frequently SAS is used to describe both conditions) (James Turenne, USDA-NRCS pers. comm.). With changes in soil physical and chemical properties, changes in other processes within the soil are expected to occur across the new hydrosequence, with depth, and over time (Demas & Rabenhorst, 1999, 2001). For example, during SAS pedogenesis, physical and chemical processes will result in morphologically distinguishable features and soil horizons (Figures 1 and 2d,e). Inundation of a subaerial soil by water decreases soil O_2 availability and the soil shifts from an oxic to an anoxic reducing environment characteristic of saturated and submerged soils (Vespraskas and Fulkner, 2001). Chemical characteristics likely to change in a freshwater system are pH, Fe and Mn speciation, S mineralogy and soil organic carbon (SOC) accumulation. Notable morphological changes may occur with horizon and soil structure development, changes in the abundance and kind of redoximorphic features, particle size distribution and organic matter accumulation (Vaughan *et al*., 2008). As a result of a shift to an aquatic environment with submergence, there is potentially also a shift in bioturbation as new species of organisms populate the former subaerial soil. Lastly, nutrient cycling and plant support are likely to change with submersion as has been seen from research on drainage ditches (Bowmer *et al*., 1994).

Subaqueous soils in freshwater systems express morphological features characteristic of hydric soils (Erich *et al*., 2009). In place of O_2, anaerobic microorganisms use NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-} and CO_2 as terminal electron acceptors in reducing reactions, which with Mn^{4+} and Fe^{3+}, can result in soil colour changes (redoximorphic features) (Vespraskas and Fulkner, 2001) (Figure 1, 1.65 m). Ferric iron (Fe^{3+}) is directly reduced to ferrous iron (Fe^{2+}), and Mn^{3+} and Mn^{4+} are reduced to Mn^{2+}, transforming iron and manganese from an immobile to a mobile state (Kirk, 2004). As available iron and manganese are used in redox reactions, soil gleying and redoximorphic features (RMF) develop with iron and manganese oxide concentrations in oxic zones, and depletions of Fe in gleyed anoxic zones. Prolonged reduction may produce a gleyed horizon with pronounced leaching of reduced Fe and Mn (Vepraskas, 1992). Relict redox features from historic hydric soils may be preserved in SAS as has been seen in freshwater SASs as observed in Pennsylvania (Erich *et al*., 2009).

Subaqueous soils often exhibit important soil chemistry related to sulphide mineralogies. For example, estuarine soils excavated via dredging and subsequent oxidation can evolve into an acid sulphate soil (Fanning and Burch, 1997) and thus impose land use problems due to the resulting lower soil pH, excess S and aesthetic discoloration of infrastructure surfaces. Sulphidic materials most commonly accumulate in coastal marshes and estuarine SAS, but they may occur in freshwater marshes if there is sulphur in the water. Acid sulphate soils are soils that contain iron sulphides mostly in the form of pyrite (FeS_2) with typically smaller quantities of other products of sulphide oxidation such as iron monosulphides (FeS) (Ward *et al*., 2004). Iron monosulphides (FeS) are often associated with organic-rich sediments, drains and lake bottoms and oxidize rapidly when exposed to oxygen (Sullivan *et al*., 2002; Smith & Melville, 2004). When soils high in monosulphides are disturbed the sulphide oxidizes very rapidly and consumes the dissolved oxygen in the water and potentially causing fish and biota kills (RTA, 2005). In freshwater systems, SO_4^{2-} reduction is limited by its availability (Craft, 2001), but global and/or regional acid deposition, largely from coal fired power generation, can increase S inputs to ecosystems (Smith *et al*., 2001). Submerged soils with high sulfur content experience S fractionation. Upon fractionating, most S remains in organic form or as reduced inorganic sulphides, some as dissolved SO_4^{2-}, a small percentage reacting with Fe to form pyrite (Vaughan *et al*., 2008), or to form gases consisting of H_2S and dimethyl sulphide (Vespraskas and Fulkner, 2001). The presence of reduced sulphur can be determined in the field via the characteristic smell of H_2S gas, or a reaction to the application with hydrogen peroxide (Vaughan *et al*., 2008).

One of the most significant changes in a soil with submergence is the increase in SOC following submergence. The carbon cycle, methanogenesis and carbon storage in submerged systems are regulated by dynamics between the soil, landscape hydrology and vegetation (Zhang *et al*., 2002). With submergence, anaerobic conditions will slow organic matter decomposition rates considerably (Craft, 2001), and as decomposition slows, soil organic matter accumulates as organic bodies or mucky or histic soils. Resultant accumulation of organic carbon in submerged soils could become a sink for atmospheric CO_2 (Markewich & Buell, 2008) and other organic carbon associated elements such as Hg (Homann and Grigal, 1996).

Subaqueous soils typically have high SOC and can be an important carbon sequestration sink. In estuarine environments, in low-energy depositional landscape units subaqueous carbon pools can be very high (180 t/ha). This is much higher than submerged upland soils in these same estuaries (Payne, 2007). Former subaerial soils flooded to power a mill in Pennsylvania (Erich *et al*., 2009) have been found to accumulate significant carbon in comparison to their pre-flooded condition. Ideally, such carbon should accumulate and have a long residence time (Wang & Hsieh, 2002). Vaughan *et al*. (2008) hypothesized that SOC in agricultural ditch soils that had both hydric and SAS morphology was higher than in pre-ditch conditions. Wills *et al*. (2008) evaluated soil carbon distribution changes in a restored marsh and found surface carbon accumulation rates of 1.8 t C/ha/yr. While Wills *et al*. (2008) focused on saltwater systems, freshwater systems are known to be sinks for SOC, as seen in freshwater Histosols (Craft, 2001; Kirk, 2004).

Changes in SOC content across a landscape are linked to topography (Homann and Grigal, 1996), climate, soil chemical and physical properties, and vegetation (Xu & Prisley, 2000). In freshwater SASs, SOC is likely to be most influenced by hydrology, topography, soil temperature and carbon cycling (Zhang *et al*., 2002). In subaerial soils, the spatial distribution of SOC in known to not only change across a landscape but also with depth (Jobbagy & Jackson, 2000; Davis *et al*., 2004). As with subaerial landscapes, SOC content has been seen in SASs to be higher in upper profile horizons (Demas & Rabenhorst, 1999; Bradley and Stolt, 2003; Jespersen & Osher, 2007) or in buried horizons of former higher profile positions (Bradley & Stolt, 2003; Jespersen & Osher, 2007).

SAS management

The identification of sediments as SASs extends the traditional soil-landscape continuum and enhances understanding of biogeochemical and ecological processes across the interface between subaerial and SASs. This new and exciting area of soil science allows scientists and land managers to couple research between subaqueous, hydric and subaerial soils resulting in improved resource management decisions for flora and fauna. For example, Demas & Rabenhorst (1999) note in their review of traditional sediment sampling that layers of shallow sediment materials are often mixed during sampling, potentially resulting in layers with major physical and chemical differences being combined. With the development of concepts explaining SAS genesis (Demas, 1998; Demas & Rabenhorst, 1999), horizons with different physical and chemical characteristics are specifically described resulting in greater understanding of many aquatic dependent processes that affect vegetation (Bradley & Stolt, 2003, 2006; Jespersen & Osher, 2007).

The occurrence of SASs in estuarine, near-shore environments and freshwater ecosystems places them at the centre of many ecosystem-dependent processes, which support food webs linked directly to the human population. Examination of SASs and the food industry has resulted in the realization that many parallels exist between subaerial farming and the use of SASs in shellfish aquaculture (Figure 3). For example, in many coastal US states, estuarine areas are leased to farmers who grow shellfish. In Florida, the *Mercinaria* sp. clam is the primary commodity of shellfish aquaculture and SAS research is now focused on relating subaqueous landforms to aquaculture productivity

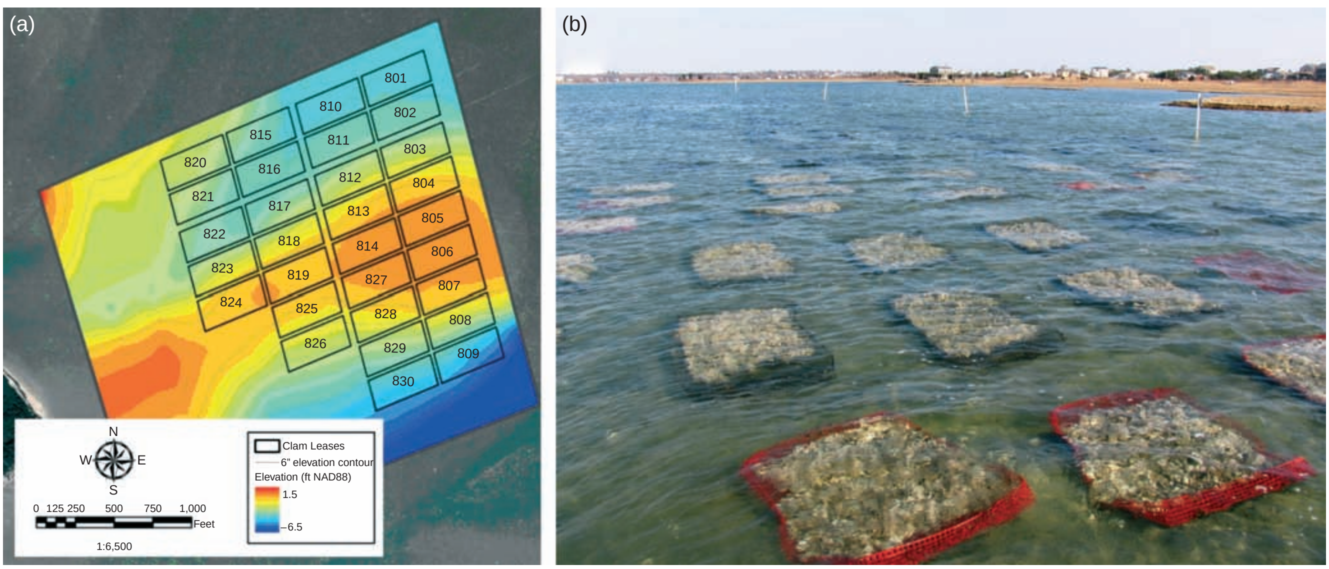

Figure 3 (a) Bathymetric map of a clam lease site near Cedar Key, Florida. The numbered rectangles are 2 acre clam lease areas. The map was created by interpolating bathymetric data collected during a high tide event. The orange areas (> 1 ft NAD88) are exposed on normal low tide events. (b) Rhode Island oyster aquaculture in a coastal lagoon (Winnapaug Pond, in Westerly, Rhode Island).

(Figure 3a). On Rhode Island, shellfish aquaculture exceeded a value of 1 million dollars in 2007 ($12 862 per acre) (Alves, 2007). Nearly all (99%) of the total aquaculture in Rhode Island consists of the eastern oyster (*Crassostrea virginica*) (Figure 3b), while the hard clam (quahog, *Mercenaria mercenaria*) makes up the remaining 1%. Oysters are typically raised on sand, hard mud or a reef bottom and are generally absent from soft mud or areas of high sedimentation rates (Burrell, 1986; Stanley & Sellers, 1986). Subaqueous soil type has been recently shown as a possible surrogate for determining areas of favourable water quality and food availability, and could thereby be used to predict areas in an estuary with the highest potentials for shellfish growth (Salisbury, 2009).

Early research on SASs has also been driven by addressing habitat support questions for US subaquatic vegetation populations (SAV) (Demas *et al*., 1996). In the decade following the work of Demas (1998) other researchers have similarly used SASs to better discern SAV populations in New England (Bradley & Stolt, 2006; Bradley *et al*., 2007) Maryland and Florida (Ellis, 2006). These SAV beds are highly valued nursery habitats that support 75% of the catch of all USA commercial fish species and involve ca.28 million jobs nationwide (US EPA, 2009). Economically, such estuarine environments support diverse recreational and commercial finfishing activities in United States of America worth ca.$30 billion annually (US EPA, 1992).

In the Indian River Lagoon, FL, the seagrass *Halophila johnsonii* occurs on intertidal landforms. This is the only seagrass listed as threatened (63 FR 49035). The soils that support this seagrass exist on landforms with variable stability, therefore the habitat can shift spatially through time. Observations of these soils indicate *H. johnsonii* can form an A horizon quickly (Figure 2d). *Halophila johnsonii* and other seagrasses have a complex relationship with the soil, water quality and hydrodynamics of the habitat making it difficult to pinpoint certain soil characteristics that promote seagrass growth and establishment. Studies in some estuaries in which seagrass populations differ significantly on adjacent yet contrasting SAS types suggest that soil does have a major impact on seagrass growth (Bradley & Stolt, 2006). Little is known about the required soil conditions of *H. johnsonii*, therefore management of these landforms is currently difficult. Carbon sequestration in vegetation supported by SASs could be significant (Jespersen & Osher, 2007; Laffoley & Grimsditch, 2009) with coastal habitats perhaps sequestering 50 times more carbon than tropical forests by area (Pidgeon, 2009).

Perhaps the most significant potential land management consequence of SAS research was identified by Bradley (2001) who concludes that SASs are hydric soils occurring in ecosystems with hydrophytic vegetation and having wetland hydrology; SAS ecosystems should therefore be treated as wetland ecosystems. This poses a significant potential conflict in the United States given many presently allowed actions in SASs such as the construction of docks and moorings and channel dredging (Bradley & Stolt, 2003). Identifying SAS areas as wetlands would allow for better regulation and record keeping of important habitat change and/or loss. Using soil data and interpretations for marine spatial planning would encourage the most environmentally benign placement of dredge channels, docks and moorings.

Land use interpretations for SASs by the USDA NRCS in Connecticut and Rhode Island have recently included bottom type, presence of sulphidic materials and potential for submerged aquatic vegetation restoration, limitations for moorings and species lists for plants and algae common to tidal areas (Surabian, 2007). The bottom type, measured by the soil structural stability *n*-value (Soil Survey Staff, 1999), provides a framework for mapping benthic habitats and managing marine resources. For example, the distribution of bottom types (soft or hard) is a fundamental parameter that: (i) largely determines the species of flora or fauna that inhabit a particular area and (ii) influences the types of anchors a boat mooring facility may use. SAS interpretations provide valuable information for making better informed natural resources decisions, mitigating hazards, creating resource inventories and tracking environmental changes.

Conclusion

Subaqueous soils are a viable, exciting frontier in soil science research that will surely involve multi-disciplinary collaborations. While current knowledge of their genesis is only just beginning, their importance in human-dependent land management issues such as soil and water quality, and food supply is great. Potential future research directions should explore the genesis of SASs in environments deeper than 2.5 m and that have the potential for significant pedogenic processes. An example of such systems might be deep-sea floor, hydro-thermal vents. In addition, we suggest other potential research areas such as SAS pollutant transport, human food supply support and SAS management, estuarine vs. freshwater SAS genesis, the use of SASs in inferring climate change, and the concept that SASs are as important as a wetland soil and thus deserve similar protection. Soils are the foundation for all ecosystems on earth, wet or dry. They provide vital functions to support all forms of life. As such, they should be managed and monitored closely (Drohan & Farnham, 2006).

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