SUBAQUEOUS PEDOLOGY: EXPANDING SOIL SCIENCE TO NEAR-SHORE SUBTROPICAL MARINE HABITATS

By

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To everyone in my family: especially my wife, son, and any future children who bless my life

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First, I must acknowledge God, for everything. May all those who walk this earth feel as blessed as I have felt. I thank all of my teachers, from the earliest years through the most recent in college. They all had an impact that individually is difficult to quantify, but collectively is apparent. They inspired me to be a teacher.

I wish to recognize some individually, based on singular events that I will always remember. I recall a comment Wade Hurt made about his passion for soil, “I love soils because they make sense.” That sums up the essence of a problem solver. On the subject of being an interdisciplinary scientist and being spread too thin, Tom Frazer once told me, “Make sure you know who you claim to be, and be at least that.” That’s the perfect advice for a person with as many interests as I have. During a conversation in which I expressed frustration about my progress because I was just floating around poking holes in the seagrass beds without hypotheses or much direction, Mark Clark said, “All science begins with observations. You have to generate observations before you can hypothesize something.” I guess it is easy to get caught up in the “publish or perish” mentality and forget that it’s the science that is important, not our personal progress.

During my qualifying exams, Mike Binford asked me about my research by posing the question, “Rex, what’s your grain size?” Scale is everything. On the subject of my work having quite a bit of qualitative data, Willie Harris told me, “I wouldn’t apologize for what you’ve done, no one else has done it.” That made me feel important, an often atypical emotion among graduate students. Finally, instead of a quote, it is the actions of

Mary Collins that I'll always remember. Every semester she has nearly 100 students, yet she takes each of their pictures in order to learn their names. About two-thirds of the way through the semester, she hangs up this sign with the words "don't quit" and a short poem underneath. The last day of class, she brings a cake and the entire class enjoys their last day together. I wonder if she has any idea how many students appreciate the personal level on which she knows them. I wonder if she has any idea how many have taken to heart the words of the poem. That's being a teacher.

My first teacher I remember was my dad. He sat on the edge of the tub while I took a bath and I remember him trying to explain to me how many atoms were in a drop of water. I was fascinated by the idea there could be "millions" of anything in a drop of water. My mom, who is the employed teacher of the family and the original super-mom, taught me to read at a young age. In turn, I taught my brother to read using the same books. My cousins learned to read on those books before I did. All of these people get my thanks for being part of my life. Most importantly, I again thank God.

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Historically, geologists (such as sedimentologists and geochemists), along with limnologists, biologists, botanists, and ecologists have been the scientists to answer the call to study shallow-water, permanently submerged areas. Only since the mid 1990s have soil scientists attempted to follow suit. Currently, subaqueous soil science is at a very early stage, with only two published studies: one from Maryland and one from Rhode Island (USA). Expanding soil science into subtropical subaqueous habitats was the focus of my study. The shallow grassflats southwest of Cedar Key, FL were chosen for study.

First, the evolving concept of soil was examined to provide a context for this new, subaqueous direction of soil science. It was determined that the historical concepts of soil were congruent with the concept of underwater soil, provided that support for rooted vegetation was possible.

Second, the idea of subaqueous soil/vegetation relationships was explored and it was found that soil properties determined in the field and in the laboratory were related to vegetation type. Organic matter and silt contents increased in proportion to vegetative cover. The dark colors of the soil (particularly in the rooting zone) predictably reflected this relationship.

Third, the soil properties below the rooting zone were investigated. A bathymetric map was created as a landscape visualization tool. Procedures for creating the map were documented. The spacing of the bathymetric transects relative to the map cell size affected map quality. The map was used to interpret the landscape. The landscape interpretations explained the spatial distribution of soils throughout the study area.

Water energy, proximity to land, water depth, and vegetative cover were the primary soil-forming factors considered. Integrating these factors with the landscape model and aerial photography, a subaqueous soil survey was created for the study area. Ten unique combinations of soil forming factors were identified to create a total of ten subtropical subaqueous soil map units. Research on the shallow, open nature of the Cedar Key flats provided a valuable addition to existing lagoonal subaqueous pedology.

CHAPTER 1
INTRODUCTION AND DESCRIPTION OF THE STUDY AREA

Introduction

Concept of Subaqueous Soil

Many definitions or concepts of soil exist. Generally, soils are considered the clastic upper portion of the earth's surface that supports plant growth. Rocks, man-made structures such as roads, and large organisms such as trees are not considered soil. The remainder of the land, if it can support rooted plant growth, is soil. Applying this concept to wet and aquatic areas is less straightforward than applying it to terrestrial areas. Land that is under water is continuous with land that is not under water. If the land is continuous, shouldn't the soils also be continuous? If rooted vegetation is supported by underwater land, then that land is soil. These areas, until recently, have been ignored by pedologists.

Recently, the term "subaqueous soil" was proposed by Demas (1993). The term "subaqueous" is typically used as an adjective to describe objects that occur or are adapted for underwater. Therefore, "subaqueous soils" are generally considered soils that occur underwater. Although some pedological research has been carried out on "subaqueous soils" the field the field is still in its infancy. Many fundamental concepts have yet to be developed, and even the definition of subaqueous soil has not been widely accepted within the field of soil science. There is no consensus as to the frequency and duration of flooding for a soil to be considered "subaqueous."

Previous Subaqueous Pedological Research

While there has been no official definition of "subaqueous soil," such as the United States Department of Agriculture's (USDA) definition of "soil" in *Soil Taxonomy* (Soil Survey Staff, 1999), the main pedological research focused on subaqueous soils thus far (Demas and Rabenhorst 1999; Bradley and Stolt, 2003) has been centered on shallow marine habitats (lagoon estuaries). Typically, most of the water in these lagoons ranges from intertidal to a few meters deep. Deeper areas have not been investigated.

Demas and Rabenhorst (1999) investigated Sinepuxent Bay, MD while Bradley and Stolt (2003) investigated Ninigret Pond, RI. Bradley and Stolt (2003) specified that the soils they investigated were marine subaqueous. Using this label, the soils in Sinepuxent Bay would be marine subaqueous also. Bradley and Stolt (2003) defined subaqueous as the depth range, "immediately below the intertidal zone to water depths of 2.5 m at extreme low tide." So far this is the only attempt to define the depth limit of subaqueous soils.

The research conducted in both Sinepuxent Bay and Ninigret Pond focused on landscape-level pedology. The pedological approach of conducting a second order (e.g., 1:20,000 scale) soil survey was used in both areas. Additionally, the soils in those areas were characterized by analyzing for typical soil characterization properties (e.g., particle size distribution, pH, and organic matter content) using standard soil science techniques.

Other pedologically-based research that could be considered subaqueous pedology has focused on inland subaqueous soils in Florida rather than marine subaqueous soils. Ellis (2002) investigated lake-fringe hydric and subaqueous soils of Sandhill Lake in Clay County (FL), by examining the continuous soil morphologies of the lower portion of a landscape that extended from above the highest recorded lake stage to an elevation that was flooded more than 95% of the time. Expanding this work, the St. Johns River Water Management District is investigating more lakes in Florida and then developing a set of soils-based indicators that could be used to predict lake stage in Florida's sandhill lakes.

Regardless of setting (marine or inland) the previously mentioned landscapes in Maryland, Rhode Island, and Florida are underwater most of the time. Therefore they are subaqueous and have subaqueous soils.

Subaqueous Pedology: Applying the Pedological Paradigm to Aquatic Habitats

Pedology, a discipline within soil science, has its own paradigm. The pedological paradigm can be divided into three parts: theory, tools, and approach

- Theory: a set of empirically testable statements and observations used to explain and understand systems
- Tools: A set of research tools for observing, measuring, and modeling systems
- Approach: together, the theory and the tools help form the approach(s) used for solving a problem or answering questions.

The theory part of the paradigm consists mainly of the concepts of soil, the soil individual (poly-pedon), soil-forming factors, soil genesis, and soil/landscape relationships. The tools part consists of items such as soil pits, augers and shovels, Munsell® color charts, existing soil landscape models, as well as standard methods of analysis and standard soil parameters of interest (e.g., particle-size distribution and pH as outlined in Soil Survey Staff, 1996). The approach part is more difficult to define because it is largely controlled by the scale of the pedological investigation. Typically, for investigations at second soil-survey order scales (e.g., 1:24,000), the approach is to build a conceptual soil/landscape model using a small number of direct soil observations, and then apply that model by delineating landscape units on basemaps. The view that the land is soil and that pedons are related to the landscape via the soil-forming factors is central to the pedological paradigm.

To study subaqueous soils from a pedological perspective requires applying the pedological paradigm. The current pedological theory, pedological tools, and pedological approach therefore would all be used to observe, describe, measure, and model aquatic habitats. Doing so assumes that the theory, tools, and approach are valid in an aquatic environment. Demas and Rabenhorst (1999) examined these assumptions first by testing the definition of soil and later (Demas and Rabenhorst, 2001) by modifying the five soil-forming factors (Dokuchaev, 1883; Glinka 1927; Jenny, 1941) to fit the subaqueous environment studied. Demas and Rabenhorst also modified the tools portion of the paradigm by using a vibracore to sample soils, rather than more traditional soil augers. Demas and Rabenhorst (1999) and Bradley and Stolt (2002; 2003) created topographic basemaps from bathymetric data. This was not a major modification, since elevation basemaps have been previously used by terrestrial pedologists. However, the methods used to create the basemaps (e.g., acquisition of bathymetry via acoustical sounder) were new to pedology.

The approach part of the pedological paradigm has not been significantly modified for aquatic habitats. Both the Sinepuxent Bay and Ninigret Pond studies modeled the subaqueous soils by delineating the landscape based on the soil/landscape models developed for those lagoons. Doing so in an aquatic environment assumes that the subaqueous landscape is stable. Bradley and Stolt tested that assumption by creating a contemporary elevation map based on measured elevations and a historical basemap based on nautical charts with historical point soundings. They determined the landscapes to be very similar, thus the landscape was judged to be stable over the time interval of interest.

Based on past subaqueous pedology and the pedological paradigm, the study of aquatic bottoms as soil appears promising. In cautious application of the paradigm to subtropical aquatic habitats, the following questions must be addressed:

- Do soils exist in a subtropical aquatic habitat?
- Do soil-forming factors exist in a subtropical aquatic habitat?
- Can those factors be considered to create a conceptual subtropical subaqueous soil / landscape model?
- Can that model be expressed in the form of a subaqueous soil survey?
- What portions of the pedological paradigm need further testing and/or refinement?

Objectives of the Study

This research is an effort to apply and refine the pedological paradigm for a subtropical subaqueous environment.

- **Overall objective:** Apply the pedological paradigm to a subtropical shallow-water marine habitat.
- **Specific aim 1:** Determine and compare chemical and physical properties of subaqueous soils and relate these properties to the submerged aquatic vegetation (SAV).
- **Specific aim 2:** Construct a digital terrain model of the subaqueous topography in the study area.
- **Specific aim 3:** Build and evaluate a conceptual soil/vegetation/landscape model in a marine environment.
- **Specific aim 4:** Create and demonstrate the need for a subaqueous soil survey.

Hypotheses

The general hypothesis for this research was that the terrestrial pedological concepts may be applied to subtropical subaqueous soils. It is proposed that soil-forming factors exist in shallow marine environments along the Gulf Coast of Florida.

- **Hypothesis 1:** Soil morphologies as well as chemical and physical properties within the rooting zone are related to SAV.
- **Hypothesis 2:** A conceptual soil/landscape model can be used to predict the morphologies of the pedons based on the subaqueous soil-forming factors.
- **Hypothesis 3:** That soil/landscape conceptual model can be expressed as a subaqueous soil survey at a second-order scale (e.g., 1: 20,000).

Rationale and Dissertation Format

It has been claimed that the concept of soil needed to be revised to include aquatic bottoms (Demas 1993; Demas *et al.* 1996; Demas and Rabenhorst 1999). The USDA revised its definition of soil as a result of these claims (Soil Survey Staff 1998; 1999). At first, it appears that a major change has taken place within soil science creating a new view that underwater areas are soil, not sediment. Therefore, a review of historical and contemporary concepts of soil and the implications of that evolution for subaqueous soil science are the focus of Chapter 2.

Pedogenic theory dictates soil-forming factors, specifically biota (e.g., native vegetation), will have an influence on the soil morphology and associated physical and chemical properties. Because of this and because of the ecological and economical importance of seagrasses, the soil / vegetation relationships within the upper portion of the soil (e.g., the rooting zone of seagrasses) will be the focus of Chapter 3.

The creation of subaqueous terrain models is a necessary step in the application of the pedological paradigm to aquatic habitats. In these habitats, it is difficult to obtain elevations by traditional survey methods. Also, methodology for collecting and modeling those elevation observations to create a subaqueous terrain model has not been standardized. Therefore, the collection and modeling of subaqueous elevation observations will be the focus of Chapter 4.

The focus of Chapter 5 will be the combination of the elevation map created in Chapter 4, the soil/vegetation relationships discovered in Chapter 3, and investigations of soils and landscapes to create a conceptual soil/landscape model and a subaqueous soil survey. The conceptual soil/landscape model will be based on considerations of soil-forming factors. Traditional soil-forming factors will be considered as well as those proposed by Demas and Rabenhorst (2001). New soil-forming factors are proposed.

Study Area

The study area is approximately 6 km by 4 km (Figure 1-1). The study area selected represents a system of shallow (1 to 2 m deep at mean high water, 0 to 1 m at mean low water) flats 5 km southwest of Cedar Key, FL (Center of study area: 29^{o}5’49”N, 83^{o}5’49”W) (Figure 1-1). Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW) and Mean Lower Low Water (MLLW) are defined by the National Oceanographic and Atmospheric Administration (NOAA) based on NOAA Tidal Station 8727520 located at Cedar Key.

The area was selected for study because of its extensive seagrass beds adjacent to both deep water and land. Most portions of the flats were heavily vegetated with *Thalassia testudinum*, *Syringodium filiforme*, and *Halodule wrightii*. The average tidal fluctuation is 1.5 m with a period of 11 hours. This “Big Bend” area of Florida is called a a low or zero energy coast. This area represents the large portion of the Gulf Coast of Florida that has shallow and extensive off-shore seagrass flats.

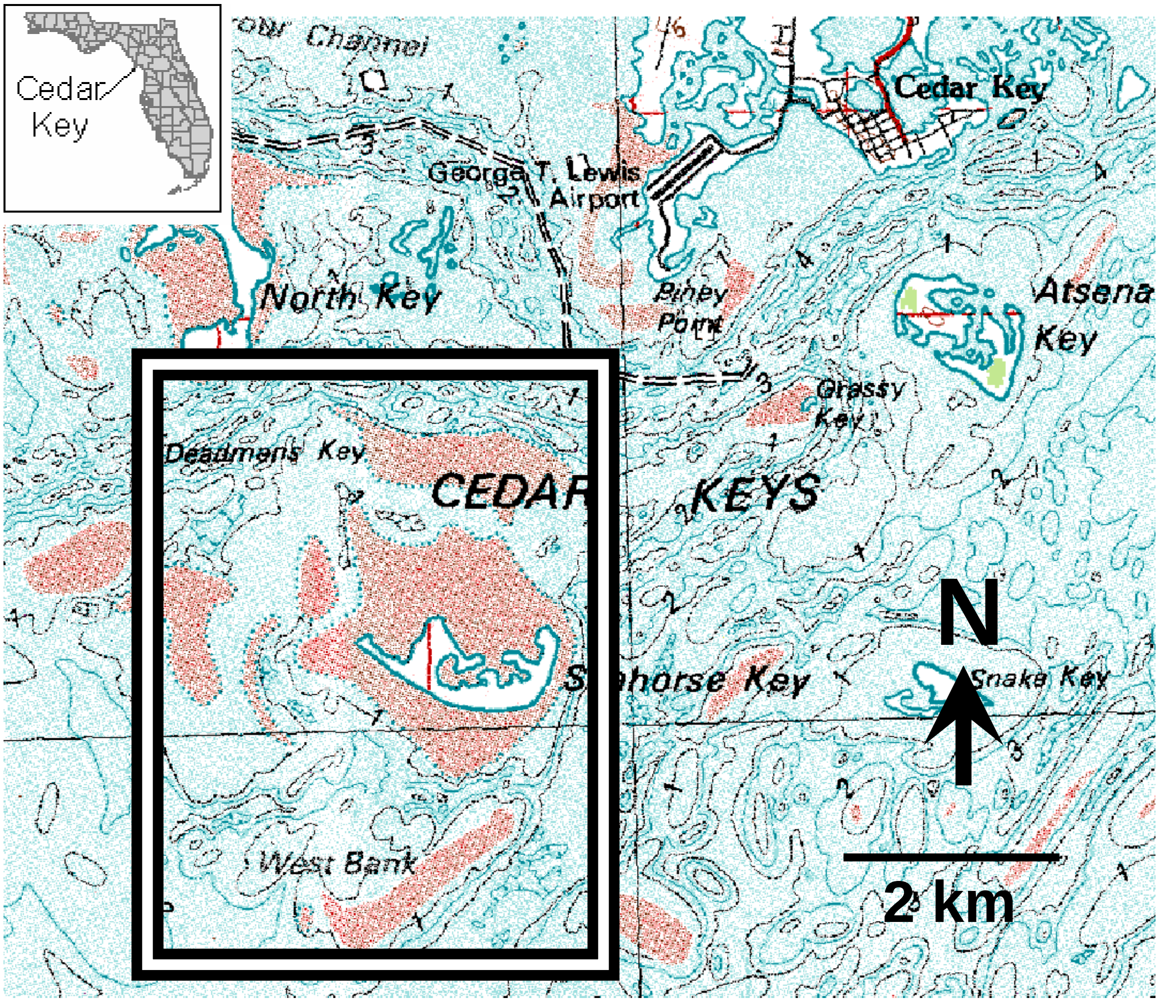


Figure 1-1. Location of the study area. The white and black box is the study approximately five km southwest of Cedar Key, FL. Image source is the United States Geological Survey's 1:100,000 Topographic maps.

Climate

The term *subtropical* is used to describe the climate of the study area. Specific climate classes and exact definitions of those classes differ among various climate classification systems. Many systems are based on the Köppen classification system proposed in the early 1900s. In these systems, a subtropical climate is generally considered similar to a tropical, but with less rain and colder temperatures in the winter months. This is typical of Levy County, FL. Slabaugh *et al.* (1996) reported average temperatures in Cross City (Levy County) of 11^{o}C in January (winter) and 25^{o}C in July and August (summer). Winter freezes occur annually throughout Levy County. However, the study area exists near the upper latitude limit of two Caribbean (tropical) species of seagrasses: *Thalassia testudinum* and *Syringodium filiforme* (Zieman and Zieman, 1989). Despite the presence of tropical seagrasses, the water temperature fluctuates about 20^{o}C annually (Figure 1-2).

Geology and Soils

The following description of Levy County geology and soils is based mainly on the United Stated Department of Agriculture's (USDA's) Soil Survey of Levy County (Slabaugh *et al*, 1996). Levy County geology is typical of counties in the "Big Bend" region. The geology is karst, typically limestone overlain by sands of variable thickness. In low-lying areas, the sand veneer is thinner than in the higher, dune areas. The limestone consists mainly of Ocala and Avon Park formations. The overlying sands consist of undifferentiated quartz Plio-Pleistocene sands. Isolated patches of the Miocene-aged Hawthorn group occur throughout the county.

All seven soil orders that occur in Florida occur in Levy County: Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Spodosols, and Ultisols (Table 1-1). Typically, the Mollisols, Histosols, and Spodosols occur in the low-lying portions of the landscape.

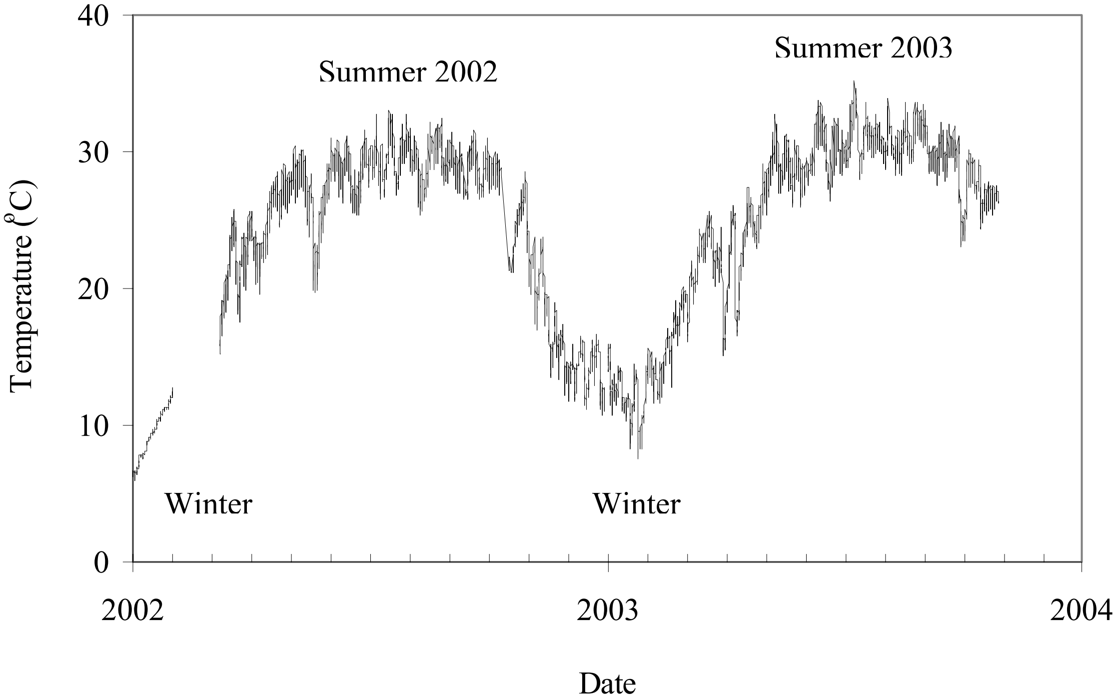


Figure 1-2. Water temperature record for National Oceanographic and Atmospheric Administration tidal station 8727520 at Cedar Key, FL. For the period of record, January 2002 to October 2003, the maximum water temperature was 35°C in July 2003 and the minimum water temperature was 7°C in January 2002. In both years, there was a marked water temperature shift from the cold winter months of temperatures near 10°C to the warm summer months with temperatures near 30°C. This fluctuation in water temperature follows a similar fluctuation in air temperature.

Table 1-1. Summary statistics of Levy County soils. Source data from the Levy County soil survey (Slabaugh *et al*., 1996).

Soil Order	Number of Mapped Series	Percent of Mapped Soil
Alfisols	23	28
Entisols	13	25
Histosols	4	2
Inceptisols	3	17
Mollisols	3	7
Spodosols	10	19
Ultisols	6	3

Histosols also occur in the coastal marshes along southwestern Levy County. Some of the Entisols occur in well drained areas such as sand dunes while others occur in wetter areas in and around the salt marshes.

CHAPTER 2
THE EVOLVING CONCEPT OF SOIL: IMPLICATIONS FOR SUBAQUEOUS SOIL SCIENCE

Introduction

Almost all terrestrial vegetation is rooted and grows in soil, or is attached to something that grows in soil. As the most biologically active portion of the lithosphere, soils have become the focus of an entire scientific discipline (i.e. soil science). Early in the discipline, many were concerned with defining the concept of soil. This activity was necessary because soil is not a single object, rather a continuum on the Earth's surface. Thus, it is more difficult to identify a soil. Soils are not individual objects, thus we must conceive of ways to compartmentalize soil into observable units that can be identified, described, and studied. How one perceives soil determines how one analyzes it. Thus, the concept of soil is very important to its science.

Concepts of soil have evolved over time and so have the paradigms of soil science. Generally, though, concepts of soil have been centered on the growth of rooted plants as a main function of soil. Recently, it has been proposed that the concept of soil be expanded to include submerged areas, called "subaqueous soils" (Demas, 1993). This suggestion fostered soils-based research in submerged areas (Demas *et al*., 1996; Demas, 1998; Demas and Rabenhorst, 1999) and then led to a change in the United Stated Department of Agriculture's (USDA) wording of its definition of soil (Soil Survey Staff, 1998; Soil Survey Staff 1999). This recent development raises several questions.

- How has the concept of soil evolved through time?

- Prior to 1993, what was the official position of the USDA, as outlined in the first edition of *Soil Taxonomy* (Soil Survey Staff, 1975), on semi-permanently and permanently submerged lands; what is soil and what is not?

- What are the specific differences in the USDA's current concept of soil, as expressed in second edition of *Soil Taxonomy* (Soil Survey Staff, 1999), when compared to the previous concept as expressed in the first edition of *Soil Taxonomy* (Soil Survey Staff, 1975)?

- To comply with traditional themes of soil as supporting vegetation, does the USDA's current concept of soil allow for sufficient inclusion of all submerged areas that can or do support rooted vegetation?

- How will the wording in the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999) affect and soil research and U.S. soil survey efforts?

- What is the current direction of subaqueous soil science?

These questions are proposed because they focus on the where soil science has come from and where it is going with respect to aquatic areas. To maintain congruency with the traditional concept of soil as a medium for plant growth, a goal of subaqueous soil science should be the proper inclusion of all subaqueous areas that fit within this concept of soil. Specifically, this is the inclusion of all subaqueous areas that can or do support rooted vegetation.

Historical Concepts of Soil

Different Concepts of Soil

There are as many concepts of soil as there are uses for it. One of the earliest uses of soil was for growth of crops to sustain human life. Today, soils are still used to grow life-sustaining crops. Because of this, it is most often defined as the upper portion of the earth that supports plant growth. As various disciplines of earth-based science have evolved (e.g., geology, geography, engineering, etc.), so to have their concepts of soil.

To every earth-based science, the various portions of the earth each have a function within the system of interest. The focus of a particular discipline necessarily shapes that discipline's view of the soil's function. For example, an engineer might consider soil to be surficial particles with a collective plasticity, bearing capacity, mass, and infiltration rate. In contrast, a geologist might consider soil to be the clastic products of weathered bedrock or the wind/water/glacial transported clasts that comprise sedimentary and other geological layers. A biologist or botanist might consider the soil as a home for burrowing organisms and the medium in which plants are rooted. All of these concepts are correct. However, none of the above view the soil holistically as the soil system.

The discipline of soil science focuses on the soil as the system, rather than a component of another system. Generally, soil scientists view soils as independent, natural bodies (pedons and polypedons) with identifiable physical, chemical, and biological characteristics. These soil individuals make up many sub-populations that, when combined, comprise the upper portion of the earth. This population is called soil. The evolution of this concept is best understood by examining the historical concept of soil. In this respect, previous soil classification schemes provide valuable insight The following are examples of soils-based concepts/classifications. Much of this summary is based on Arnold's (1983) review of the historical concepts of soil.

Greek Concept of Soil

Aristotle (384 to 322 BC) viewed everything to be made of four elements: fire, air, water, and earth. The earth has attributes of warm or cold, dry or wet, heavy or light, and hard or soft. This could be viewed as a recognition of soil's variable moisture content, bulk density, and bearing capacity. Theophrastus (371 to 286 BC) viewed the earth as two parts: the edaphos and the tartarus. The edaphos is a comprised of two layers: the surface stratum and the subsoil. The surface stratum contains variable amounts of humus while the subsoil provided nutrients and "juices" to the plants. The "taratarus" is the “realm of the darkness,” which could be viewed as analogous to the bedrock underlying soil. Theophrastus grouped soil into six classes based on crop suitability. Thus, the Greeks concept of soil was that it was (i) part of the earth, (ii) variable in weight, compaction, and mass, and that variability could be (iii) classified to better understand plant growth.

Roman Concept of Soil

Cato (234 to 149 BC) classified soil into nine major classes and 21 subclasses based on farming suitability. Varro (116 to 27 BC) was reported to have focused on the physical composition of soil while Columella (4 to 70 AD) focused on physical properties of soil, and Plinius (23 to 79 AD) focused on geology as a mineral source for soil formation. The Roman concept of soil thus evolved into a more sophisticated focus on soil attributes, while still recognizing soil’s importance to agriculture.

Russian Concepts of Soil

V.V. Dokuchaev (1846 to 1903) is the Russian credited with maturing the concept of soil into a pedological concept. He stated that surface layers of the earth should be considered soil, and that the parent material was transformed by organisms and climate as a function of relief and time (Dokuchaev, 1883). K.D. Glinka (1867 to 1927) (1927) summarized Dokuchaev’s ideas, but added that transported soil should not be considered soil, but instead as parent material that will become soil upon the action of forces that form soil. Dokuchaev’s writings were in Russian but translated to German. Glinka then translated the German writings to English. Marbut (1863 to 1935) read those works and was greatly inspired by them introducing them into the soil survey program.

Quite often, however, it is H. Jenny (1904 to 1972) who is cited when soil-forming factors are discussed. While not a Russian, Jenny’s work is included here because he proposed the quantification of soil formation by considering each of Dokuchaev's soil-forming factors as independent variables in the formation of soils. Out of the Russians' concept of soil came the sub-discipline of pedology. From hereafter, soils have been considered by pedologists to be individual bodies upon which the five soil-forming factors operate.

- **Soil forming factor 1:** Biota
- **Soil forming factor 2:** Climate
- **Soil forming factor 3:** Parent material
- **Soil forming factor 4:** Relief
- **Soil forming factor 5:** Time

Early American Concepts of Soil

Arnold (1983) pointed out that Hilgard's (1833-1916) (1906) view was that soils are the physically and chemically weathered products of rock, highlighted the support for plant growth. Additionally, Hilgard acknowledged the affect of climate on plant distribution. This acknowledged three of Dokuchaev's soil-forming factors. King (1848 to 1911) (1902) considered soil to be not only important for agriculture, but to the support of all life on earth. A more geological view was communicated by Lyon *et al*. (1916) that soils' past and future was rock, but that soils provided a medium for crop production. Coffey (1912) focused on landscape controls of soils while Whitney (1925) focused on the physical and chemical properties of soil.

Marbut (1921) suggested that soil mapping was helping to refine the concept of soils by focusing on the spatial inventory of soil horizons and the focus on soil classification. Later, Marbut (1922) emphasized the idea of soils as natural bodies. Weir (1928) echoed the concept of soils as natural bodies by explaining that soil individuals are described, while the common characteristics of soil populations are defined. Throughout civilizations and cultures the concept of soil has evolved, but support for plant growth has remained an important function of soil.

Contemporary American Concept of Soil: *Soil Taxonomy*

Pedons and Polypedons

From the Russian thought that soils are natural bodies shaped by the five factors has grown the concept of a polypedon. *Soil Taxonomy* (Soil Survey Staff, 1975; 1999) outlines the concept in detail. A polypedon represents the soil individual that exists on the landscape, and is comprised of at least two pedons. A pedon is considered to be the smallest volume of soil that captures the soil variability.

The minimum breadth of a pedon is 1 m^2 and the maximum about 10 m^2. Note that a pedon is defined as the smallest volume that can be called soil but its size is given in an area. The reason for this is that the depth (third dimension) is not defined but allowed to vary. The minimum depth of a pedon is generally considered the lower limit of biological activity or pedogenesis. Practically, 2 m has been applied as a lower limit of pedons due to suggestions in *Soil Taxonomy* (Soil Survey Staff, 1975; 1999). It is openly conceded in *Soil Taxonomy* that the lower limit of soil is difficult to define as the vertical boundary between soil and parent material can be very gradual.

Soil Defined in the First Edition of Soil Taxonomy (1975 to 1999)

Soil Taxonomy (Soil Survey Staff, 1975) guides soil survey and soil research activities in the U.S. The first edition of *Soil Taxonomy* (Soil Survey Staff, 1975 page 1), discusses defining soil.

> Soil, as used in this text, is the collection of natural bodies on the earth's surface, in places modified or even made by man of earthy materials, containing living matter and supporting or capable of supporting plants out-of-doors. Its upper limit is air or

> shallow water. At its margins it grades to deep water or to barren areas of rock or ice…

Based on this, the Greek and Roman theme of soils providing the function of support for plant growth persists. Soil is not restricted to natural, undisturbed settings "in places modified or even made by man of earthy materials". Soil is bound by various types of non-soil: rock, ice, or deep water. The top of soil is suggested to be air or shallow water. Where "deep water" exists, soil does not. Here, "deep" is not defined, but the passage discusses the support of plants "out-of-doors" so it can be inferred that deep is in reference to the support of plants. Therefore, in 1975 areas under shallow water were identified as soil. The function of soil to support plants is reiterated in subsequent paragraphs of *Soil Taxonomy* (Soil Survey Staff, 1975, page 1)

> The word "soil," like many common old words, has several meanings … Soil, in its traditional meaning, is the natural medium for the growth of land plants, whether or not it has discernible soil horizons. This meaning, as old as the word soil itself, is still the common meaning, and the greatest interest in soil is centered on this meaning …

The support for plants is identified as the defining characteristic of soil. Whether or not the soil has undergone pedogenesis to a large enough degree that soil horizons have formed is not considered in the 1975 definition of soil. *Soil Taxonomy* clarified the term "plants" to mean "land plants." This was not defined as an exclusion of aquatic plants. Regarding pedogenesis, *Soil Taxonomy* (page 1) states that soil formation as expressed by soil horizons is not a requirement of soil.

> Soil, as used in this text, does not need to have discernible horizons, although the presence or absence of horizons and their nature is of extreme importance to its classification. Soil is a natural thing out-of-doors. It has many properties that fluctuate with the seasons …

Soil Taxonomy also addresses the difficulty of defining the boundary between soil and non-soil and therefore the difficulty in classifying some soils. This is done by addressing soils as they grade into exposed bedrock in deep water (page 1)

> Since one cannot distinguish precisely under all conditions between what is and is not a part of the soil, a short, precise, general definition is perhaps impossible … Some soil landscapes that support plants gradually thin to open water or to lichen-covered rock and finally to bare rock with no clear separation that applies generally between soil and not-soil.
>
> Areas are not considered to have soil if the surface is permanently covered by water deep enough that only floating plants are present or if survival conditions are so unfavorable that only lichens can exist, as on bare rock. Yet soil does not necessarily have plants growing on it at all times … The point is that the soil that concerns us when making soil surveys must be capable of supporting plants out-of-doors.

Soils are simultaneously a continuum of features (e.g., expansive horizontal layers of clay and sand), a population of individual natural bodies across the landscape, and a collection of countless particles, liquid, gas, humus, and organisms. *Soil Taxonomy* essentially reiterates two previously stated points. First, if surface water is too deep for rooted plants to survive, no soil exists in that area. Second, the soil's primary importance is the support of "plants out-of-doors." Furthermore *Soil Taxonomy* states that the support for plants, not the presence of plants, which is required for soil to exist. Finally, *Soil Taxonomy* states that the purpose of *Soil Taxonomy* is to facilitate soil survey. That fact is also explicitly stated in the subtitle of the text: *A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. The opening pages of *Soil Taxonomy* illustrated an important concept of soil. This concept was that soils are natural bodies of the earth that support rooted plants.

If it can be demonstrated that rooted vegetation can grow, then regardless of hydrology, soil exists according to the first edition of *Soil Taxonomy* (Soil Survey Staff, 1975). Demas (1993) suggested submerged areas be considered soils instead of sediments. He focused on a popular interpretation of the definition of soil; the support for rooted plants refers to emergent rooted plants. The soils Demas investigated supported submerged rooted plants. He concluded with a suggestion that the definition of soil be modified to include soils supporting submerged plants: subaqueous soils.

Strictly adhering to the wording in *Soil Taxonomy* (Soil Survey Staff, 1975) these areas were already considered soil. These areas were, however, ignored by soil scientists until Demas studied them in 1993. Why? Probably because the concept of soil was directed to the functions of the soil survey program. Those functions were agronomically based.

Demas (1993) also discussed the importance of submerged aquatic vegetation. Demas *et al.* (1996) continued to study subaqueous soils, producing the first subaqueous pedon descriptions. In 1998, the USDA's modified the definition of soil. This modification was published in the seventh edition of *Keys to Soil Taxonomy* (Soil Survey Staff, 1998) and in the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999). In 1999, the research leading to those changes was published (Demas and Rabenhorst, 1999).

Soil Defined in the Second Edition of Soil Taxonomy (1999 to Present)

The USDA's guidance on the concept of soil was updated to highlight shallow water soils (Soil Survey Staff, 1999, page 9)

> The word "soil," like many common words, has several meanings. In its traditional meaning, soil is the natural medium for the growth of land plants, whether or not it has discernable horizons.
>
> Soil in this text is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are

> distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment. This definition is expanded from the previous version of Soil Taxonomy to include soils in areas of Antarctica where pedogenesis occurs but where the climate is too harsh to support the higher plant forms.
>
> The upper limit of soil is the boundary between soil and air, shallow water, live plants, or plan materials that have not begun to decompose. Areas are not considered to have soil if the surface is permanently covered by water too deep (typically more than 2.5 m) for the growth of rooted plants. The horizontal boundaries of soil are areas where the soil grades to deep water. In some places the separation between soil and nonsoil is so gradual that clear distinctions cannot be made.

The traditional spirit of the soil definition is left partially in tact. Soils are still considered to be a natural body. However, it is quite clear that a shift in focus from plant growth to soil genesis has taken place. The wording in the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999) emphasizes horizon formation and pedogenesis, via reference to soil-forming processes while still allowing for the option of plant growth. It is explicitly stated that this change is meant to include Antarctic soils because it is difficult for plants to grow there. This clarification on what soil is could be applied to subaqueous soils. Evidence of pedogenesis can qualify a subaqueous portion of the earth as soil, regardless of the support for vegetation, as is the case in Antarctica.

In addition to the importance of vegetation support apparently being reduced, the term “shallow water” was retained from the first edition. However the phrase “typically more than 2.5 m” was included as guidance as to what is too deep. This depth guidance follows the spirit of the pedon description limit of 2 m found in both editions of *Soil Taxonomy*. In that spirit, the purpose could be viewed as a guideline, from the experts, as to what one should expect as a reasonable depth. There are clearly exceptions.

Harris *et al.* (2005) pointed out examples of where the 2 m hinders the interpretation of the landscape. Areas of Florida where Bh horizons were present at 3.3

m were identified as Entisols in the county-level soil survey. These soils were considered to have undergone little pedogenesis because no pedogenesis was observable within 2 m. In fact, the upper 3.3 m of the soil was severely leached and had undergone much pedogenesis. This was likely not discernable during the mapping process because observations below 2 m do not routinely occur. In this situation, the 2 m depth guidance of *Soil Taxonomy* was not deemed appropriate. Similarly, the 2.5 m limit of “deep water” is suggested in *Soil Taxonomy* (Soil Survey Staff, 1999) but may not be appropriate in many areas where plants can grow in water deeper than 2.5 m.

The USDA does concede the fuzzy nature of the resultant water-ward limit of soil by stating that “clear distinctions cannot be made” in situations where the transition from soil to non-soil is gradual. However, the guidance of “typically 2.5 m” stands out as a target depth which may be used to delineate subaqueous soil from sediment. If broadly accepted by soil scientists as the maximum depth of water allowed for soil to exist, then the extent of soil may be underestimated in some geographic areas and over estimated in others.

Implications for Subaqueous Soil Science

Shallow Subaqueous Areas Not Considered Soil

Conceptually, aquatic areas that are shallow enough to support rooted vegetation have been considered soil in both editions of *Soil Taxonomy*. The changes in the USDA’s definition of soil (Soil Survey Staff, 1999) may appear to better incorporate subaqueous areas, but actually restrict their inclusion within the pedosphere. This restriction is generated by the quantitative guidance of the 2.5 m water depth as the typical water-ward extent of soil.

Areas “greater than 2.5 m” deep, are not technically excluded in the updated definition of soil (Soil Survey Staff, 1999). The phrase “typically greater than 2.5 m” means that atypical situations can exist. However, this quantitative advice on water depth has already had an effect on pedologists’ conception of what subaqueous soils are. For estuarine environments, Bradley and Stolt (1993) defined subaqueous soils as those occurring in areas with a water depth ranging from intertidal to 2.5 m. The deeper areas could support SAV, depending on water clarity. On the other hand, the areas between the intertidal and 2.5 m at low tide may not support SAV if they occur in systems with low water clarity such as salt marshes.

In some cases, the intertidal areas could be considered a zone of non-soil between terrestrial soils and subaqueous soils. However, in many such cases, evidence of pedogenesis could likely be observed. Therefore, based on the support for soil, the 1999 definition of soil does include these intertidal areas, but the 1975 definition did not. In all likelihood, these intertidal areas will be considered in subaqueous soil survey efforts because they are the connection between subaqueous and terrestrial landscapes.

Subaqueous Soil Survey Efforts

Currently, subaqueous soil survey is in its early stages. Demas’ doctoral research (1998) was a subaqueous soil survey of Sinepuxent Bay, MD. Bradley and Stolt (2003) identified subaqueous landforms in Ninigret Pond, RI at a scale slightly finer than a typical U.S county soil survey. These efforts exemplify the application of the pedological paradigm to subaqueous habitats. They focused on the classification of landscapes into units and reporting the soil patterns related to those units. The deliverables of the results were prototype subaqueous soil surveys. Much more work is needed to identify subaqueous landscape units and resultant soil patterns that occur in other geographic areas. In addition to the soil/landscape relationships that were the focus of the aforementioned research, emphasis needs to be placed on the A horizons of subaqueous soils.

Typically, for example we take for granted that a soil will have accumulations of organic matter in the surface, resulting in O and/or A horizons. When accumulations of organic matter are encountered under water, they are assumed to be the result of the same processes that formed these horizons on land. Testing assumptions such as this will be a necessary part of subaqueous soil survey efforts.

Clearly defining the purpose of a soil survey is of paramount importance to the success of the survey (Smith, 1986). Initially, terrestrial soil surveys were intended for the agronomic interpretation of soil productivity. In later years, soil surveys have been used for non-agronomic purposes such as engineering (e.g., on-site waste water systems). In these cases, a different application of the survey means that different data are needed (Fanning and Fanning, 1989). For instance, a soil description may only be reported for the upper 100 cm if it was a soil known to have restrictive layers that resulted in being very poorly suited for crops. Designing a shopping mall in an area having shrink-swell clays would require much deeper soil inventories. If the original purpose of the survey was multi-use, then all observations would need to be tailored to its objectives.

So, the question is: What is the purpose(s) of subaqueous soil surveys? The majority of subaqueous areas are not going to be used for traditional agriculture or construction, especially not the marine areas. Of immediate concern in Florida is the inventory of seagrass resources. Soils that can or do support seagrasses are valuable resources that need protecting. In the Florida Keys example, the vegetation grows at depths much greater than along the west coast of Florida. Should all surveys extend out to the same depth to preserve contiguity?

Discussion

The recent changes to the USDA's definition of soil resulting from some initial subaqueous pedology and preceding other subaqueous pedology raised the following questions:

- How has the concept of soil evolved through time?

It appears that the concept of soil has not changed much through time. It has been and still is seen as the upper portion of the earth that supports plant growth. What has changed is the acknowledgement of the non-agronomic role of soil. Support for non-agronomic plants such as seagrasses has recently become of interest to soil scientists. Additionally, soil science as a discipline has developed a more quantitative focus.

- Prior to 1993, what was the official position of the USDA, as outlined in the first edition of *Soil Taxonomy* (Soil Survey Staff, 1975), on semi-permanently and permanently submerged lands: what is soil and what is not?

The official position of the USDA was that if vegetation growth was or could be supported by the earth, out-of-doors, in natural conditions, then soil was present. Semi-permanently and permanently submerged lands were specifically addressed as needing to have shallow enough water for rooted plants to grow. Emergent plants may have been assumed by readers of *Soil Taxonomy* (Soil Survey Staff, 1975), but no distinction was made between submerged and emergent plants. The distinction that was made was between floating and rooted plants. Therefore, any land under water with the support for plants or the potential for plant support would have been considered soil.

- What are the specific differences in the USDA's current concept of soil, as expressed in second edition of *Soil Taxonomy* (Soil Survey Staff, 1999), when compared to the previous concept as expressed in the first edition of *Soil Taxonomy* (Soil Survey Staff, 1975)?

The primary difference is the inclusion of "evidence of pedogenesis" as an indicator that soil is present. The requirement that soils support vegetation was de-emphasized. Instead, soil-forming processes were discussed. Technically, this is an expansion of the pedosphere because now areas can either provide plant support, the potential for plant support, or show evidence of pedogenesis. Generally, this focus on soil-forming factors and pedogenesis could be interpreted as a more quantitative concept of soil. The most notable difference with respect to subaqueous areas is the guidance that "shallow" water is "typically 2.5 m" deep. This was not stated as a requirement, but its mention is significant as soil scientists may adhere to this guidance.

- To comply with traditional themes of soil as supporting vegetation, does the USDA's current concept of soil allow for sufficient inclusion of all submerged areas that can or do support rooted vegetation?

Assuming the 2.5 m water depth guidance represents the USDA's belief that vegetation in water deeper than this does not grow, then no. All submerged areas that can or do support rooted vegetation would not be sufficiently included. In Florida, rooted vegetation can grow in water deeper than 2.5 m. Many sandhill lakes as well as marine areas have clear enough water to allow plant growth in water below 2.5 m deep.

- How will the wording in the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999) affect and soil research and U.S. soil survey efforts?

It is too early to conclude the effects of this revised definition. Only a few published studies have followed this definition: Demas and Rabenhorst (2001), Ellis, (2002), and Bradley and Stolt (2002; 2003). Bradley and Stolt, in both of their papers, state that subaqueous soils occur in water depths up to 2.5 m (Bradley and Stolt 2002; 2003). If others follow this interpretation, then one effect of the new wording would be the exclusion of subaqueous soils that occur under water > 2.5 m deep. In Florida, this could be a considerable amount of soil. Aside from this, the likely effect of the new wording will be increased awareness of subaqueous areas as soil. This should foster more research in these areas. The more quantitative nature of the wording could inspire subaqueous research focused on soil-forming process, but this remains to be seen. Given the purpose of *Soil Taxonomy* is to facilitate soil survey in the U.S., then these surveys will likely include at least some subaqueous areas. The tone of the 1999 definition has decidedly more focus on subaqueous areas than the 1975 definition. Research and survey efforts should follow this focus.

- What is the current direction of subaqueous soil science?

To date, the marine subaqueous pedological research has focused on the soil survey aspect of pedology (Demas, 1993; Demas *et al.*, 1996; Demas and Rabenhorst, 1999; Bradley and Stolt, 2002; 2003). Demas and Rabenhorst (2001) modified Jenny's (1941) model of soil formation and stated the model needs testing and quantification. They highlighted the use of this model in subaqueous soil survey. Based on the marine subaqueous pedology thus far, the direction appears to be toward subaqueous soil survey. No pedological research has been presented to address subaqueous soil formation, such as A horizon formation.

Conclusions

The early Greek and Roman concept of soil as a medium for plant growth has remained central to soil science. The concept of soil has evolved with time not by rejecting this view, but rather adding to it. As the understanding of soil-forming processes has grown, the view of soils as objects of study has formed. Soils are now viewed as individuals who support the growth of plants.

Soil science has matured as a science. It has a paradigm, which places at the center of focus, the soil as an individual body. Soil scientists attempt to isolate, observe, describe, sample, manipulate, and model soil to improve our understanding of it. With the recent focus on subaqueous soils, the application of this paradigm will require testing, quantification, and likely modification of fundamental pedological principles.

Currently, the focus of subaqueous soil science is pedological. Specifically, the focus is on subaqueous soil survey. As advancements are made in this area of pedology, perhaps more process-based research will reciprocate ideas so that subaqueous soils are better understood.

CHAPTER 3
RELATIONSHIPS BETWEEN SUBAQUEOUS SOILS AND SEAGRASSES

Introduction

Subaqueous Soils

Near-shore marine as well as estuarine environments are often home to marine angiosperms, or seagrasses. These seagrasses are rooted in the “bottom” of marine environments. This bottom, typically referred to as sediment, provides a medium for both anchoring via roots and the uptake of nutrients. This is parallel to the role that terrestrial soils serve for terrestrial plants, which is a holdfast for rooting and a source of nutrients. In recognition of this, soil scientists have recognized marine bottoms capable of supporting plants to be included in the definition of soil (Demas and Rabenhorst, 1999; and Chapter 2).

Within the field of soil science, this represents a major expansion of pedology because the traditional paradigm was unconcerned with aquatic soils. Within the field of sedimentology, this represents a position that aquatic bottoms are stable, since soil formation and rooted plant growth occur on stable substrates. Within the field of marine botany, this will hopefully add to the understanding of the role sediments/soils have in seagrass ecosystems.

Although soil science is generally concerned with the upper few meters of the earth’s surface, the focus on the rooting zone is a natural place to begin subaqueous soil science, as it is the most likely portion of the soil to be influenced by rooted vegetation. Vegetation is an important terrestrial soil-forming factor (Dokuchaev, 1883; Glinka, 1927; Jenny 1941) and is likely an important subaqueous soil-forming factor (Demas, 1993; Demas *et al*., 1996). This had previously been acknowledged by the USDA in 1975 (Soil Survey Staff, 1975; Chapter 2) but was demonstrated, in principle, by Demas and Rabenhorst (1999; 2001). However, their research was limited to the temperate seagrasses occurring in the Mid-Atlantic United States. Along the Southeastern and Gulf coasts of the U.S., Caribbean species of seagrasses exist in the warmer, subtropical/tropical, environment. These species include *Thalassia testudinum*, *Syringodium filiforme*, *Halodule wrightii*, and various species of *Halophilia*. Soils supporting Caribbean grasses in the subtropical Southeastern U.S. are likely to be different from the other subaqueous soils in the U.S. Climate, water clarity, parent material, biota, and age of landforms are unique to each area of the world. Because of the general role soil has in supporting vegetation physically (e.g., root support) and chemically (e.g., nutrients), the focus of this chapter will be studying the soil properties within the rooting zone of Caribbean seagrasses occurring in the Gulf of Mexico.

Seagrass Productivity

Seagrasses are highly productive marine angiosperms. Generally, seagrasses are considered to be among the highest production ecosystems in the world. Phillips and McRoy (1980) report an average productivity of 500 to 1000 g C m^{-1} yr^{-1} for seagrasses, based on Wood *et al.* (1969). Wood *et al.* (1969) also acknowledged the additional productivity of the epiphytes on seagrass leaves, which were reported to rival the seagrass blades in biomass. Duarte and Chiscano (1999) similarly reported a productivity rate of 1012 g C m^{-1} yr^{-1} for seagrasses. In an estuary in Beaufort, North Carolina, *Zostera marina* covered only 17% of area but contributed 64% of the total primary production in the estuary (Williams, 1973).

These numbers can be misleading as seagrass production and biomass within and between species vary with geography (Duarte and Chiscano, 1999). Additionally, estimates of seagrass production can vary based of time of year and method used (Zieman, 1982). Production estimates based on O_2 liberation are likely to be high since the oxygen evolved is the product of the seagrass plant community. This community may include epiphytes and other algae. Additionally, organic matter (OM) based estimates of productivity are probably low, since seagrasses can internally cycle CO_2 to supplement C uptake from the water column (Phillips and McRoy 1980; Zieman 1982). In fact, Zieman (1975) reported a doubling of seagrass blade volume due to CO_2 build up.

Zieman (1982) suggested leaf marking as a technique for directly measuring seagrass growth. This focus on the blade/productivity relationship of seagrasses assumes that the increases in blade length are proportional to primary production. Below-ground biomass is also storage for C. Variability in C partitioning may confound comparisons of productivity based on leaf marking. Supporting the assumption that blade growth is proportional to productivity, Dawson and Dennison (1996) reported UV photo damage caused stress and reduced productivity. Thus, in shallow water grasses can be less productive due to photo-stress and, therefore, have relatively shorter blades than the deeper water grasses.

An alternate explanation of blade-length/water-depth relationships is that in shallow water, where light is more available, seagrasses may need less surface area to perform adequate photosynthesis. Where light is ample, a short blade may provide enough surface area for adequate photosynthesis. It would follow that long blades would be required to perform the same amount of photosynthesis in deeper water where less light is available.

Compiling existing productivity estimates to gain an overall understanding of seagrass productivity is difficult due to the production variability within and between species coupled by the differences in methodologies. However, it can be assumed that seagrass ecosystems are very productive, generating a considerable amount of OM in shallow marine systems. The fate of the OM has impacts on the seagrass, the soil, and surrounding aquatic systems.

Organic Matter Cycling in Seagrasses

Depending on the species and density of seagrass, time of year, and level of disturbance to the grasses, the export of seagrass blades to surrounding aquatic systems can vary. During times of high seagrass biomass, typically summer and fall, racks of seagrass leaves are usually visible along proximate shorelines (Zieman, 1982; Zieman and Zieman, 1989; Hemminga and Duarte, 2000).

While some of the seagrass-derived organic matter (OM) is lost due to leaf export, much of it can remain within the system. Additionally, seagrasses act as traps for suspended particles (Phillips and McRoy, 1980; Ward *et al*. 1984; Zieman 1982; Zieman and Zieman, 1989; Duarte and Chscano, 1999; Gacia *et al*. 1999; Barron *et al*., 2004; Papadimitriou *et al*., 2005). These suspended particles can be particulate OM. In addition to the initial trapping of sestonic material imported into a seagrass bed, the squelching of particulate export can be affected by seagrasses. Gacia *et al*. (1999) determined that within *Posidonia oceanica* beds, the trapping of re-suspended material was more important that the trapping of imported material.

Since most seagrasses beds occur near land, they are near the influence of that land. The export of particulate OM from the land to the seagrasses is an important influence. Hemming and Duarte (2000) point out that productive vegetative systems on land, such as salt marshes and mangrove forests, export leaf litter to the seagrasses (Hemminga *et al*, 1995; Slim *et al*.1996).

It is generally accepted that seagrasses trap and bind suspended particles much of which is organic in nature. If a sediment accreting scenario is assumed, which is typically the case when seagrass substrates are viewed from a sedimentological perspective, then the fate of some of the trapped OM is burial by sedimentation. From a soils perspective, sedimentation is not soil formation. Rather, it is the accumulation of parent material that could later undergo pedogenesis. Post-depositional changes to the sediment are considered soil formation. However, if deposition is amplified by vegetation rooted in and supported by the soil, then the soil is essentially feeding itself sedimentary material. This should be considered soil formation. Whether organic particles settling out is labeled soil formation or sedimentation may be particularly important to the study of seagrasses simply because it changes the perspective, set of biases, and approach (the paradigm) from which one views the marine bottom.

In an environment where the accretion of sedimentary material is uniform in amount and composition, the concentration of OM should decrease with depth in the sediment simply because the deeper OM has been subjected to decomposition for a longer period than the shallower OM. An example of this OM depth distribution in a subaqueous soil was given by Demas and Rabenhorst (1999). The explanation given for the OM depth distribution was not a sedimentary process. Instead, it was inferred that the carbon concentration indicated the formation of an A horizon. The A horizon concept is terrestrially based, but was invoked in this instance due to the perspective of soil scientists that surficial accumulations of OM are indicative of A horizon development. In terrestrial environments this is almost always the case. Is it the case for subaqueous environments?

A Horizon Formation in Terrestrial Soils

In terrestrial soils, the surface horizons are usually highest in OM concentration. This is because rooting and other biological activity (bioturbation) is the highest in the surface of the soil. These are the vectors for organic additions to the soil.

As the collective action of the five soil-forming factors varies across the landscape, so too does the concentration of A horizon OM. Typically, however, the vertical profile of soil OM is consistent across the landscape. Soil OM is highest at the surface and decreases with depth. Most soils support biota that add OM to the soil, thus most soils have A horizons. Subaqueous soils support both vegetative and burrowing biota. Do these soils have A horizons as well?

A Horizons in Subaqueous Soils

A fundamental difference between terrestrial and subaqueous environments is the density of the fluid above the soil surface. The density of water is much greater than air, thus more material can be suspended above an aquatic soil than above a terrestrial soil. This decreases the stability of subaqueous soils relative to terrestrial soils. An enhanced ability to suspend material results in more source material for sedimentation. Thus, sedimentation is more pronounced in an aquatic environment. To what degree, then, does sedimentation contribute to the surficial accumulation of OM? To what degree do plant inputs contribute to the accumulation of OM? Are the surficial accumulations of OM in subaqueous soils actually A horizons? Addressing these questions will likely be the goals of future subaqueous research. Currently, there is a need to document the nature and distribution of subaqueous "A horizons" as they relate to seagrasses.

Initially Investigating Soil/Vegetation Relationships in an Aquatic Environment

In aquatic areas, because of the likelihood of re-suspending soil material and because of the lack of vertical drainage, the terrestrial model of leaching/translocation of soil material, cannot be assumed as it is for terrestrial soils. Because vertical drainage is probably absent in subaqueous soils, subsurface horizons such as spodic or argillic horizons are likely to reflect past terrestrial conditions, not present subaqueous conditions.

The most likely portion of soil that will reflect the contemporary intersection of the five soil-forming factors (Dokuchaev, 1883; Glinka, 1927; Jenny, 1941) is the soil surface horizon. The injection of OM via roots, the vertical movement of OM due to animal burrowing, and the burial of OM due to sedimentation can all occur in a seagrass bed (Zieman and Zieman, 1989; Hemminga and Duarte, 2000; Barron *et al*., 2004). These processes add OM to the soil, thus forming A horizons.

Before undertaking large pedological efforts such as subaqueous soil surveys or before making interpretations/inferences based on soil morphology, it is important to first understand, among other things, how and why the soil properties of the surficial horizon are related to organic-ground cover. Some relationships have already been established.

Demas (1993) pointed out that the firmness of the bottom was related to the presence/absence of *Zostera marina* but did not state what that relationship was. Most reviews of seagrass ecology state that seagrasses trap and bind particles, some of which are high in OM (Phillips and McRoy, 1980; McRoy and Helfferich, 1980; Zieman, 1982;

Zieman and Zieman, 1989; Hemminga and Duarte, 2000; Dawes *et al.* 2004). In terrestrial soils, most rooted plants deposit OM into the soil, creating A horizons. These A horizons are typically darker in color than the horizons below (e.g., A horizon color of 10YR 3/1 and E horizon color of 10YR 6/1). Demas *et al*. (1996) reported dark soil colors 5YR 3/1 and 3/2 where *Zostera marina* was present, but did not compare to colors of adjacent unvegetated areas. Demas and Rabenhorst (1999) offered an explanation of surficial subaqueous soil morphologies:

> "Elevated levels of OC in the surface layers accompanied by (sometimes irregular) decreases with depth are exactly what are found in terrestrial analogs. These data suggest that epipedons are forming as a result of pedogenic processes."

The suggestion here is that high levels of OM and dark colors are identified at the surface of vegetated subaqueous soils as is in the case with terrestrial vegetated soils; A horizon formation.

Objectives

Florida is a predominantly subtropical state with over 1200 km of coastline, much of which supports seagrasses. The subaqueous soils that occur there have yet to be investigated from a pedological perspective. Because these soils support rooted vegetation it is important to understand the soil/vegetation relationships. The most likely place to observe soil/vegetation relationships should be within the rooting zone. To avoid confusion with the term "epipedon" which has strict taxonomic implications (Soil Survey Staff, 1999) the term upper-pedon is used to refer to the upper portion of the soil (0 to 30 cm) in which vegetation can be rooted.

- **Objective 1:** Determine spatial patterns in species of seagrasses in the study area.
- **Objective 2:** Determine the usefulness of Landsat satellite in mapping seagrass extent.

- **Objective 3:** Document the morphology of the soil within the upper-pedon
- **Objective 4:** Document physical and chemical properties of the soils within the upper-pedon
- **Objective 5:** Determine relationships between soil properties and seagrasses supported by the soil.

Materials and Methods

A description of the study area can be found in Chapter 1.

Aerial Photography

The Suwannee River Water Management District supplied scanned and rectified, 1:24,000 true-color aerial photography for the Cedar Key area. This imagery was projected in State Plane North, Feet, NAD 88 HARN with a cell size of approximately 1 m. The photographs were used as the basemap for the rectification of satellite imagery.

Satellite Imagery

Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite imagery (http://landsat.gsfc.nasa.gov) was acquired for the study area (Path 17, Row 40). Landsat 7 ETM+ is a multispectral dataset which allows for the visualization of landscapes by combinations of the individual bands and/or statistical classification of those bands. Vegetation, urbanized areas, water, etc. are identifiable because of the unique spectral signature that various land-covers/land-uses impart on the landscape.

Landsat imagery is delivered the form of band-layer scenes. Each Landsat 7 ETM+ scene covers approximately 35,000 km^2 of the earth's surface with a 6-day period of return. Each band-layer is a regularly spaced grid of spectral values. The data on six of the bands (Bands 1-5, and 7) are spaced by 30 m. The thermal band (Band 6) data are spaced 60 m and the panchromatic band (Band 8) data are spaced 15 m. The light attenuation by water restricts the use of all bands in aquatic systems, but more so for the bands of longer wavelength (Bands 4 to 7).

Scene Selection: Attenuation of bands by water or cloud cover within the study area was minimized using a set of three criteria for scene selection:

- **Criteria 1:** Scene acquisition time coinciding with low turbidity and long seagrass blade length
- **Criteria 2:** Scene acquisition time coinciding with low water levels
- **Criteria 3:** No cloud cover visible within the study area portion of the scene

Scene selection was narrowed starting with Criteria 1. Near Cedar Key, FL low turbidity months are generally occur when waters are cold and phytoplankton growth is at a minimum (November-March, with January and February being the clearest). Within the study area it was observed that seagrass blades are the shortest during the winter months (January through March). Therefore, November and December were selected as possible months of clear water and long seagrass blade length.

To satisfy Criteria 2, National Oceanographic and Atmospheric Administration (NOAA) tidal records for Cedar Key, FL were used to determine which of the available November and December Landsat 7 ETM+ scenes were acquired at low tide.

Prior to purchase, scene previews are made available (http://www.landsat.org). These previews were used to determine which scenes satisfied Criteria 3. Additionally, cloud cover percent was reported in the metadata for all Landsat scenes. Scenes with a cloud cover of greater than 10% were excluded from the visual inspection. The most recent scene with the no visible cloud cover within the study area and satisfying all three criteria was purchased for analysis.

The Landsat 7 ETM+ scene for November 7, 2002 (path 17, row 40) satisfied all the selection criteria and was therefore purchased (Figure 3-1). This scene was compared to another path 17 row 40 scene (10-30-1999) that was acquired near high tide (Figure 3-2). Visual inspection of 5-4-3 band layer composites of both scenes showed that upland vegetation was visible at both tides but SAV was only visible at low tide (Figure 3-2a). This confirmed that the 2002 scene was acquired at a low enough tide to observe seagrasses.

Pre-analysis data configuration: Before analysis, the scene was rectified to the aerial photography. The scene was radiometrically corrected so that vegetation indices would produce meaningful values. The procedures for correcting the scene are outlined in Thome *et at*. (1994) with modifications made by Teillet and Fedosejevs (1995). Also, prior to analysis, portions of the scene greater than 20 km outside the study area were removed to expedite analysis. The 1990 United States Census Bureau TIGER/Line File layer was converted to raster (30 m cell size) then used to remove upland portions of the scene. The remaining areas of the scene were determined to be aquatic.

Seagrass Mapping

Patterns in seagrass distribution were visually observed in the field when water levels were at or below MLW. Specific attention was placed on vegetative gradient where elevation changed (e.g., around bars and on the edges of flats). This information was used to interpret aerial and satellite imagery. Seagrass distributions were initially investigated using photo tone of the aerial photography coupled with the field observations.

Although high quality color aerial photography was available for the entire study area, it was desirable to determine the usefulness of Landsat satellite imagery for

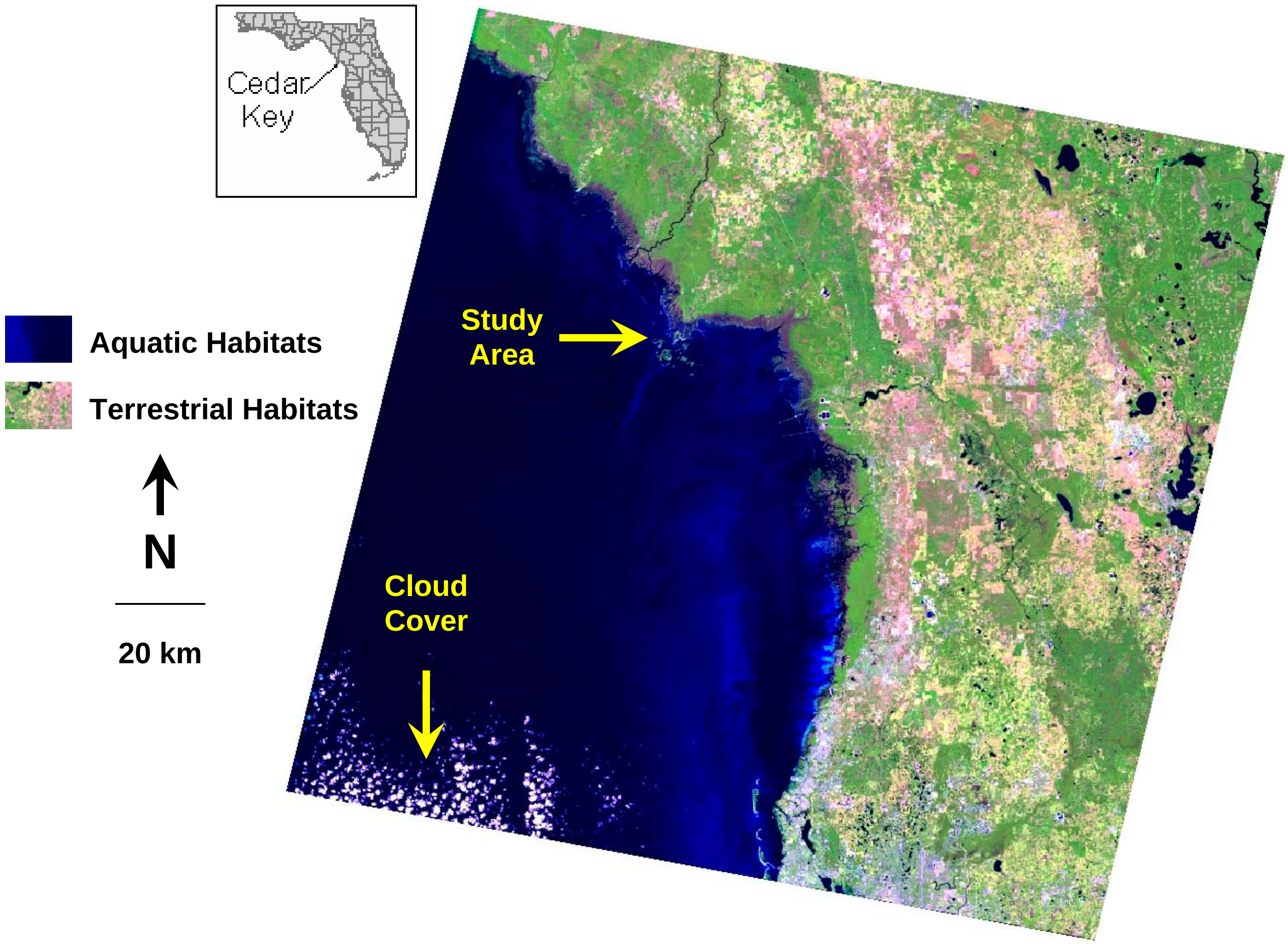


Figure 3-1. Bands 5-4-3 composite of Landasat 7 ETM+ scene: Path 17, Row 40. The date of the scene was November 7, 2002. Projection shown is UTM Zone 17 NAD83. The study area 5 km southwest of Cedar Key, FL and is approximately identified by the yellow arrow.

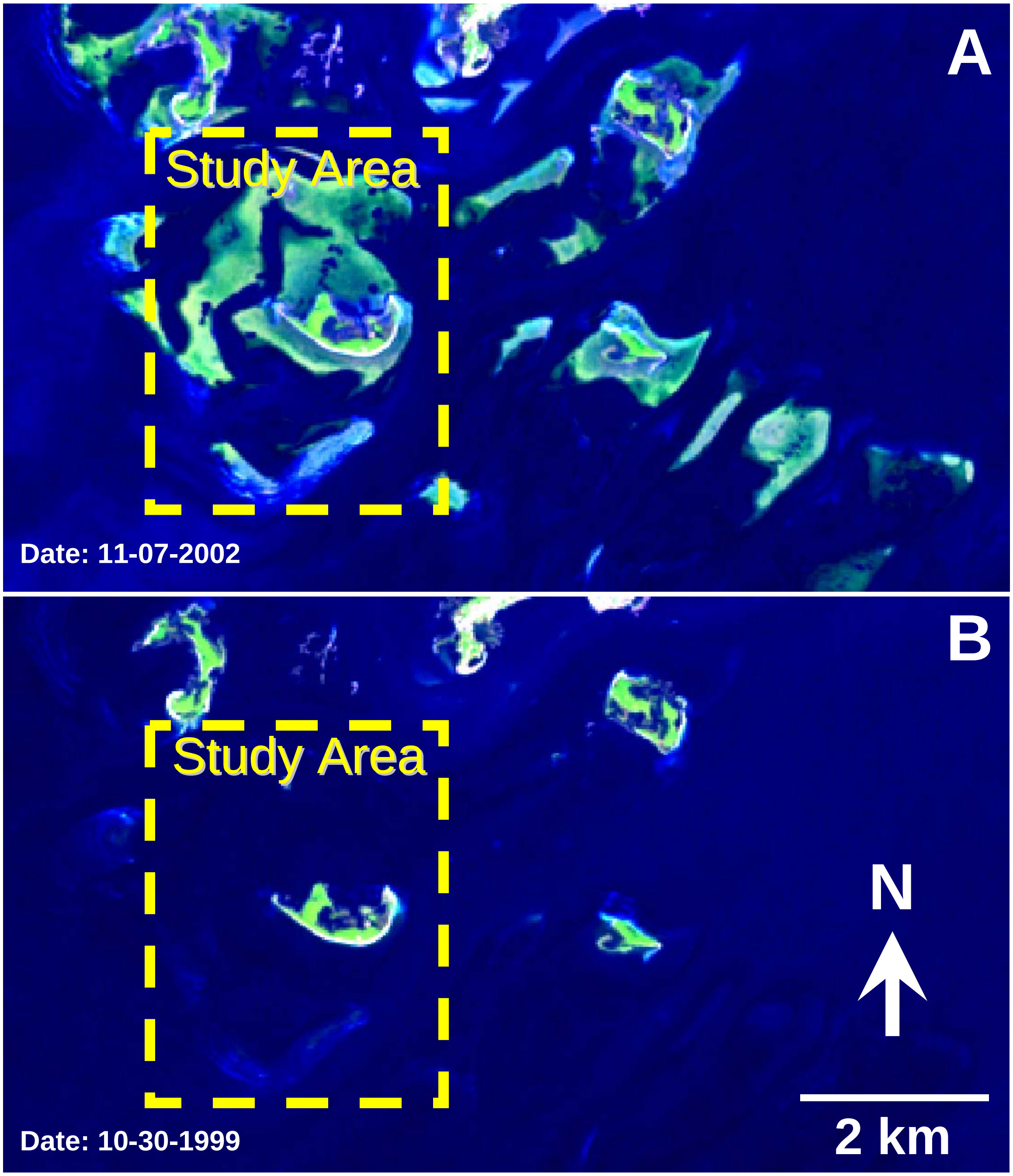


Figure 3-2. Comparison of Landsat 7 ETM+ imagery acquired for study area (Path 17, Row 40) A) at low tide, B) and high tide. Images are composites (Band 5 = red display colors, Band 4 = green display colors, Band 3 = blue display colors) designed to color vegetation green. Because of the high attenuation of near-infrared (Band 4: 0.76-0.90 μm) and mid-infrared (Band 5: 1.55-1.75 μm) by water, composites of Bands 5, 4, and 3 do not penetrate very well into the deeper aquatic portions (>1 m depth) of the study area. The result is a dominance of blue display colors from Band 3 red: (0.63 μm - 0.69 μm) in the deeper areas.

mapping seagrasses. Since the seagrass blades were likely exposed at the time of scene acquisition, a Normalize Difference Vegetation Index (NDVI) was calculated to enhance photosynthetically active areas (Rouse *et al.*, 1974; Deering *et al.*, 1975; Huete *et al.*. 2002).

Using the aerial photography, locations where seagrasses transitioned into unvegetated areas and where shallow water transitioned into deep water were identified. Within these zones, 100 deep-shallow water locations were digitized and 30 seagrass-unvegetated locations were digitized. The reason less seagrass-unvegetated locations were digitized is that there were fewer areas where these transitions occurred. These locations were then used to extract the NDVI values.

The average NDVI values for the seagrass-unvegetated and the deep-shallow water transitions were used as threshold NDVI values. These threshold values were then used to classify the study area into three classes: deep water, seagrass, and unvegetated. A fourth class, uplands, was pre-determined by using the TIGER county boundaries.

The final NDVI-derived seagrass map, the aerial photography, and the field observations were used to characterize the distribution of seagrasses within the study area. This understanding was then used to construct a sampling design for soil analysis.

Soil Sampling and Analyses

Sampling design: For soil sampling, seagrass-cover of the shallow-water soils (< 1 m deep MLLW) was divided into four classes: 1) *Halodule wrightii* (HAL), 2) *Thalassia testudinum* (THAL), 3) *Thalassia* / *Syringodium filiforme* mixed stand (THAL/SYR) and 4) unvegetated (UNVEG). For each of the four seagrass cover classes, five random locations were chosen for soil sampling (Figure 3-3). No soil samples were collected in deep (>1 m at MLLW) water areas. At each site the upper 30 cm of the soil

Figure 3-3. Location map of soils sampled according to seagrass species. The cover site abbreviations are: unvegetated (UNVEG), *Halodule wrightii* (HAL), *Thalassia testudinum* (THAL), and *Thalassia / Syringodium filiforme* mixed stand (THAL/SYR). The X locates a pedon (THAL-REP) that was sampled to represent *Thalassia testudinum* areas.

(hereto referred to as the "upper-pedon") was sampled using a spade shovel with a 40 cm long, 10 cm wide blade. The term *upper-pedon* is used to avoid confusion with the term *epipedon*, which has a strict taxonomic definition. The design of the shovel allowed the retrieval of an in-tact upper-pedon. The upper pedon was split into three samples: 0 to 10 cm, 10 to 20 cm, 20 to 30 cm. An additional site, THAL-REP was chosen for deeper analysis. The pedon was sampled from the surface to a depth of 160 cm, at 15 cm intervals.

Soil morphology: To provide a single assessment of soil color for each depth zone sampled, the immediate, crushed colors of the upper pedons samples were determined. A uniform soil mixture was obtained by gently rubbing a portion of the soil three times between the thumb and forefinger. This was done to achieve a soil color that represented all the soil material in the sample. The rubbed soil was visually compared to a Munsell® Color Book (Gretag/Macbeth, 2000). It was important to determine soil color immediately because inundated soils often change color when exposed to oxygen (Figure 3-4). Once soil color was determined for all upper-pedon samples, those and the THAL-REP samples were collected for laboratory analysis

Laboratory analyses: All samples were analyzed for particle-size distribution (PSD) using the pipette method (Gee and Bauder, 1986) and organic matter content by weight loss on ignition (Donkin, 1991). Soils were not acidified to remove carbonates. Additionally, the THAL-REP samples were analyzed for biogenic silica (Hallmark, *et al*., 1986).

After the sampling was conducted and soils/landscapes observed, a representative soil location was chosen for each cover class (Figure 3-5). At each representative

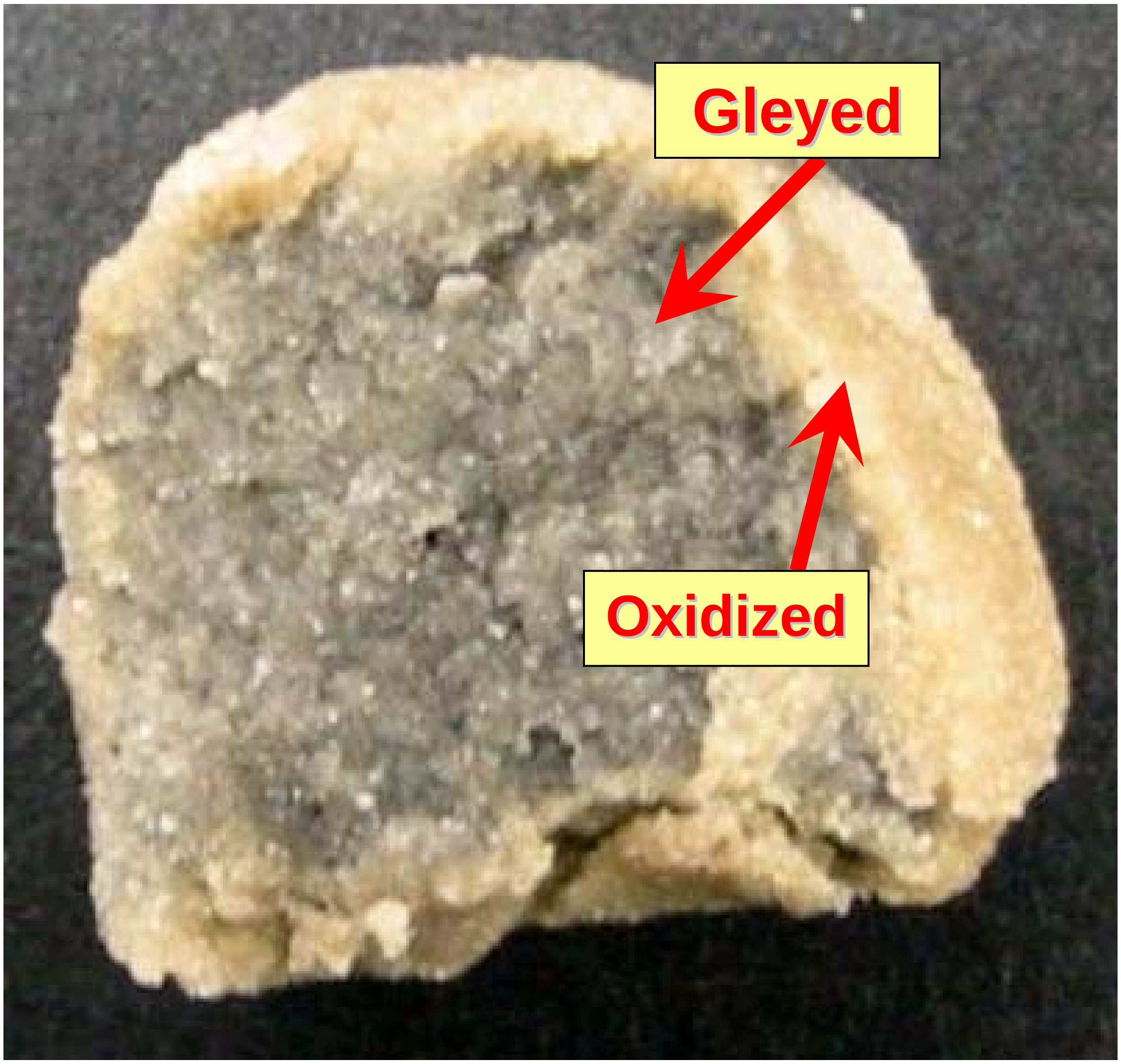


Figure 3-4. Example of a ped from the C horizon of an unvegetated subtropical subaqueous soil showing the oxidized exterior and gleyed (reduced) interior. The ped was immediately removed from the soil after sampling and exposed to air for 30 min prior to sectioning. Note the gleyed colors in the interior of the ped and the oxidized colors on the outside of the ped. The entire ped was one color (the gleyed color of the interior) prior to the 30 min of air exposure.

Figure 3-5. Locations of modal upper-pedons respresenting the soils sampled in the different seagrasses. Upper-pedon HAL-T was located on the protected side of a bar that typically occurs on the edge of grassflats adjacent to channels. The vegetative cover was *Halodule wrightii*. Upper-pedon THAL-T was located 30 m away from HAL, in the direction of the grassflat. The vegetative cover was *Thalassia testudinum*. Upper-pedon THAL/SYR-T was located in the interior of a grassflat. The vegetative cover was a mixed stand of *Thalassia* and *Syringodium filiforme*. Upper-pedon UNVEG-T was located on an unvegetated area adjacent to an erosional beach.

location, the in-tact upper-pedon was sampled with the spade and immediately described. Soil descriptions included USDA textural class, which was estimated in the field. After describing an upper-pedon, it was placed in-tact into a plastic tray for storage and transport. After five days of exposure to air, the upper-pedons were photographed and described to document changes in soil color.

Additionally, to investigate the genesis of the OM in soils, a soil supporting a mixed stand of *Thalassia* and *Syringodium* was sampled every 15 cm to a depth of 160 cm. These samples were analyzed for OM content, biogenic silica, particle size distribution (PSD), and C:N ratios. OM and PSD were determined as previously described. Biogenic silica was determined colormetrically (Hallmark *et al*., 1986). C:N ratios were determined from Total Carbon and Total Nitrogen measured using a Costech Model 4010 Elemental Analyzer.

Results and Discussion

Submerged Aquatic Vegetation Mapping

Ground-truth observations revealed that most vegetated areas had a water depth of approximately 10 cm at MLLW. Areas that were slightly exposed (< 20 cm above MLLW) were unvegetated to vegetated sparsely. Areas higher in elevation were not vegetated. The shallow, vegetated areas were arranged as extensive flats. Vegetation was ubiquitous across these flats. Deep areas (> 1 m deep at MLLW) adjacent to the flats were not vegetated. The elevation range of seagrass vegetation was therefore 100 cm below MLLW to 20 cm above MLLW. These areas are referred to as “shallow-vegetated areas”. The areas greater than 100 cm deep at MLLW are referred to as “deep water”. The remaining areas, greater than 20 cm above MLLW, are therefore referred to as “shallow-unvegetated” (Table 3-1).

Table 3-1. Land classification scheme based on water depth.

Water Depth Range (relative to MLLW)	Depth Classification	Soil/Non-soil?
< 20 cm	shallow unvegetated	soil
20-100 cm	shallow-vegetated	soil
> 100cm	deep water	non-soil

Thus, deep water was considered to be any area greater than 1 m deep at MLLW. Shallow water areas were the remainder. For this study, "non-soil" was considered to be unvegetated areas too deep to currently support seagrass growth (Figure 3-6).

A visual analysis of the study area and surrounding areas using the 5-4-3 composite of the Landsat scene revealed that an appreciable amount of the aquatic area was vegetated and thus very shallow at low tide (Figure 3-7). Shallow areas extended from land but also occur as isolated areas. The shallow portions of the study area were dissected by channels of deep water.

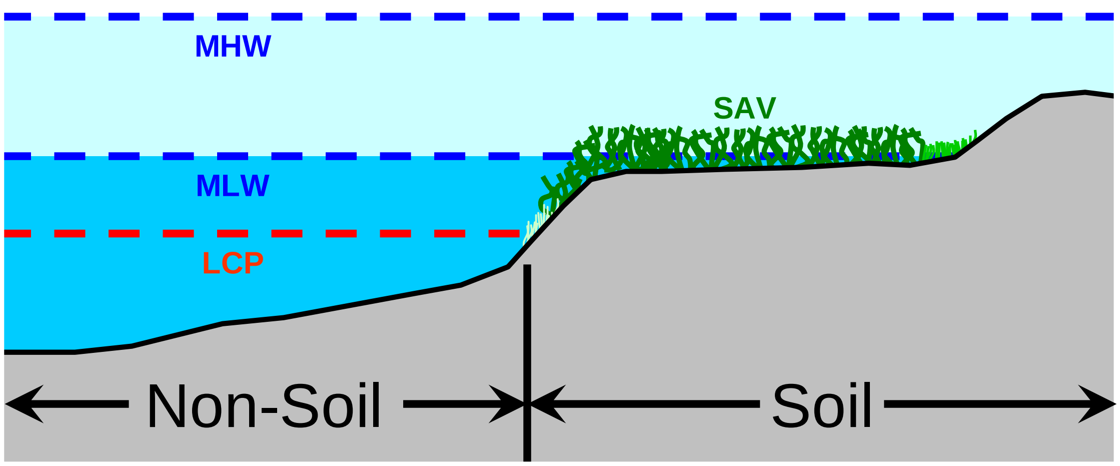


Figure 3-6. Subaqueous landscape showing the waterward extent of soil. The red dashed line is a conceptual representation of light compensation point (LCP) where the soil does not receive enough light to support submerged aquatic vegetation (SAV). The zone between Mean Low Water (MLW) and Mean High Water (MHW) is dominantly unvegetated, however rising sea level may allow for vegetation to spread into these areas.

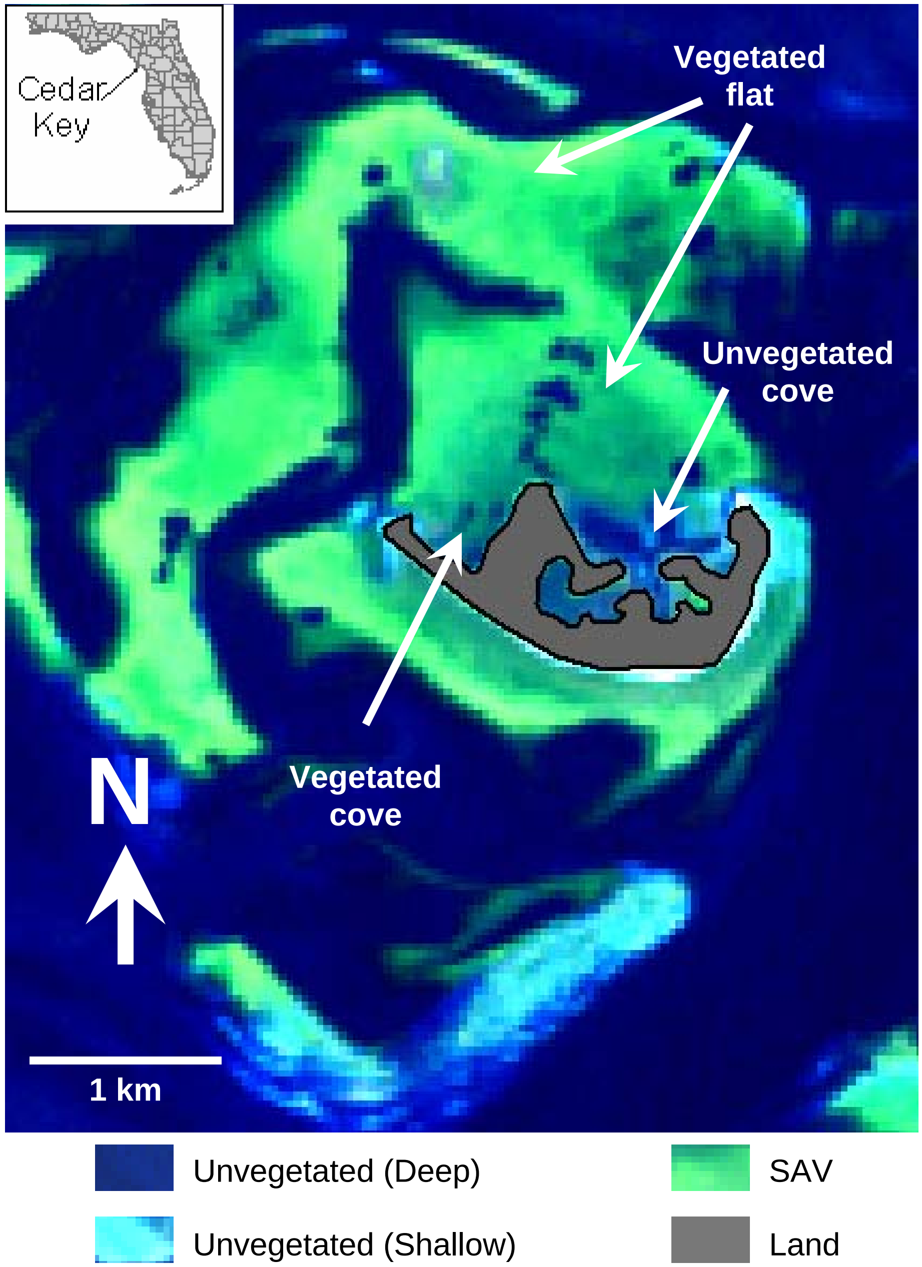


Figure 3-7. Satellite image of study area near Cedar Key, FL showing the classification of vegetation. The basemap is a Landsat 7 ETM+ 5-4-3 composite (November 7, 2002) which was acquired at an extreme low tide. Terrestrial areas mapped by the US Census Bureau are colored grey and the shorelines are outlined in black. The 5-4-3 band composite imparts green colors to vegetated areas. Therefore, green areas in the figure are mostly submerged aquatic vegetation (SAV) beds that are exposed at low tide or under less than ~ 50 cm of water. At normal high tide, the water is 1.5 m higher. Note the presence of seagrass around each of the barrier islands. Some vegetated areas are protected and influenced by the islands while other areas are more isolated from land and thus more exposed to wind and waves. Darker blue areas are deep water and light blue or white areas are shallow sand bars.

Visual inspection of the seagrass flats at MLLW revealed that seagrass coverage was extensive and dense in most shallow, open portions of the study area away from Seahorse Key. There are two coves, one was vegetated and one unvegetated. The unvegetated cove had deeper water than the flats. Where it merged with land, it supported a salt marsh community. The vegetated cove was similar in elevation to the flats (Figure 3-7). Vegetated areas ranged in water depths from 20 cm above water at MLLW to 100 cm at MLLW. No vegetation was observed in the areas deeper or shallower than the flats. At MLLW, it was confirmed that the water level was low enough for the seagrass leaves to be exposed to air.

The NDVI derived from the satellite imagery was also used to classify the aquatic portions of the study area into shallow vegetated, shallow unvegetated, or deep unvegetated. This classification was based on an NDVI threshold of 0.25. This value was determined by comparing NDVI values at several locations along the shallow vegetated to deep water transition and the shallow vegetated to unvegetated transition. These points were identified using aerial photography and the coordinates were used to extract the NDVI values from the NDVI map (Figure 3-8). The average NDVI value at the shallow vegetated to deep water transition was 0.23. The average NDVI value at the shallow vegetated unvegetated transition was 0.26. A threshold value of 0.25 was therefore used to identify the shallow vegetated areas. Areas with an NDVI > 0.25 were classified as shallow vegetated. Manual inspection of many shallow unvegetated pixels revealed that NDVI values were not below 0. Therefore areas with NDVI values between 0 and 0.25 were classified as unvegetated. NDVI could not be used to differentiate between shallow unvegetated and the unvegetated fringe slightly deeper than

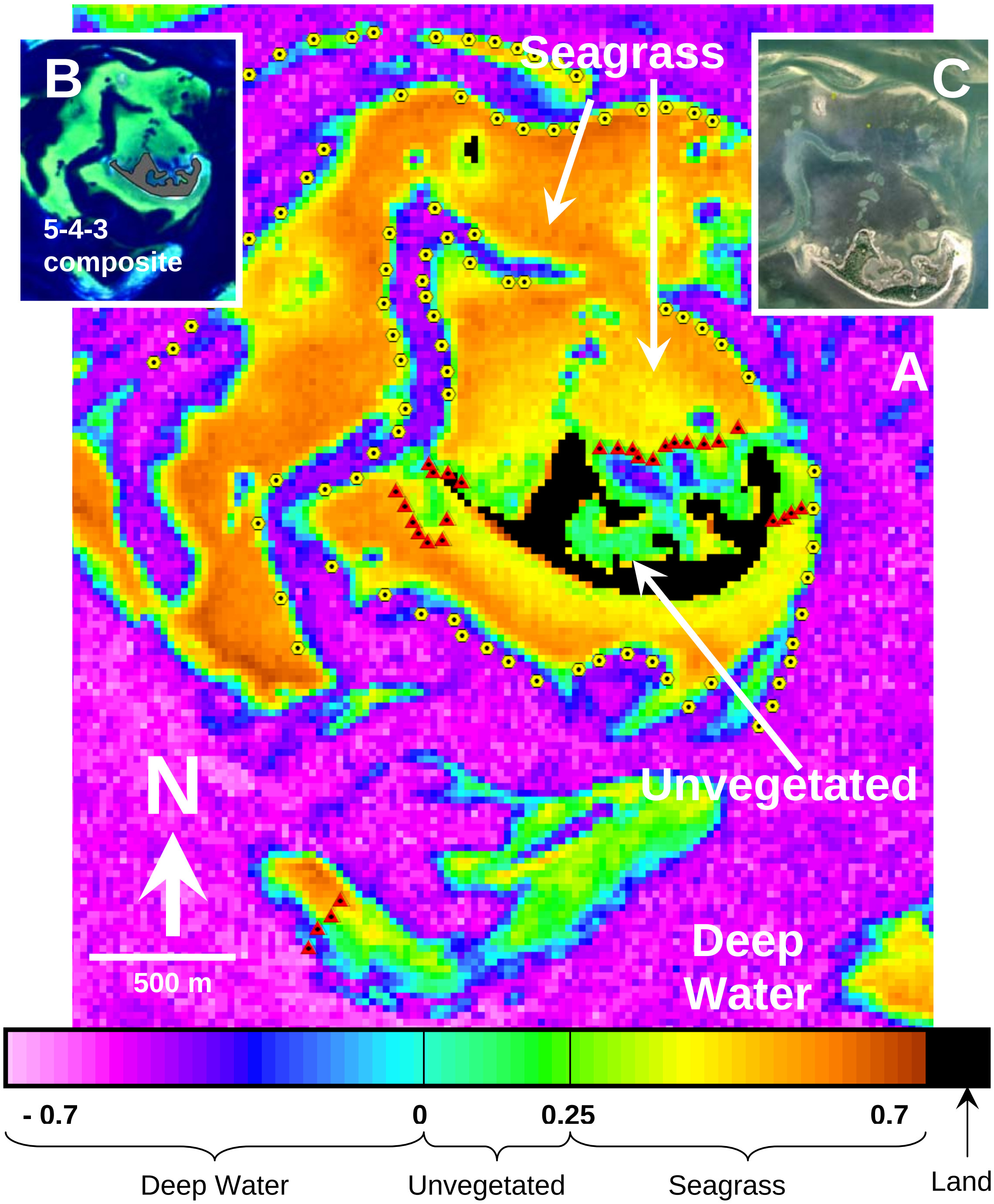


Figure 3-8. Normalized Vegetative Difference Index (NDVI) view of the study area (A) calculated from a Landsat 7 ETM+ scene (B). Generally, seagrasses exist in shallow areas with NDVI > 0.25. The unvegetated areas, both shallow and deep have NDVI values ranging from 0 to 0.25. Deep water areas have NDVI values < 0. Yellow circles represent points at the transition from deep to shallow water. Red triangles represent points at the transition from seagrass to unvegetated These locations were determined visually using aerial photography (C).

the vegetated areas (Figure 3-9). The ratio of shallow area to deep area was 0.23, thus the extent of soil within the study area is 23% of the total aquatic area.

Landscape and Seagrass Patterns

Field observations revealed subtle patterns in the landscape and vegetation. The interior portions of the grass flats were slightly higher in elevation (~10 cm) than the outer portions. The interiors were vegetated with *Thalassia* (Figure 3-10) while outer portions of the flats were vegetated with a mixed stand of *Thalassia* and *Syringodium* (Figure 3-11). *Thalassia* displayed a phenotypic plasticity with shorter blades where it occurred in the shallow, inner portions of the flats and had longer blades where it occurred in the deep, outer portions of the flats. The edges of the flats sharply graded in elevation to deep, unvegetated areas (Figure 3-12).

Along some channel edges and near some shores of Seahorse Key raised bars occurred. The shallowest portions of the bars were more than 20 cm above MLLW and were unvegetated. The deep portions of the bars were a few cm above and below MLLW. These deeper areas were sparsely vegetated with *Halodule*. Adjacent to and a few cm lower in elevation than the bars, were areas of dense *Halodule* (Figure 3-13). Adjacent to those areas and grading down into the flats were areas of monotypic, short-bladed *Thalassia*. These bar-to-flat transitions of landscape and vegetation were consistent for most of the flats that were adjacent to channels. Within a range of elevation of 20 cm above MLLW and 1 m below MLLW, SAV was ubiquitous. Some small patches of unvegetated soil occurred in the grass beds, but these were of minor extent.

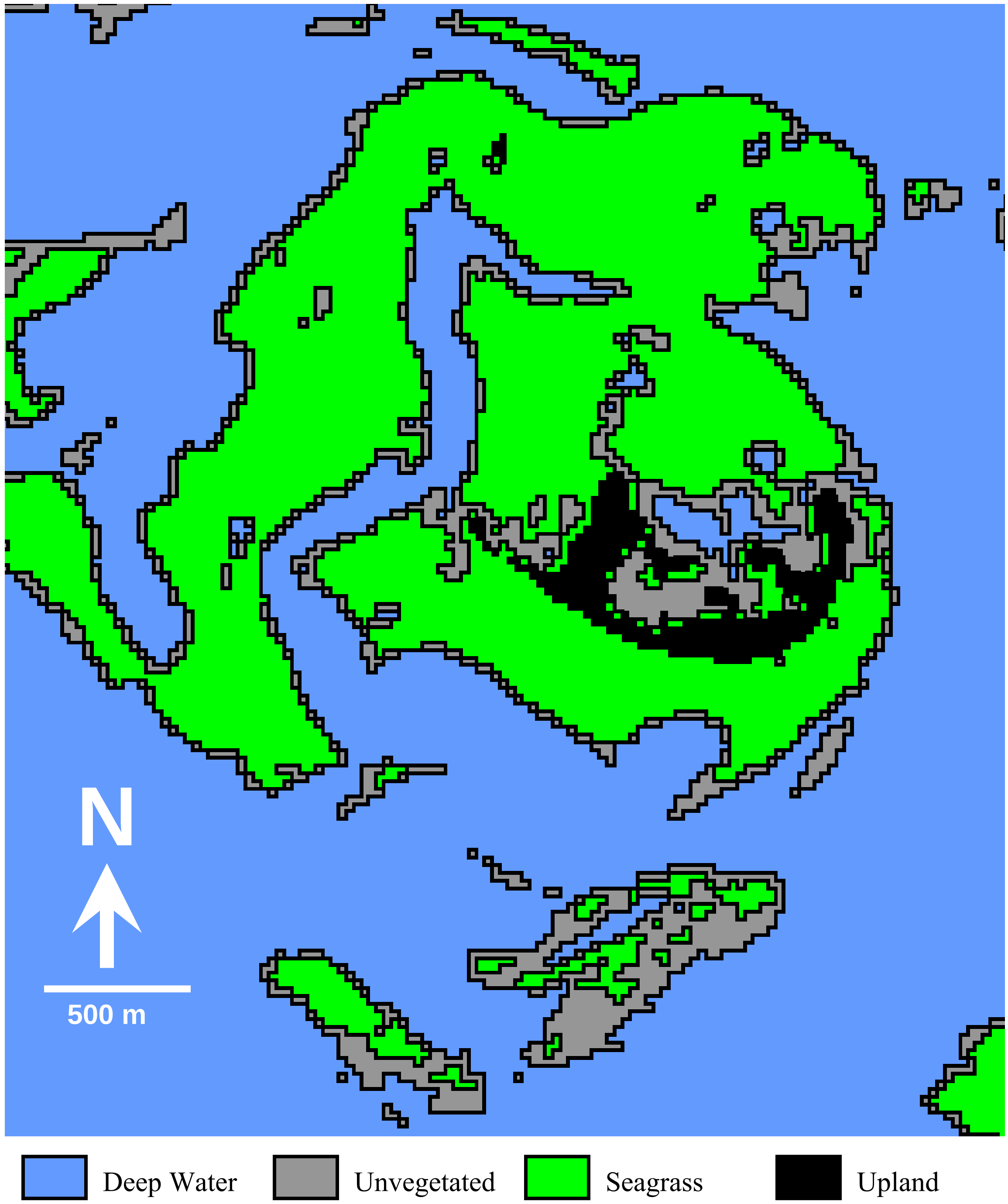


Figure 3-9. Benthic classification of the study area. The classification was conducted using a Normalized Vegetation Difference Index (NDVI) calculated from a Landsat 7 ETM+ scene acquired at low tide. The following NDVI ranges were used: Deep water (< 0), Unvegetated (0 to 0.25), and Seagrass (> 0.25). Upland areas were not included in the analysis.

Figure 3-10. Monotypic stands of *Thalassia testudinum* growing on a shallow flat near Cedar Key, FL. Pictures were taken at mean low water. A) Long grass blades. B) Short grass blades.

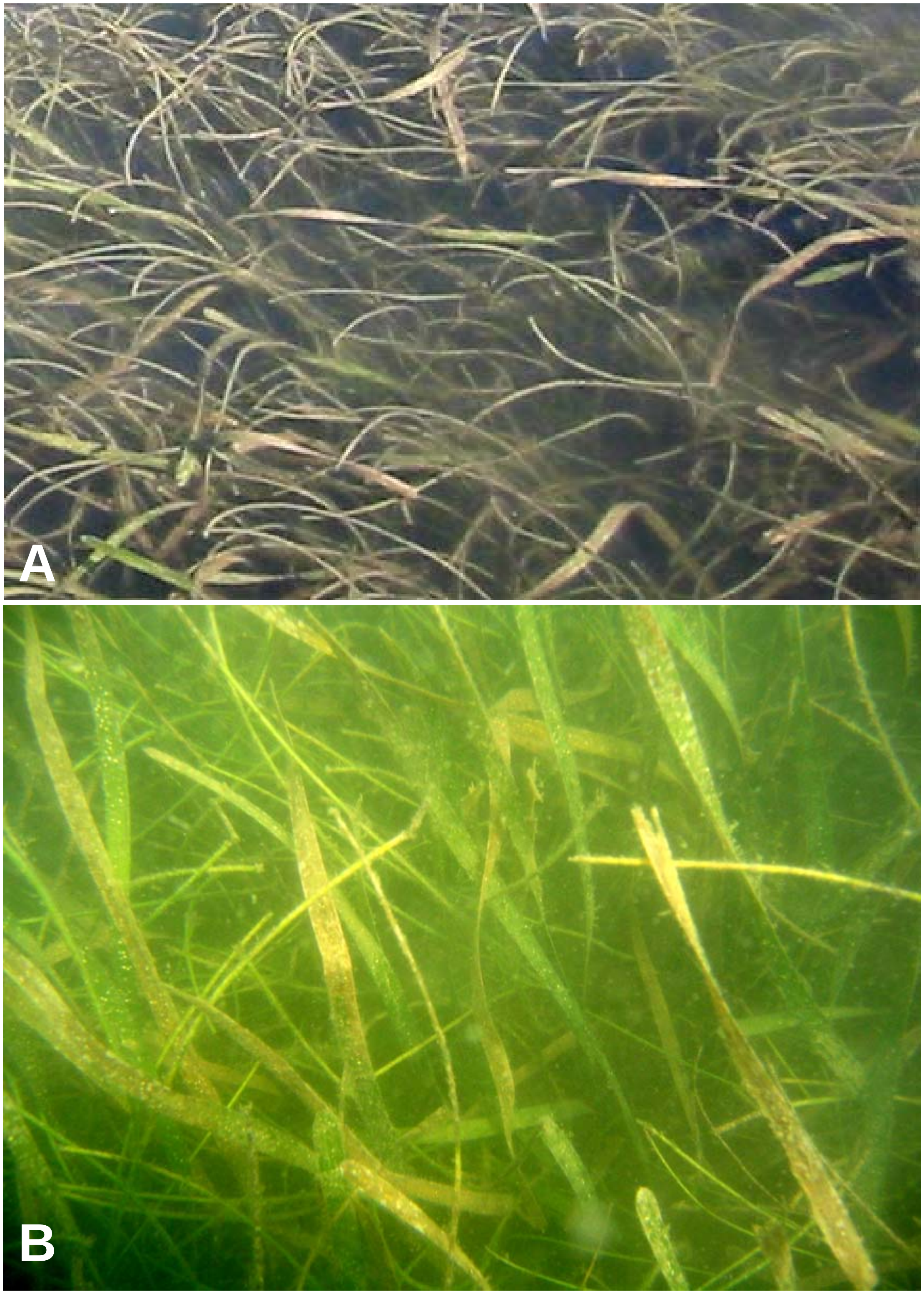


Figure 3-11. Mixed stand of *Thalassia testudinum* and *Syringodium filiforme* growing on a shallow flat near Cedar Key, FL. Pictures were taken with water elevation 50 cm above mean low tide. Photograph A was taken above water and photograph B was taken below water.

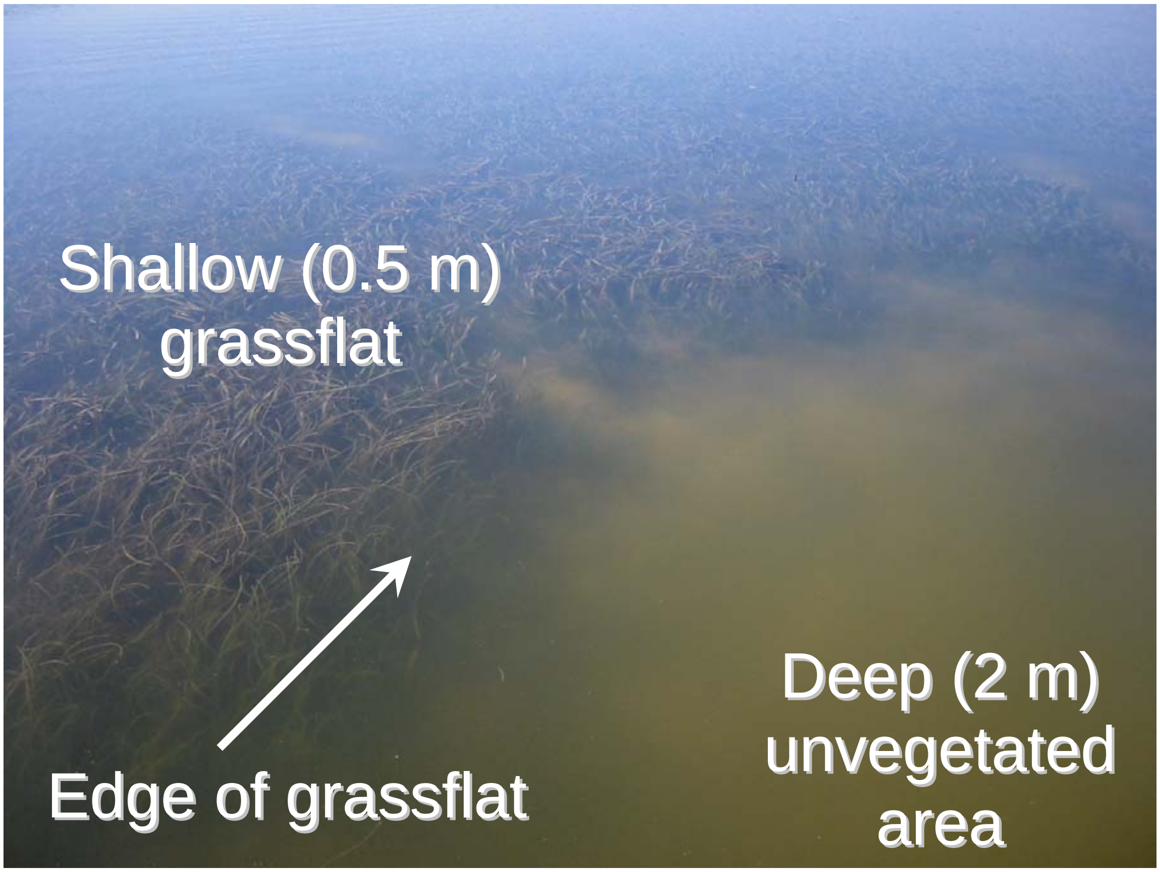


Figure 3-12. Typical edge of a shallow seagrass flat near Cedar Key, FL. Vegetation is a mixed stand of *Thalassia testudinum* and *Syringodium filiforme*. The picture was taken with a water depth 50 cm above mean low tide. The lower right portion of the picture is typical of the deep, unvegetated areas that exist on the edge of the grass flats.

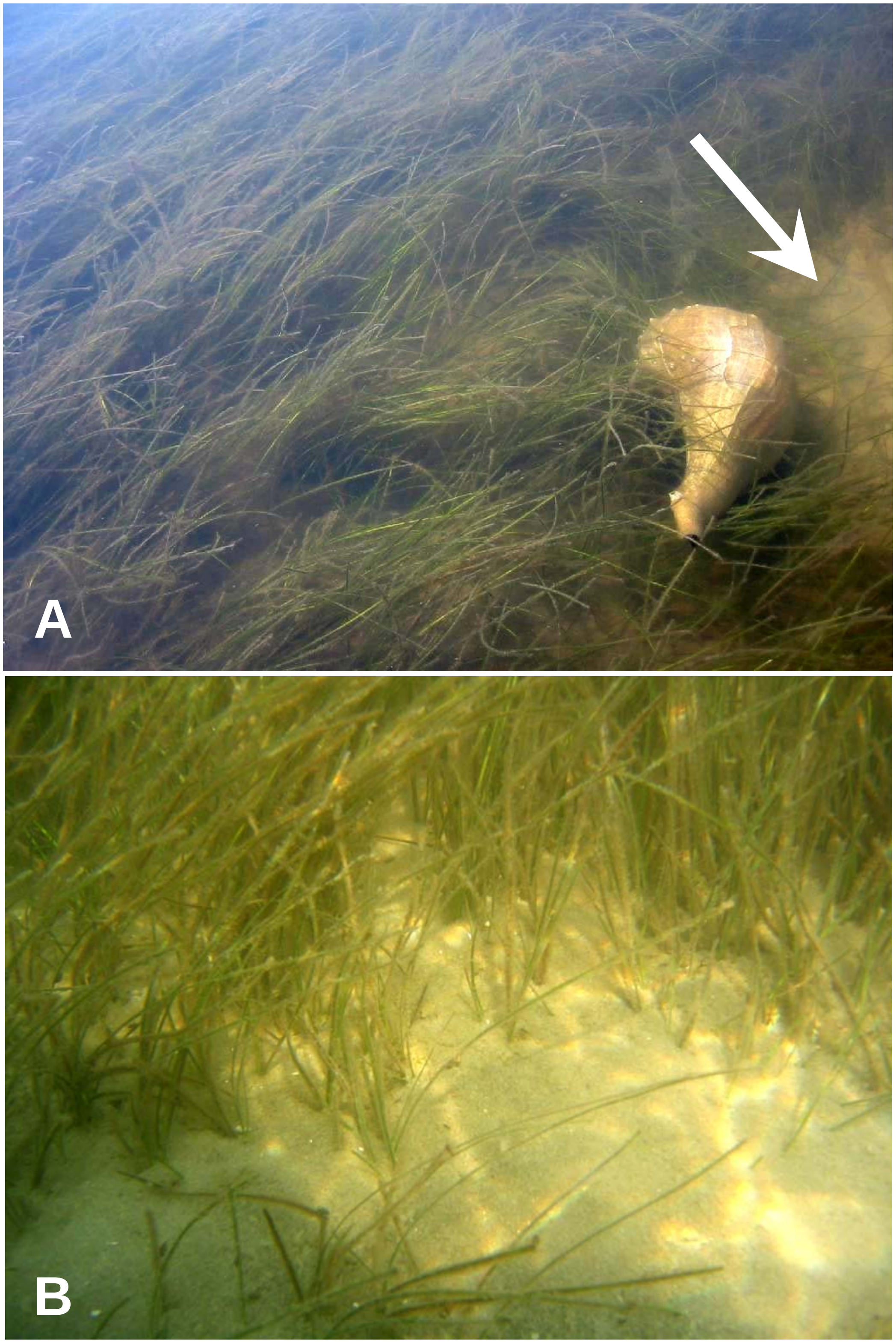


Figure 3-13. Monotypic stand of *Halodule wrightii* growing on a raised portion of a shallow flat near Cedar Key, FL. A) the grass bed shows the dense coverage of *Halodule*. The white arrow in A points to the location of the underwater picture (B).

Upper-Pedon and Vegetation Relationships

The three soils sampled at each site were analyzed for OM content and PSD. These data were averaged to provide a composite estimate of soil properties at each site (Appendix A-1). Soil color(s) was also described. It is possible to average Munsell® color parameters. For example, the average Munsell® color of the five UNVEG samples in Appendix A-1 is 4.0Y 6.8/1.0. The closest Munsell® color chip available for visual comparison is 5Y 7/1. The parameters of this chip are determined by rounding the average parameters. Hue is rounded from 4.0 to 5, value is rounded from 6.8 to 7, and chroma is rounded from 1.0 to 1. This is done simply to provide a Munsell® color that is available in the Munsell® color book to accompany the average soil properties reported in Table 3-1.

The chroma values for all sites were either 1 or 2, except for one site which had a chroma of 3 (Appendix A-1). The soil values, however, ranged from 2.5 to 7. Soils, therefore, ranged from dark to light, low chroma colors. Soil color value was negatively correlated with OM content (Figure 3-14) and silt content (Figure 3-15a), but positively correlated with sand contents (Figure 3-15b).

While no quantitative assessment of above seagrass biomass, blade length, or percent cover was conducted, it was evident in the field that HAL areas had the shortest blades, lowest percent cover, and lowest above-ground seagrass biomass. THAL had a moderate blade length, percent cover, and above-ground seagrass biomass. THAL/SYR had the greatest blade length, percent cover, and above-ground seagrass biomass.

The sand and OM contents were negatively correlated (Figure 3-16a) while the silt and OM of contents were positively correlated (Figure 3-16b). Care must be taken when interpreting PDS values, however, because clay contents were very low for all soils

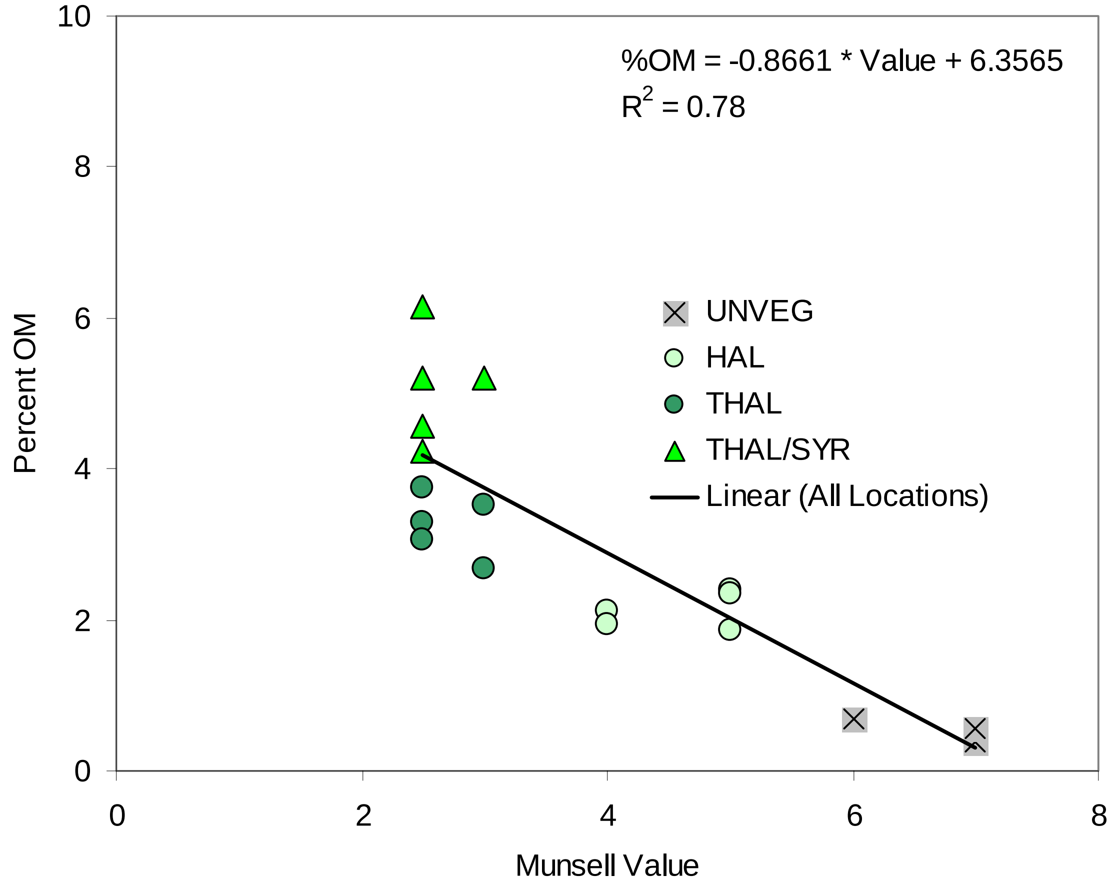


Figure 3-14. Negative relationship between OM content and soil color value. The clustering of points at a value of 2.5 is an artifact of the visual soil color technique. The 2.5 value color chip is the lowest value on the 5Y and 2.5Y pages in the Munsell® Color book (Gretag/Macbeth, 2000), thus soil colors darker than this chip were assigned a value of 2.5. Ground cover class abbreviations: unvegetated (UNVEG), *Halodule* (HAL), *Thalassia* THAL, and *Thalassia*/*Syringodium* (THAL/HAL).

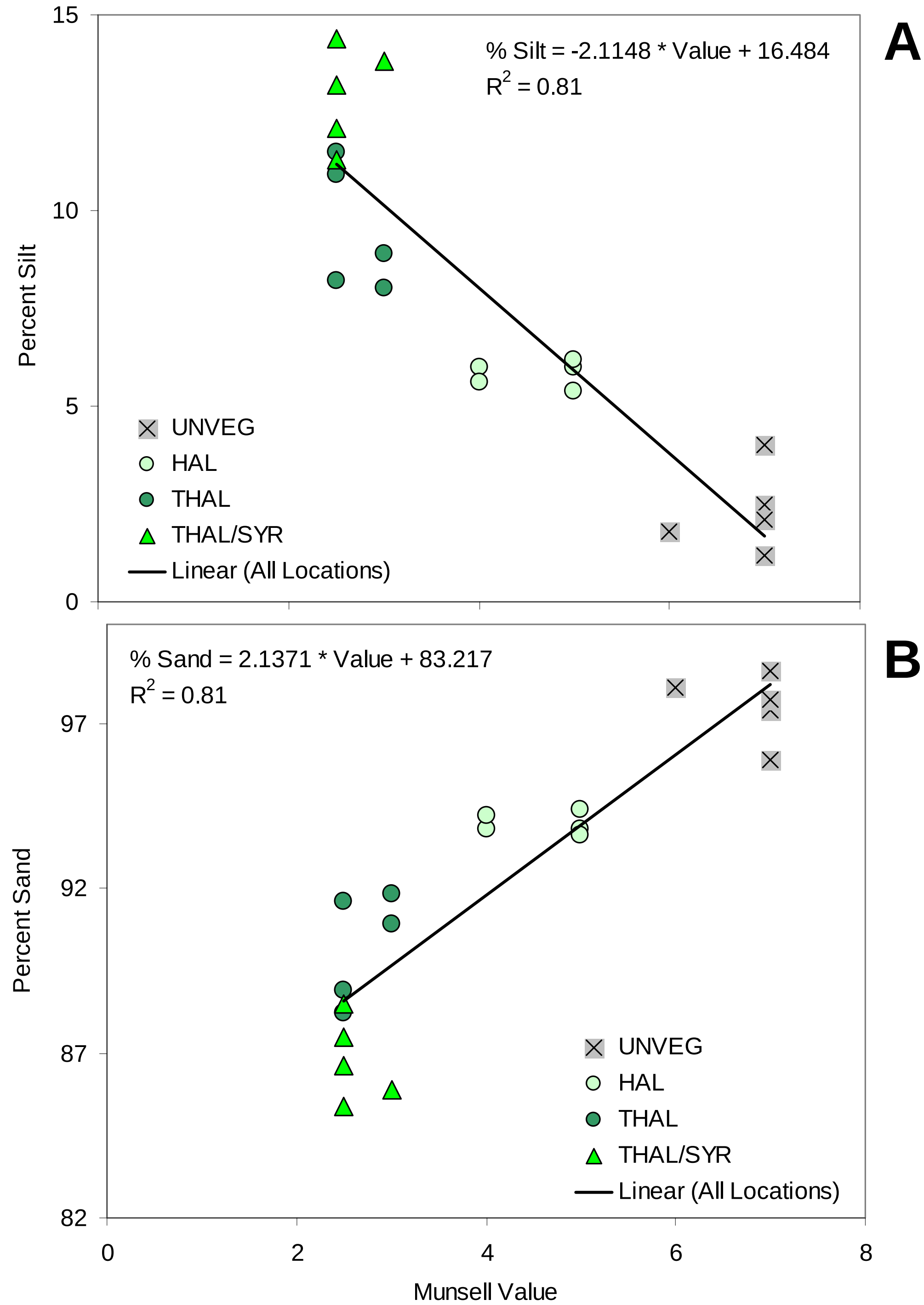


Figure 3-15. Relationship between silt and sand contents related to soil color. Note that silt (A) and sand (B) show equally as strong but opposite linear relationships with soil color value. Ground cover class abbreviations: unvegetated (UNVEG), *Halodule* (HAL), *Thalassia* THAL, and *Thalassia*/*Syringodium* (THAL/HAL).

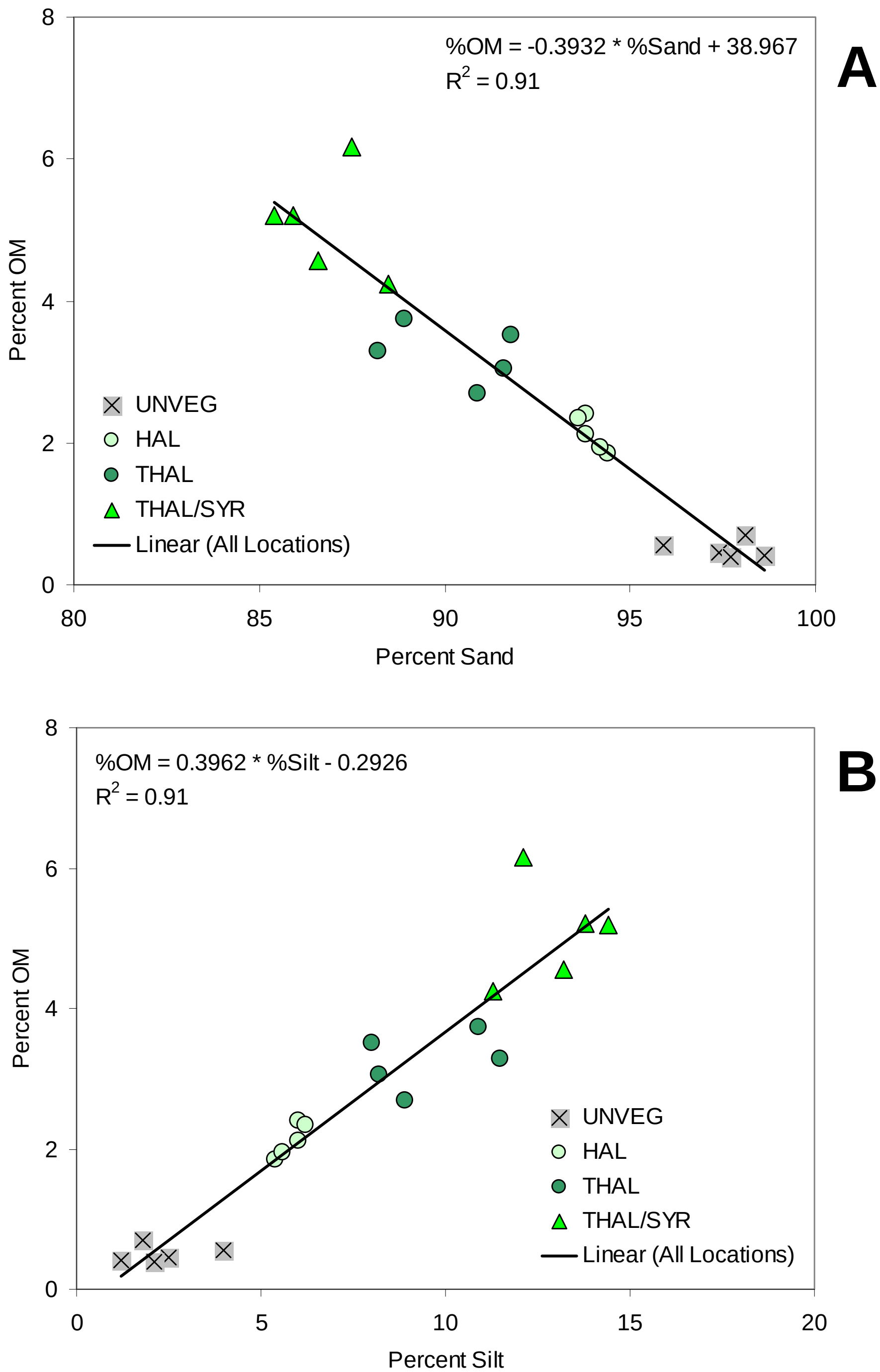


Figure 3-16. Strong linear relationship between the amount of OM in the soil and percent sand (A). An inverse relationship exists with percent clay (B). Ground cover class abbreviations: unvegetated (UNVEG), *Halodule* (HAL), *Thalassia* THAL, and *Thalassia*/*Syringodium* (THAL/HAL).

sampled. Because silt was calculated as the residual mass once sand and clay contents had been measured, the sand and silt were strongly correlated for all sites (Figure 3-17). Being a residual, silt would also be sensitive to experimental error. Sand contents, however, are directly measured, so the relationship between sand and OM contents is valid. The strong linear relationships between soil color and OM content and PSD suggest that for this area, soil properties may be confidently inferred simply by observing soil color. If this relationship exists for other subaqueous soils, pedologists can simply observe soil as it occurs in the field and infer the OM contents and PSD values.

Visual inspection of Figures 3-14 through 3-17 reveals strong clustering of soil properties according to seagrass cover class. Therefore, the soil properties of each site (Appendix A-1) were averaged for each seagrass cover class to summarize the soil properties as they relate to seagrass cover type (Table 3-2). To determine the average soil color for each cover class, the hue, value, and chroma of all five sites were averaged, and that average was rounded to the nearest Munsell® color chip. Although Munsell® colors can exist for hue-value-chroma combinations other than those in a Munsell® color book, rounding to the nearest chip provided a single color designation that was consistent with how soil colors are reported.

Moving from one portion of the landscape to another, vegetative characteristics changes from unvegetated to *Halodule* to single stands or mixed stands of *Thalassia* and *Syringodium*. The averages in Table 3-2 show that soil properties therefore grade across the landscape with vegetation. The heavier cover of *Thalassia* and *Syringodium* mixed stands may be contributing to the larger amounts of OM and silt, thus resulting in darker colors in the soil (Table 3-2). Alternatively, the high amounts of OM and silt may

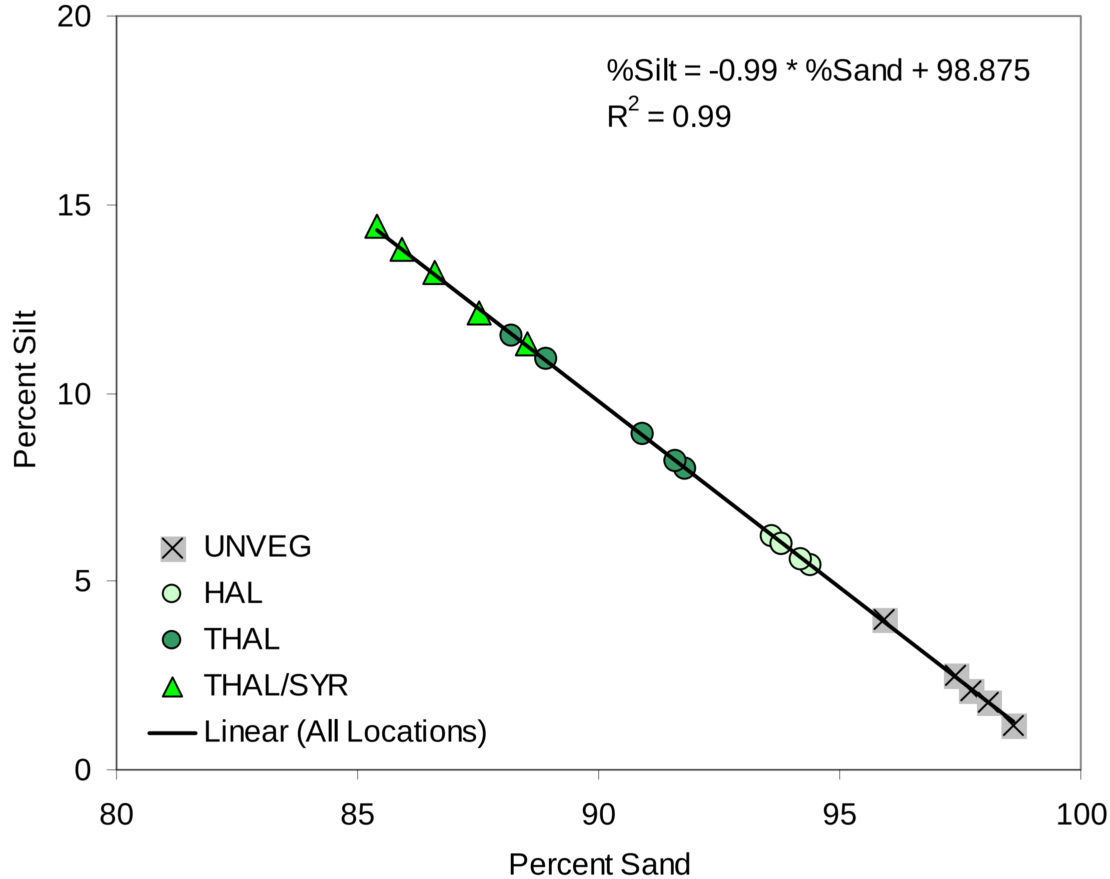


Figure 3-17. Strong linear relationship between the sand and silt contents of all sites sampled. This resulted because silt was calculated as a residual after determining clay and sand contents. Clay contents were very low for all samples. Ground cover class abbreviations: unvegetated (UNVEG), *Halodule* (HAL), *Thalassia* THAL, and *Thalassia*/*Syringodium* (THAL/ HAL).

Table 3-2. Upper-pedon average organic matter content and particle-size distribution for sites located in four seagrass cover classes: unvegetated (UNVEG), *Halodule wrightii* (HAL), *Thalassia testudinum* (THAL), and *Thalassia / Syringodium filiforme* mixed stand (THAL/SYR). Averages are based on five locations per seagrass cover class (See Appendix A-1 for site data). The numbers in parentheses are standard deviations of the five observations.

Cover Class	Estimated Biomass	Organic Matter % by LOI	Particle Size Distribution %			Soil Color Moist Rubbed		
			Clay	Silt	Sand	Hue	Value	Chroma
UNVEG	None	0.5 (0.1)	0.2 (0.1)	2.3 (1.1)	97.5 (1.0)	5Y	7	1
HAL	Low	2.1 (0.2)	0.2 (0.0)	5.8 (0.3)	94.0 (0.3)	2.5Y	5	2
THAL	Medium	3.3 (0.4)	0.2 (0.0)	9.5 (1.6)	90.3 (1.6)	2.5Y	3	1
THAL/SYR	High	5.1 (0.7)	0.2 (0.0)	13.0 (1.2)	86.8 (1.2)	2.5Y	2.5	1

encourage the growth of thick cover plants. In either case, the following generalizations can be made:

- The upper-pedon of soils are related to the vegetation they support.
- Soil OM increases as the vegetative biomass increases.
- Percent silt increases as the vegetative biomass increases.

Upper-pedon Soil Morphologies

Detailed investigations of the morphologies of soils occurring at the modal locations (Figure 3-5) revealed that the patterns of colors are related to seagrass species. The UNVEG-T soil was similar in oxidized color to the soils on the nearby land (Seahorse Key), a likely source of sedimentary material to the subaqueous environment. The colors of the soil were 5Y 7/1 when immediately sampled (Figure 3-18a), but changed to 10YR 7/4 when oxidized (Figure 3-18b). No OM, roots, or shells were visible within the upper-pedon. The USDA Soil Survey Report for Levy County, FL (Slabaugh *et al.*, 1996) depicts Orsino, a hyperthermic, uncoated, Spodic Quartzipsamment, as the dominant soil on the island. The Bw horizon (94 cm to 175 cm depth) was reported to have a color of 10YR 7/6 while the C horizon (> 175 cm depth) was reported as 10YR 7/4. The similarity in soil color between the unvegetated areas and the Orsino on the adjacent island indicates the soils of the island are most likely a contributor of parent material via erosion to these unvegetated soils.

The HAL-T soil occurring in the areas vegetated by *Halodule* had a matrix color of 2.5Y 6/1 when reduced and 10YR 7/2 when oxidized. Light areas (5Y 7/1 reduced;10YR 7/3 oxidized) and dark areas (5YR 3/1 reduced; 10YR 3/1 oxidized) were apparent throughout the upper-pedon (0 to 10 cm). The colors of the upper-pedon increased in value and chroma upon exposure to air along with changing to a redder hue, but retained

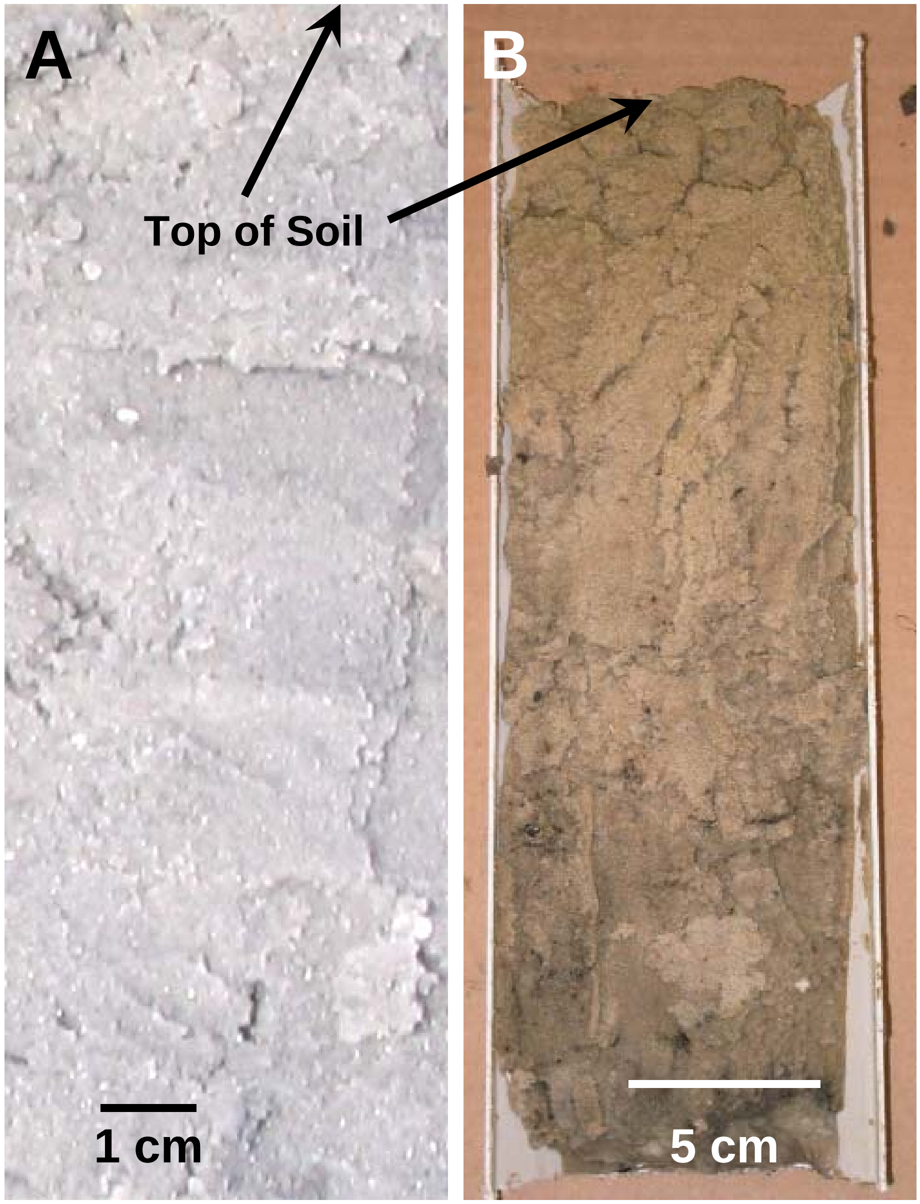


Figure 3-18. Upper-pedons of a soil occurring at location UNVEG-T: a shallow unvegetated area adjacent to an erosional beach on Seahorse Key. The photograph on the left (A) was taken immediately after the soil was retrieved, therefore colors are of the moist soil in its natural state. The photograph on the right (B) was taken of moistened soil, one day after the soil sampling. Therefore colors are of the moist soil in its oxidized state. The colors closely resemble those of the sands from the adjacent land, Seahorse Key. No evidence of pedogenesis is evident within the soil. The soil was extracted 20 m from a mangrove tree that had begun to take root. Thus potential support for vegetation was offered by this soil.

the contrast between matrix, light, and dark areas. Generally, the dark areas occurred as small spheroid or cylindrical areas, occupying less than 50% of the total area of a soil profile. Typically, the spheroids were a few mm in diameter while the cylindrical dark areas were a few mm in diameter and a few cm in length.

The THAL-T location was 30 m from the HAL-T location. The soil was vegetated with short-bladed *Thalassia*. The oxidized and reduced colors of the upper-pedon were identical to those in the HAL-T soil. The pattern of dark and light areas was also similar, but the dark areas were more numerous, typically occupying up to 70% of the area in a profile. This gave the soil a dark appearance in its oxidized (Figure 3-19) and reduced states (Figure 3-20). The greater volume of darker soil when compared to HAL-T (Figure 3-21) is probably the reason for differences in average value along with average OM, silt, and sand contents between the HAL and THAL soils.

The THAL/SYR-T soil was dark in matrix color (5YR 3/1 reduced; 10YR 3/1 oxidized) throughout the upper pedon (Figure 3-22 for reduced colors and Figure 3-23 for oxidized colors). Of minor extent in the upper-pedon were small areas of light color soil (5Y 5/1 reduced; 10YR 6/2 oxidized). Mollusk shells were observed through the upper-pedon, possibly indicating a large amount of bioturbaton or sedimentation. Clams are burrowing organisms, so the presence of clam shells suggested bioturbation was taking place resulting in light colored areas in the soil. Scallops reside on the benthic surface, therefore the presence of these shells throughout the upper-pedon suggest past soil surfaces were buried through sedimentation.

Combined, the lab and field data show that OM and silt contents are high where dense beds of seagrass (mixed stands of *Thalassia* and *Syringodium*) are rooted in the

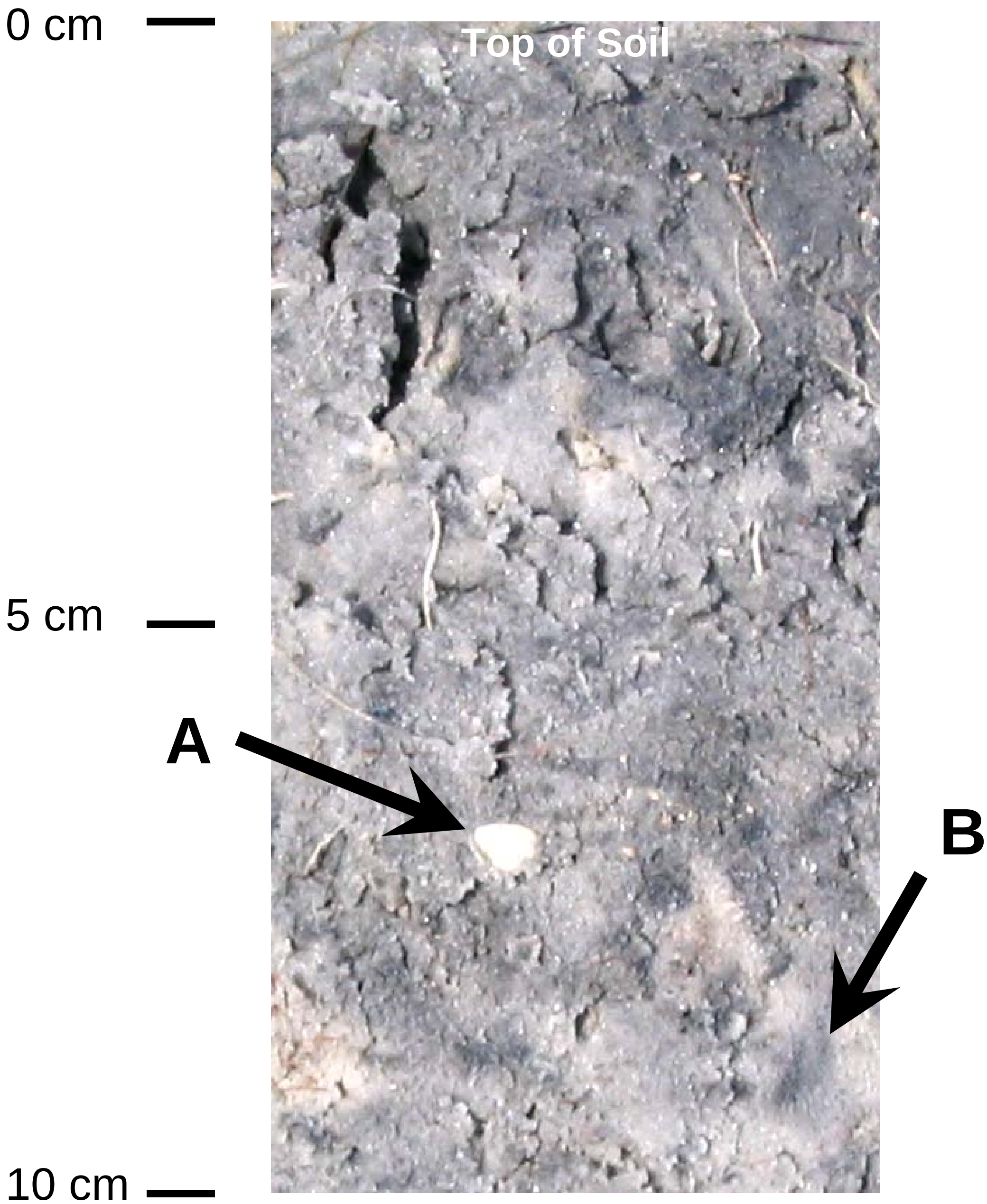


Figure 3-19. Upper-pedon of a soil occurring at location HAL-T: a soil occurring on a bar near Cedar Key, FL vegetated with *Halodule wrightii*. Note the polychromatic nature of the soil. A shell is visible about 7 cm deep in the soil (A), probably indicating bioturbation as a possible reason for the intermingled colors. Diffuse boundaries exist between the dark splotches and the lighter matrix (B). This indicates a gradient of material (e.g., organic matter) within the soil. Dead roots are also apparent within the profile, possibly contributing to soil organic matter. Near Cedar Key, this morphology seems to be consistent with the presence of *Halodule wrightii*. This photograph was taken immediately after the soil was sampled. Therefore, colors are of the moist soil in its natural state.

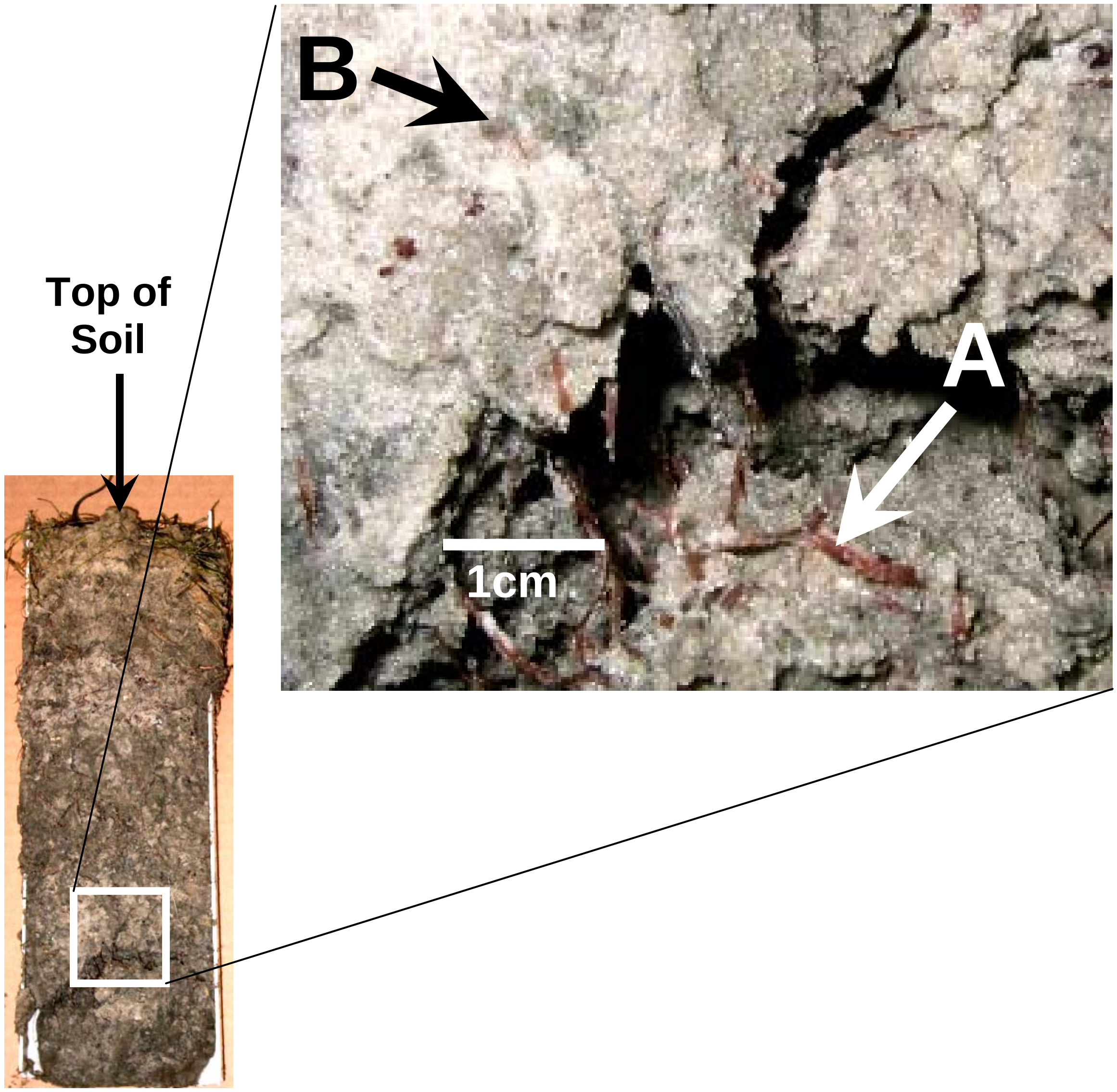


Figure 3-20. Oxidized upper-pedon of a soil occurring at location HAL-T: a soil occurring on a bar near Cedar Key, FL vegetated with *Halodule wrightii*. The red streaks are dead *Halodule* roots. The dark splotch (B) located within the lighter portion of the matrix is a feature common to soils associated with *Halodule*. These features seem to most frequently occur in and around live or dead roots (A). Where occuring below the rooting zone, they are not necessarily accompanied by visible dead roots. This photograph was taken after the soil had been exposed to air for a week. Therefore, colors are of the soil in its oxidized state.

Figure 3-21. Side-by-side comparison of upper-pedons from HAL-T (A) and THAL-T (B) soils. These soils occurred on a bar near a channel. Note the polyvalue appearance of both soils. The matrix color and color of dark and light areas are identical in both soils. There is a higher concentration of dark areas in B. This photograph was taken after the soil had been exposed to air for a week. Therefore, colors are of the soil in its oxidized state.

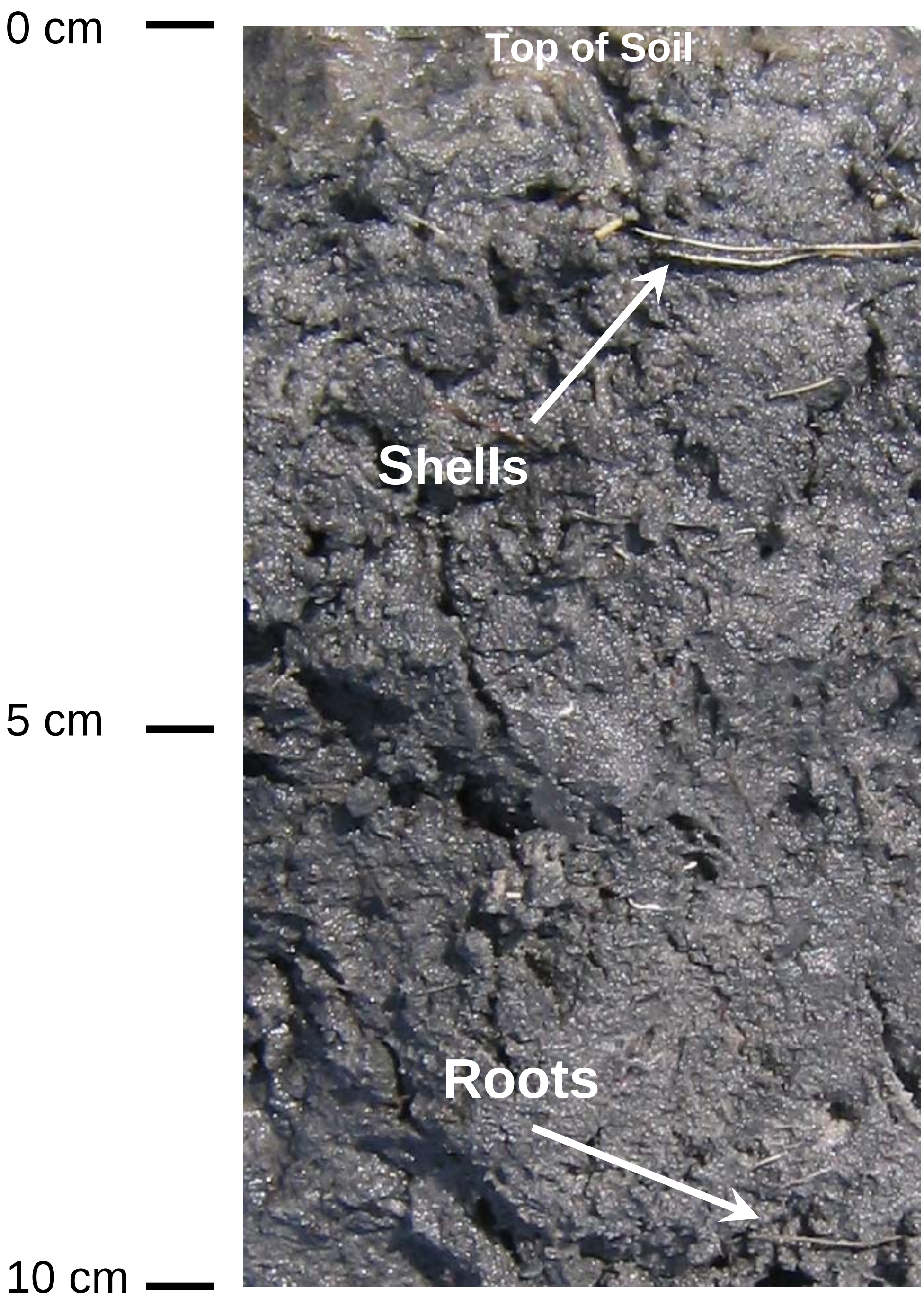


Figure 3-22. Upper-pedon at location THAL/SYR-T: a soil occurring underneath a mixed stand of *Thalassia testudinum* and *Syringodium filiforme* near Cedar Key, FL. Note the dark colors throughout the soil. Shells and dead roots are visible in the soil suggesting bioturbation from the mollusks and rooting throughout the upper 10 cm by the seagrasses. This soil appears to be typical of flats supporting a mixed stand of *Thalassia* and *Syringodium*. This photograph was taken immediately after the soil was sampled. Therefore, colors are of the soil in its natural state.

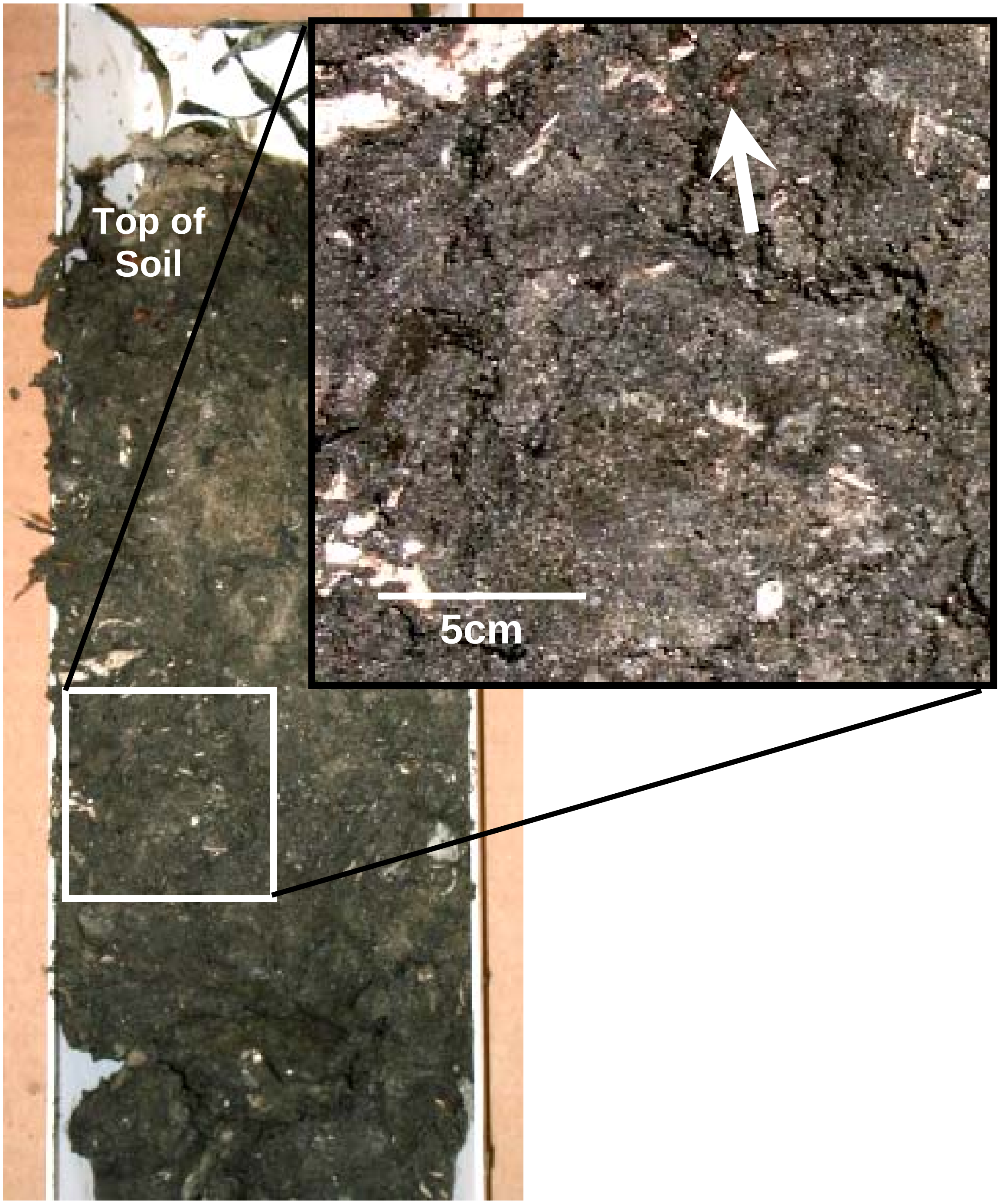


Figure 3-23. Oxidized upper-pedon of a soil occurring at location THAL/SYR-T: a soil occurring underneath a mixed stand of *Thalassia testudinum* and *Syringodium filiforme* near Cedar Key, FL. Note the dark colors throughout the soil. Some linear streaks are evident within the soil as are mollusk and clam shells. The yellow arrow points to dead roots that occur throughout the soil. This photograph was taken after the soil had been exposed to air for five days. Therefore, colors are of the soil in its oxidized state.

soil. The dark colors values of the soil reflect the high concentrations of OM and silt. Sparse vegetation (*Halodule* and monotypic *Thalassia*) are associated with moderate amounts of silt and OM. The light color values compared to soils supporting dense vegetation reflects the low concentrations of OM and silt. The unvegetated areas are devoid of rooted seagrasses and almost devoid of concentrations of OM and silt. The extremely light soil color values reflect this.

Subaqueous A Horizons

The upper-pedons of all vegetated soils are dark in color and have elevated levels of OM compared to the unvegetated soils. It appears as if these soils have A horizons. Much discussion has been made of A horizon formation in terrestrial soils (Dokuchaev, 1883; Simonson, 1959; Soil Survey Staff, 1975; Soil Survey Staff, 1993) resulting from rooted plants that add biomass (e.g., roots, leaves) to the soil. The A horizon concept is fundamental to soil science. One can assume that most terrestrial soils supporting vegetation will have an A horizon. For the purposes of this research, it will be assumed that these horizons are A horizons. The presence of rooted vegetation and elevated OM within the rooting zone support this assumption. To demonstrate that these horizons are A horizons and not just organic rich C horizons, the genesis of the upper-pedons must be studied.

Genesis of Upper-Pedon Organic Matter

Silt-sized particles and OM were related for the upper 30 cm of all soils sampled (Figure 3-16b). These soil properties were also related to seagrass cover, suggesting the OM and silt were derived mainly from the trapping and settling. If the nature of the silt-sized particles was planktonic, and if that is where the soil OM originated from, then the concentration of biogenic silica (from diatoms) in the soil would be related to soil OM. Therefore, the biogenic silica in selected soils was studied.

Biogenic silica: Depth trends in silt, biogenic silica, and OM contents are shown in Figure 3-24 for a representative soil occurring at a random location that supported mixed stand of *Thalassia* and *Syringodium* (29^{o}6’36”N, 83^{o}4’12”W). Silt, biogenic silica, and OM all fluctuate similarly within the pedon. Statistically, OM content is positively correlated with biogenic silica (R^2 = 0.74) and with silt content (R^2 = 0.68) for this pedon. The OM / silt relationships of the upper-pedons from the UNVEG, HAL, THAL, and THAL/SYR sites along with this relationship between OM, silt, and biogenic silica suggest that OM is caused by the trapping and binding of silt-sized biogenic silica particles. These particles are likely plankton.

A Young Soil: On the unvegetated flat east of Seahorse Key (Figure 3-25a), a circular mound of sand, ~30 m in diameter, had built up from what appeared to be wave action. Similar but non-circular mounds of sand were present throughout the flat, suggesting wave action created these mounds. On MLLW, it was observed that the unvegetated portion of the flat was completely drained except for the area inside the circle. The mound impeded the surface drainage of tide water from within the circle. *Thalassia* was present inside the circle, suggesting that this small portion of the unvegetated flat remained wet enough throughout all tide cycles to support *Thalassia*.

The shape of the unvegetated flat and of the adjacent shoreline suggests that erosion from Seahorse Key to the flat has occurred. In fact, the erosion from the unstable shore to the flat is probably still occurring. Therefore, it can be inferred that the

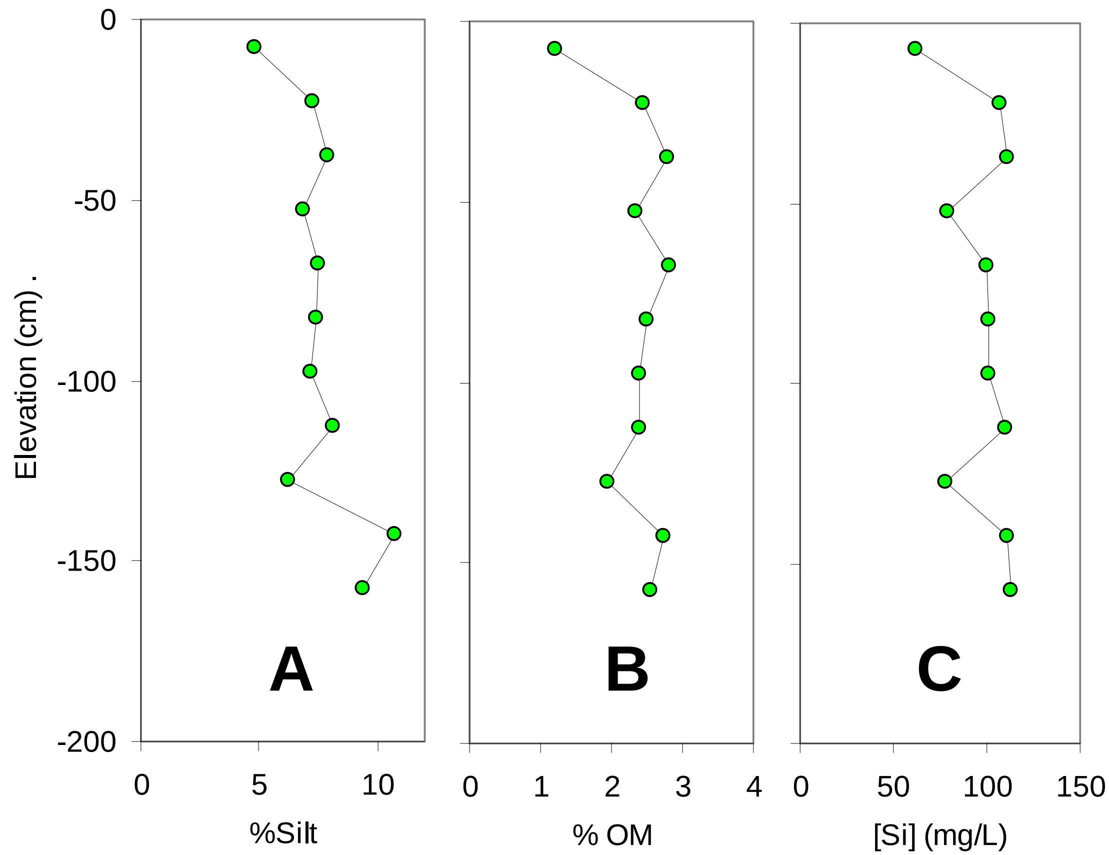


Figure 3-24. Depth distributions of silt (A), Organic Matter (OM) (B), and biogenic silica (C) for a pedon supporting a mixed stand of *Thalassia* and *Syringodium*. Elevations are in cm relative to the soil surface. Note how silt, OM, and Silica (Si) follow similar depth trends.

Thalassia inside the circle has recently colonized the soil. If this is the case, then the morphology of the soil would reflect the effects of *Thalassia* on an unvegetated soil.

In the upper-pedon of this soil, a splotchy pattern similar to those of soils supporting *Halodule* and monotypic *Thalassia* was observed. The amount of dark splotches (approximately 30%) was similar to the amounts of the HAL soils (Figure 3-25 c and d). Like all unvegetated areas observed in this study, the soils of the unvegetated areas adjacent to this soil were devoid of these morphological features.

It can therefore be inferred that *Thalassia* has begun to impart the polychromatic morphology evident in the other vegetated HAL and THAL soils. Bioturbation did not appear to be the cause of these features as no crotovena, and very few macro-invertebrates were observed in the patch of seagrass or in the adjacent unvegetated soil.

It is possible that root processes such as root exudation cause a build up of OM in the rooting zone of the soil. The presence of adhered dark soil areas to the roots (Figure 3-26) combined with the occurrence of these dark features throughout the rooting zone of this and all HAL and THAL soils is evidence that the roots of seagrasses cause these features. These features do not seem to be restricted to a single seagrass species, as they occur within the rooting zone of both *Thalassia* and *Halodule*. The fact that there were less of these dark areas in the rooting zone of a *Thalassia* patch believed to be of recent age could mean that these features build up over time.

Not only do these features seem to be independent of seagrass species, but they are also independent of salinity. An upper-pedon from a subaqueous soil occurring along the fringe of a sandhill lake in Volusia Count, FL. (28^{o}51'58"N, 81^{o}10'49"W) shows these features can occur in terrestrial, fresh water subaqueous soils that support rooted

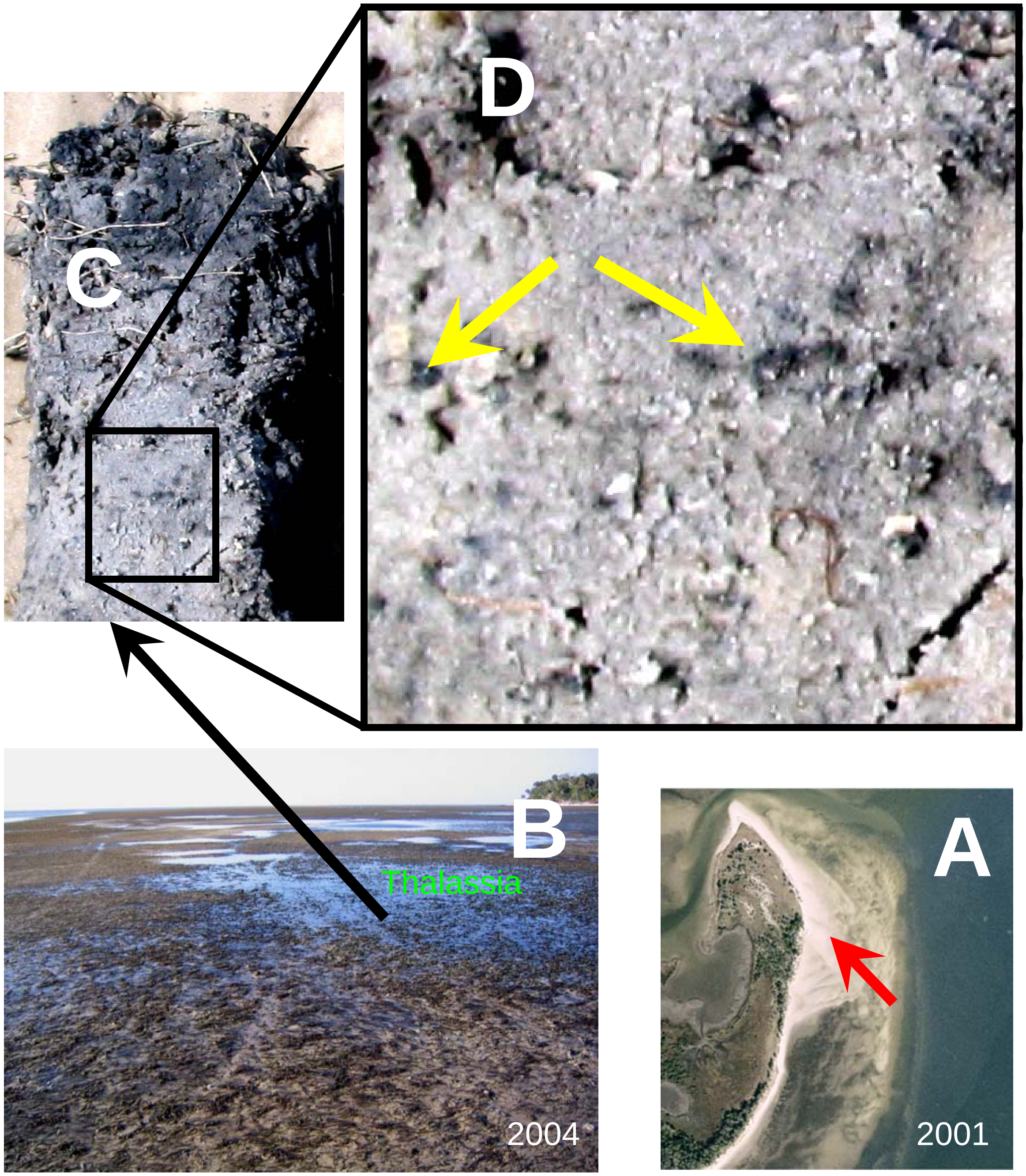


Figure 3-25. Rooting-zone morphology of an unvegetated soil recently colonized by *Thalassia*. The area shown in A was unvegetated in 2001. At some point within the next three years, seagrass colonized the area (B). The soil morphology reflects the age of the soil in that the rooting zone is not as dark as other patches of *Thalassia testudinum* (C). Within the rooting zone, spheroids of darker colored soil were ubiquitous (D). Several more upper-pedons were sampled to confirm this phenomenon and all had similar morphologies. These features are noted in most upper-pedons of *Halodule wrightii* as well, suggesting this is not a species-specific process. These features do not appear to be associated with crotovena from bioturbation.

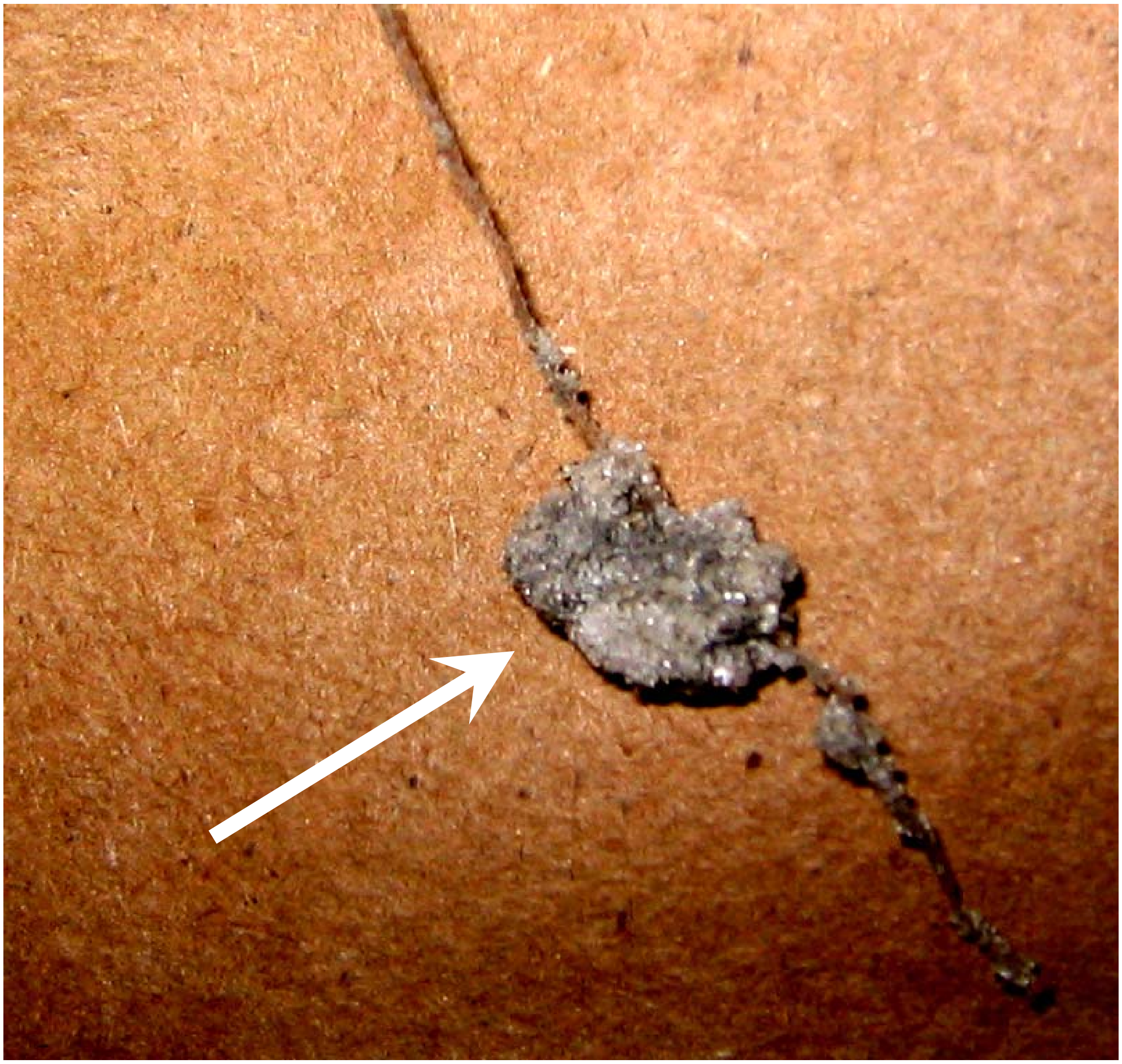


Figure 3-26. Isolated body of dark soil material typically found in the upper-pedons of areas supporting *Halodule wrightii* and areas recently colonized by *Thalassia testudinum*. White arrow points toward the soil.

vegetation (Figure 3-27). The morphological features shown in Figures 3-25 and 3-27 are similar in size, color, and placement within the rooting zone. Like the subaqueous soils near Cedar Key, FL, the texture of this freshwater subaqueous soil shown in Figure 3-27 is sand. This freshwater subaqueous soil is similar to the Cedar Key subaqueous soils in texture (both are sandy), hydrology (both are submerged), and in vegetative cover (both support rooted vegetation). The fact that dark splotches occur in both soils highlights the probability that rooted vegetation cause these features to form in the soil. This is A horizon formation. The nature and distribution of these features in both marine and freshwater subaqueous soils needs to be investigated.

Subtropical Subaqueous Soils: Indicators of Historical Conditions

Further exploration of unvegetated bars along channels revealed the presence of dark (e.g 2.5Y 2.5/1) soil material, similar in morphology to that in the surface soils of HAL, THAL, and THAL/SYR areas. It was hypothesized that these were buried A horizons. To test this hypothesis, aerial photography from 2001 and 1961 were compared to determine the vegetative history of the bars.

These bars were the edges of seagrass flats in 1961 (Figure 3-28 a and b). Expansion of the bar from 1961 to 2001 to cover vegetated areas can be seen in the imagery. Additionally, some areas vegetated in 1961 were near eroding shorelines and, therefore, buried by 2001 (Figure 3-28 c and d). The upper-pedon of the soil that occurs in the area located in Figure 3-28 a and b is shown in Figure 3-29a. The dark colors in the lower portion of the upper-pedon indicate that the area was once vegetated with *Thalassa*. The gradual decrease of dark splotches from deeper portions of the pedon to the top of the soil can be inferred as a gradual burial of *Thalassia* and subsequent

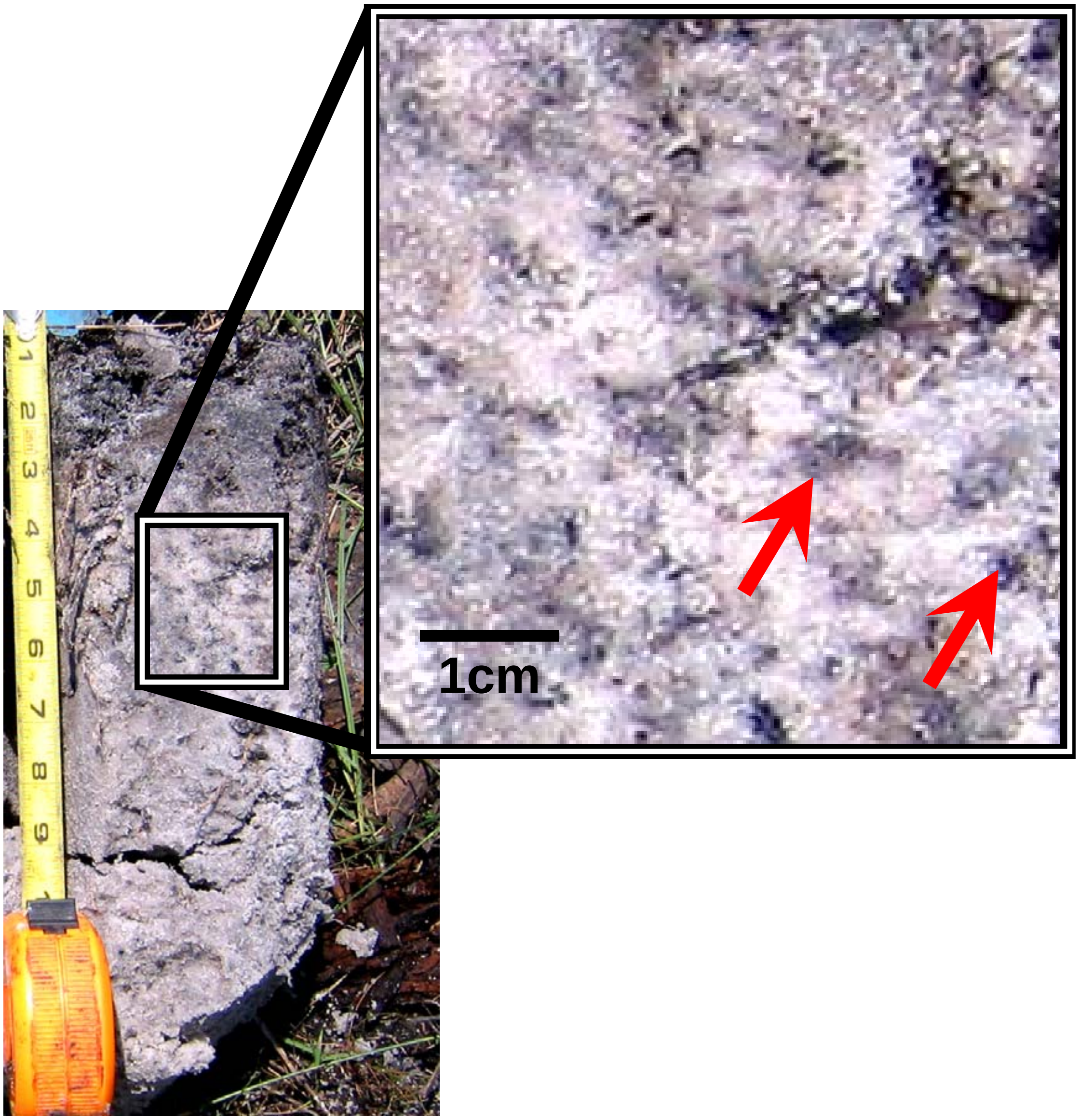


Figure 3-27. Upper-pedon of a freshwater subaqueous soil containing dark bodies. The soil occurs on the fringe of a sandhill lake in Volusia County, FL. These features are typically found in the upper-pedons of areas supporting *Halodule wrightii* and areas recently colonized by *Thalassia testudinum* in Cedar Key, FL. The red arrows point toward the dark features in the soil.

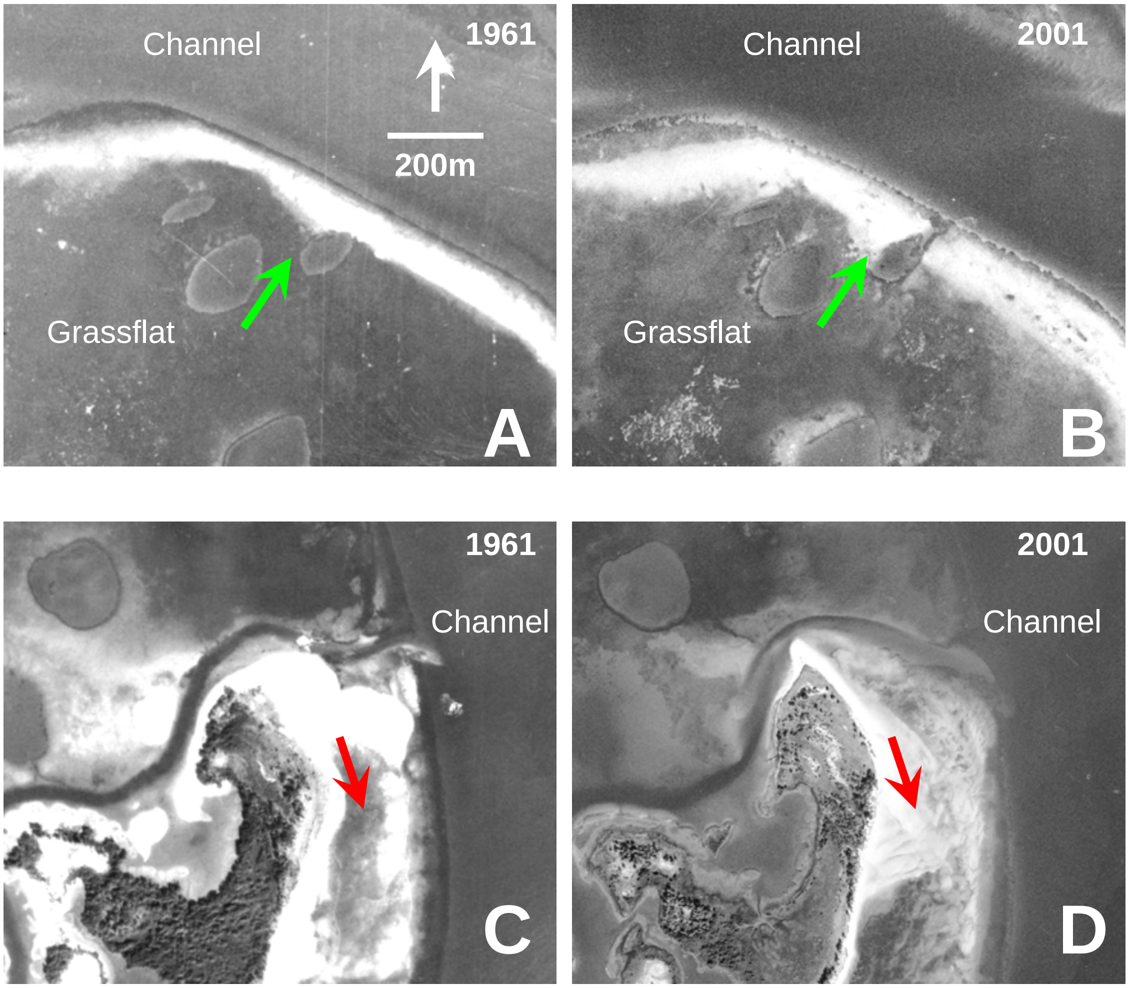


Figure 3-28. Aerial photograph showing locations of buried seagrasses. The edge of the grassflat in 1961 (A) appears unvegetated, likely due to wave action and high energy due to the proximity of the channel. From 1961 to 2001 (B) the unvegetated area spread. The green arrows in A and B indicate a location where the seagrass bed was buried sometime between 1961 and 2001. In 2004, that location was vegetated with *Halodule wrightii*. The dynamic nature of some high-energy areas is evident through the erosion that took place between 1961 (C) and 2001 (D). The red arrow indicates a location where a seagrass bed was buried by eroding sands. This area was unvegetated in 2004. At this location, an A horizon was buried beneath a C horizon. eroding sands. This area was unvegetated in 2004. At this location, an A horizon was buried beneath a C horizon.

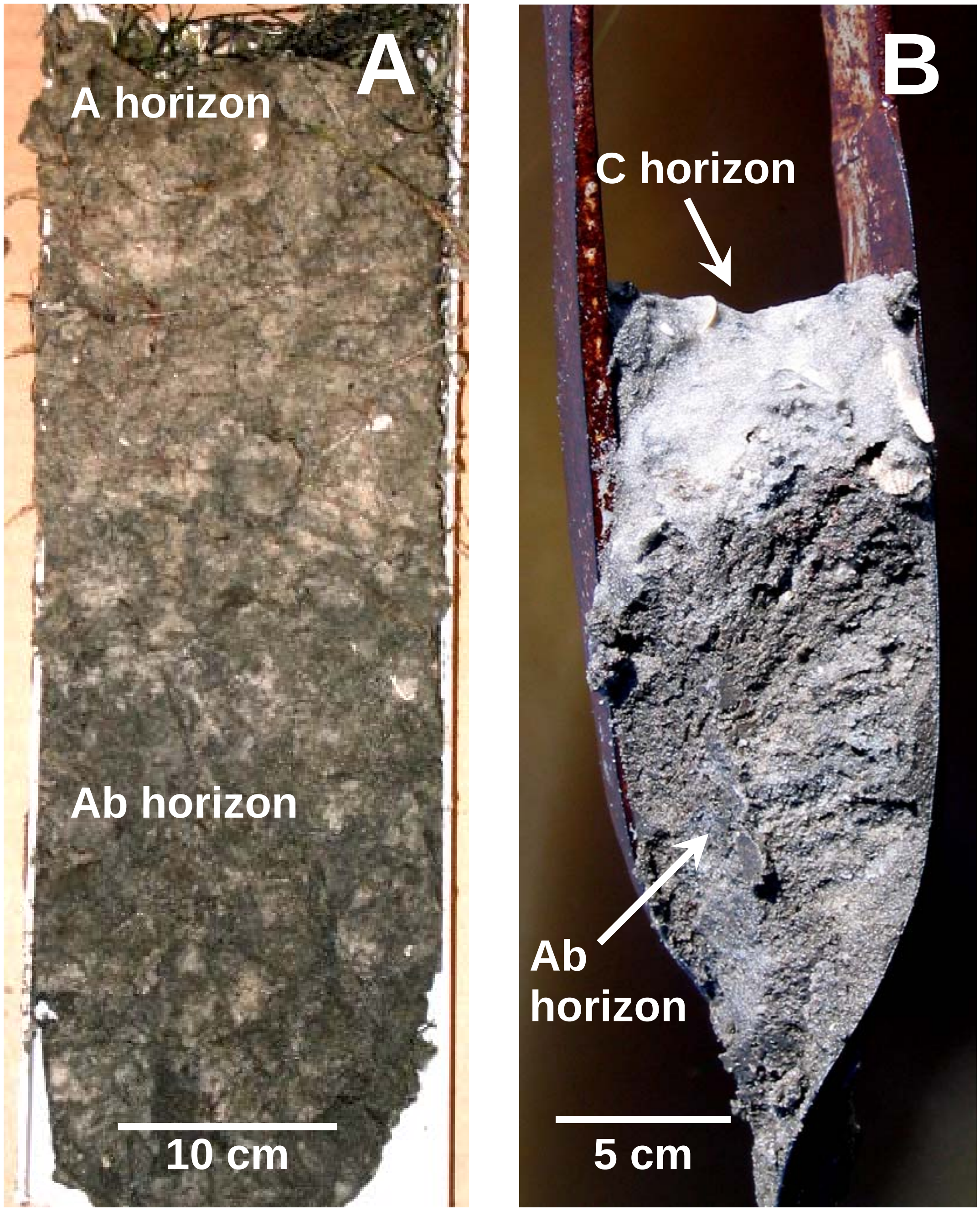


Figure 3-29. Buried A horizons in a subtropical subaqueous soil near Cedar Key, FL. The soil on the left (A) is an upper-pedon of a soil occurring on a vegetated flat where soil had been eroded from land into the seagrass over the past 40 years. The seagrass present at the time of excavation was *Halodule wrightii* but the darker colors at depth suggest *Thalassia testudinum* was the previously supported grass. This photograph was taken after the soil had been exposed to air for a week. Therefore, colors are of the soil in its oxidized state. The soil on the right (B) occurred in an unvegetated area proximate to an erosional shoreline.

conversion to *Halodule*. In contrast, the upper pedon of the soil that occurs in the area located in Figure 3-28c and d is shown in Figure 3-29b.

Note the abrupt boundary between the C and the Ab horizons. This suggests a catastrophic burial, killing all seagrasses supported by that soil. In 1961, the flat appears be vegetated (Figure 3-28c). By 2001, the shoreline has retreated, likely due to erosion from wave action, and the vegetation has disappeared, likely due to burial from this erosion (Figure 3-28d). The aerial photographs shown in Figure 3-28 c and d support the soil morphology based inference that the soils have been catastrophically buried. In both the cases of the migrating bar and the eroding shoreline, the history of the area can be inferred from the soil morphology. Similar inferences could be made in other areas where the vegetative history is not known provided the soil/vegetation relationships are understood.

Conclusions

Relationships between seagrasses and the upper-pedons of soils are apparent near Cedar Key, FL. Based on the data presented, silt and OM contents are related to seagrass vegetation. A commonly invoked sedimentologically-based explanation for this phenomenon is that high silt concentrations in the soil protected OM from oxidation. The small pores help preserve OM (Personal communication: John Jaeger, Professor, Department of Geology, University of Florida). While this may explain the persistence of OM in the soil and the correlation between silt and OM, it does not explain the genesis of the OM.

The source of the soil OM could be additions to the soil by seagrasses in the form of root die off, root exudates, leaf litter, or a combination of the three. This mechanism strongly mimics the formation of A horizons developed by terrestrial grasses. Thus, it is possible that the dark, high OM portions of the upper-pedons of marine subaqueous soils are due to plant additions to the soil via root processes. If this is the case, these are OM additions to the soil directly from the plants. Therefore, the surficial horizons of these vegetated soils should be labeled A horizons.

Another explanation is that the source of the OM could be silt-sized particulate OM that settled with mineral silt. In this case, the OM would still be preserved via the smaller pores, but the genesis of the soil would be sedimentary, making the surface of the soil a C horizon, not an A horizon. If the seagrasses occur in an environment that is low energy due to the geomorphology of the area, then the horizons should be labeled as C horizons. Instead, if the seagrasses engineer the ecosystem to create a lower energy environment, then it could be viewed that the soil is feeding itself material that would otherwise not have settled.

This trapping of suspended particulate OM is a widely accepted phenomenon by seagrass ecologists (Zieman, 1982; Zieman and Zieman, 1989; Hemminga and Duarte, 2000; Koch, 2001; Barron et al, 2004). *Thalassia* has significantly longer and thicker blades than *Halodule*. The baffling effect of blades should be proportional to the surface area of the blades. Consequently, the larger blades of *Thalassia* could provide an increased baffling effect compared to *Halodule* soils or unvegetated soils. The subsequently low energy environment of soils supporting *Thalassia* should enhance deposition of allocthonous material which is likely higher in silt and OM contents than the quartz soils of the beaches and sand bars. Less baffling would occur in the soils supporting *Halodule* and none should occur in the unvegetated soils. This would explain the OM and silt concentrations of the UNVEG, HAL, THAL, and THAL/SYR soils.

Further studies of current velocities and sedimentation rates among these soils may provide a better understanding of this phenomenon.

Of course, these three proposed mechanisms are not mutually exclusive. Seagrasses can grow in protected, naturally low-energy environments. Their growth blade growth could enhance deposition and root processes could add OM to the soil. Furthermore, bioturbation from the supported benthic communities could provide the mixing needed to create the relatively homogeneous morphology observed in the THAL/SYR compared to the HAL and THAL soils.

None of these explanations excluded these substrates from the USDA’s definition of soil as outlined in either edition of *Soil Taxonomy* (Soil Survey Staff, 1975 and 1999). While these areas may conceptually be soil, the genesis of the upper-pedons of those soils is still in question and should be the subject of future study. In the case of the buried soils, interpretation of the marine subaqueous soil morphology was possible due to the empirical relationship between soil morphology and vegetative cover demonstrated throughout the study area. A better understanding of the upper-pedon genesis would facilitate interpretations of soil morphology.

The issue of the genesis of the OM and silt in the soil is just one example of the many questions pedologists need to address in the future. Questions such as this are important precursors to the successful application of the pedological paradigm in subaqueous environments.

These empirical relationships between seagrasses and soils are promising for soil scientists since relationships such between soils, vegetation, and landscapes are central to their concept of soil. Given the ubiquitous nature of seagrasses on the Cedar Key flats, landscape/seagrass/soil relationships may be the focus of future subtropical subaqueous pedology. These relationships would be best constructed on research focused on better understanding the processes that occur in the benthic environment. Those are the processes of subaqueous soil formation.

CHAPTER 4
CREATING AND EVALUATING SUBAQUEOUS DIGITAL ELEVATION MODELS

Introduction

Basemaps in Soil Survey

Soil/landscape relationships are the cornerstone of pedology. V.V Dokuchaev's soil-forming factors (Dokuchaev, 1883; Glinka, 1927; Jenny, 1941), the catena concept (Milne, 1935), and the landscape unit (Soil Survey Staff, 1993) all demonstrate the fundamental idea that soil properties vary predictably with the landscape. Visualizing landscapes is therefore useful to the creation of a soil survey.

In a terrestrial environment, much of the landscape can be visualized in the field. This allows for the direct observation of soils and landscapes so that soil/landscape conceptual models can be developed. Large areas such as counties cannot be directly observed in an efficient manner. Mapping the soils at the county scale therefore requires the use of basemaps such as topographic maps and aerial photographs. These basemaps contain landscape information that can be used to model the landscape and thus the soils.

In the United States, the elevations of landscapes have been mapped at a 1:24,000 scale by the United States Geological Service (USGS) in the form of topographical quadrangle sheets. Most United States Department of Agriculture / Natural Resource Conservation Service (USDA/NRCS) county-level soil surveys are conducted at a map scale close to 1:20,000. Because of the smaller mapping scale of the USGS topographic quadrangles, these data are used less frequently by the USDA/NRCS than photographically derived terrain information (Soil Survey Staff, 1993).

Recently, the concept of pedology has been expanded into aquatic areas (Demas 1993). Subsequently, the topic of subaqueous soil survey in these areas has risen (Demas and Rabenhorst, 1999; Bradley and Stolt, 2002; 2003). As Bradley and Stolt (2002) pointed out, soil survey in these subaqueous areas is hindered by the difficulty of visualizing the inundated landscapes. Direct observation of the soils is possible using traditional soil sampling equipment such as soil augers (Chapter 3), but direct observation of the landscape is impeded by water. In a marine environment, the visual impedance of water can be minimizes by conducting observations low tide events, but there is still a great need to use basemaps to obtain enough terrain information to build the conceptual subaqueous soil/landscape model.

Whether the conceptual soil/landscape model requires a basemap, the mapping of the subaqueous land relies on basemaps. As with terrestrial soil surveys, the landscape is mapped efficiently by delineating the landscape using the basemaps and the conceptual soil/landscape model.

Terrain data suitable for soil survey (e.g., topographic maps) are usually not available for subaqueous areas. Aerial photographs and satellite imagery of shallow areas can provide some information about the landscape, but complete visualization of the subaqueous landscape is greatly enhanced by bathymetric terrain models.

Creating Basemaps for Subaqueous Soil Survey

Since bathymetric terrain models are not usually available at typical soil survey scales (e.g., 1:20,000), they must be created. Generally, this is done by collecting bathymetric data, converting those data to elevations, and interpolating those elevations into a “continuous” elevation surface. From this surface, the terrain can be analyzed visually in two and three dimensions, combined with aerial photography, and used to calculate terrain attributes such as slope and aspect. In a subaqueous environment, the collection of bathymetry typically uses an acoustical sounder, global positioning system (GPS), and a watercraft. Collecting these data can be time consuming. No standards have been established to determine the amount of data needed as a function of map scale. This is currently an important question for subaqueous soil survey because base maps are important and the collection of data to create those maps can be resource intensive. Additionally, traditional GPS and sounder equipment has been bulky and expensive, further consuming the resources that may be allocated to the creation of a basemap.

Recent advances such as Light Detecting and Ranging (LIDAR) show promise for efficiently gathering terrestrial terrain data, but currently require significant resources to deploy the airborne sensor. In aquatic environments, LIDAR technology is not as advanced as in terrestrial environments. LIDAR could provide an excellent alternative to the field collection of bathymetry in the future. Currently, however, the field collection of bathymetric data is still the most widely employed method. This is especially true for surveys of smaller survey areas such as individual coves and bays, where the resources necessary for the airborne equipment may exceed the resources allocated for the project.

Data Density and Digital Elevation Model Cell Size

A digital elevation model (DEM) can be any form of elevation model that is digital, however, a majority of DEM products used are raster-based. The use of the term DEM herafter assumes a raster data format with a square cell shape. This research will focus on DEMs created by interpolating point values of elevation into a raster.

The spacing of the input data affects the interpolated values in the raster as does the method of interpolation. For a given location, the more closely spaced and numerous the data points are, the higher the likelihood that the interpolated value at that point will reflect the actual value. Point accuracy, however, is not the only important metric of a digital elevation model. Since surface properties such as slope and aspect are affected by the change in elevation over a distance, model smoothness is important. The actual terrain being modeled may not be smooth. But if the DEM that represents that terrain is to have a rough surface, then that roughness should reflect the actual terrain roughness. Instead, many interpolation methods will induce a surface roughness if too small of a cell size is chosen. This roughness may confound terrain analysis, especially if the analysis is less visual and more quantitative.

DEM accuracy and smoothness are therefore affected by the spacing of the input data points. What is the data spacing needed to achieve a certain level of accuracy and/or smoothness? Bradley and Stolt (2002) addressed this question using point density. They compared their model to others and concluded that their model provided more detail. The conclusion was based on the larger data density, 14 data points/ha, of the survey data compared to the NOAA density, 4.5 points/ha. This attempt at assessing DEM quality is necessary (Wilson and Gallant, 2000), however the metric of points/ha used requires an assumption that the pattern of data spacing is consistent between DEMs in the comparison. For example, a DEM generated from 100 data points that are concentrated in the center of a 10 ha study area will produce better results in the center, and worse along the edges when compared to a DEM generated from 100 data points that are evenly distributed throughout a 10 ha study area. In both situations, the point density is 10 points/ha.

The situation is even more drastic in the case of bathymetric data, as these data are often collected along transects. The local data density in the areas near transects is much higher than in areas away from transects. If one assumes that a surplus of data are collected along a transect, then it is the distance between bathymetric transects that should affect DEM accuracy and roughness.

These issues associated with creating DEMs by interpolating bathymetric point data raise the following questions:

- What is the relationship between bathymetric transect spacing and surface roughness?
- Can this relationship be quantified into a metric that can be used in DEM creation?
- To minimize resources required for the collection of an adequate amount of bathymetric data in the basemap creation process, what is the maximum distance between bathymetric transects, assuming surface roughness is to be avoided?

To address these questions, the objectives of this study were to:

- Create a digital elevation model (DEM) of the shallow, subaqueous terrain near Cedar Key, FL.
- Determine the optimum cell size of the DEM relative to the spacing of the input data. The optimum cell size will be the smallest that does not result in a DEM with significant interpolation artifacts (described later).

Materials and Methods

A description of the study are can be found in Chapter 1. Bathymetric data were collected throughout the study area along transects. Those data were exported to a Geographical Information System (GIS) to be modeled into a DEM using several interpolation methods. The resultant models were compared to determine the best model. The final model was used to generate a DEM at various cell sizes: 5 m, 10 m, 15 m, 30 m, and 60 m. The nature of the interpolation noise, referred to here as artifacts, was investigated visually by inspecting DEM at the various cell sizes and quantitatively by examining profiles of DEM-derived slope along a transect.

The 10 m and 15 m DEMs were used to quantify the relationship between interpolation noise (expressed as artifacts) and transect spacing. A metric was created to allow the determination of optimal cell size given a known transect spacing. This metric was called the scale ratio.

Bathymetry and Equipment

Bottom elevations were determined by first collecting bathymetric sounding via acoustical sounder. The water depths were corrected for tidal fluctuations using a National Oceanographic and Atmospheric Administration (NOAA) tidal gauge located in Cedar Key, FL. Because the gauge was less than five km away from the study and because of the open nature of the water, levels recorded by NOAA were assumed to be equal to the water levels throughout the study area.

Bathymetric soundings were collected using a transom mount transducer mounted on the stern of a 5 m, shallow-draft skiff. Bathymetry was collected along transects oriented north-south and east-west (Figure 4-1). Transect spacing was held constant for the initial data collection, then additional transects were added to intensify sampling in certain areas. The bathymetric transects are shown in Figure 4-1. Since most transects were run in an east-west and north-south orientation (Figure 4-1), the transect intersections served as a check to see how the unit was performing.

The transducer specifications were: Garmin part number 010-10249-00, 200 kHz frequency, 20^{o} cone angle, plastic construction, and transom mount orientation. The data logger used to pair the sounding information with positional information was a Garmin GPSMap 178C with internal antenna. This unit contained all GPS hardware and mapping software necessary for the collection of positional coordinates using the wide area augmentation system (WAAS), which constantly reported an accuracy of +/- 3 m

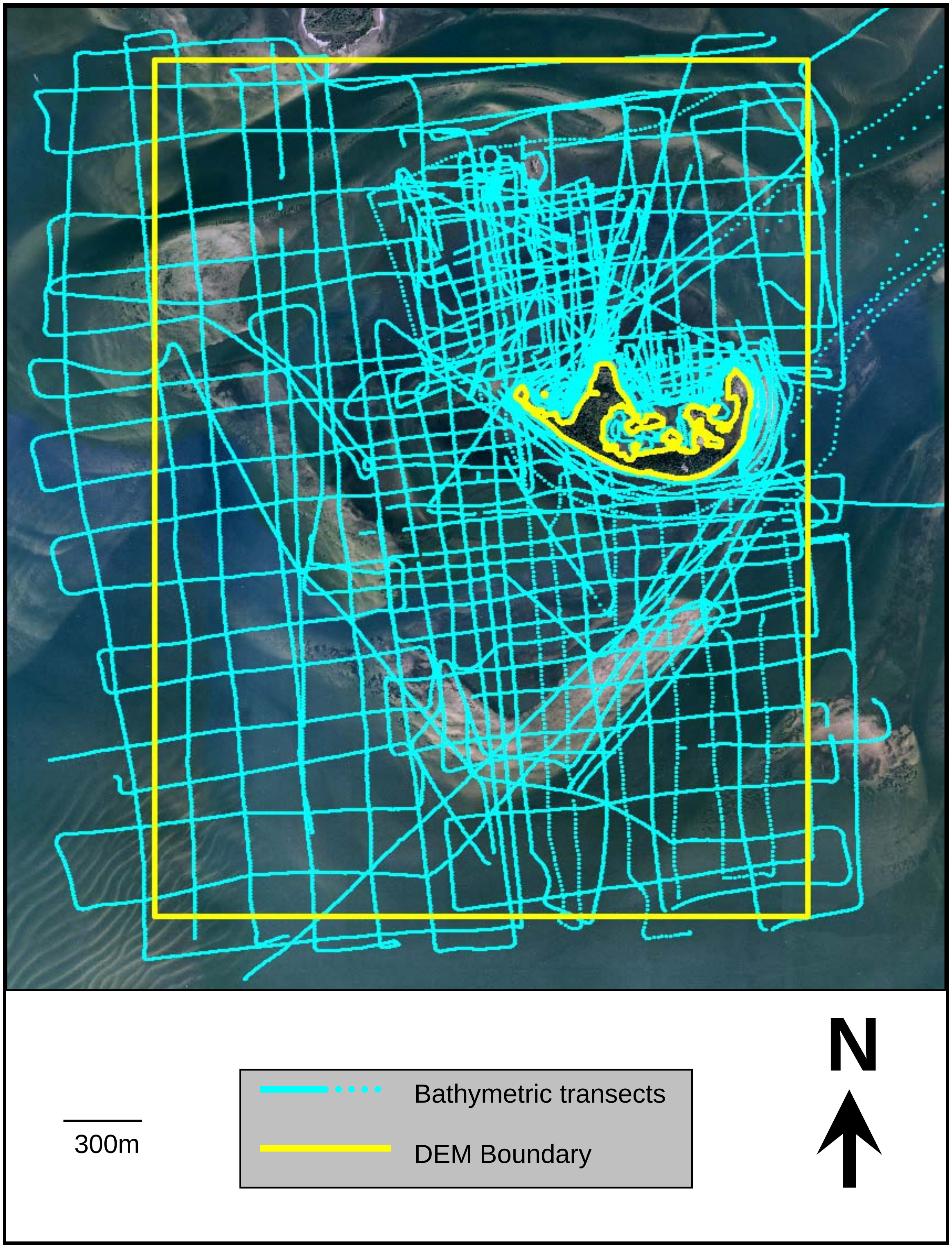


Figure 4-1. Location of bathymetric transects.

throughout the study. The unit communicated with the transducer, providing control over settings such as signal gain and water salinity and collected depth soundings, +/- 3 cm that were internally paired with WAAS GPS derived positional coordinates. The transducer was positioned such that at running speed, 35 km/hr, it was level and submersed. The data logger was able to store 10,000 soundings in the internal memory, but Garmin data cards were used to hold the data so the logger memory could be purged. This, allowed for additional mapping without requiring a computer to download the data, thus enhancing efficiency. The logger was compatible with a Microsoft Windows PC. The software used to model the data was the Geostatistical Analyst extension of Environmental Systems Research Institute's ArcGIS 9.0.

The internal settings of the logger were used to adjust the transducer gain to achieve maximum signal strength in the shallow seagrass flats. A keel offset feature in the logger was used to calibrate the transducer to the depth of water at a measured location. Depths were converted to elevations after correcting for tidal fluctuations using logs from a NOAA tidal gauge located 5 km away at Cedar Key, Fl. Data were acquired on days with calm winds (<15 km/hr) and subsequently small (<30 cm amplitude) waves. The data logger calculates a running average of soundings (personal communication with Garmin technical staff) and the skiff was designed to cut through small waves at higher speeds, so post-processing of data to remove wave noise was not necessary. In confined areas, such as those near the shore or inside of coves, speeds of 35km/hr were not practical. Soundings in these areas were acquired after readjusting the transducer position and recalibrating the keel offset to account for the different attitude of the skiff. These soundings were recorded at 5 km/hr.

The interval between soundings can be specified by time or by distance. The targeted data spacing was 10m between points along the transects, so the collection interval was set to one sounding per second on the 35 km/hr transects and one sounding every seven seconds on the 5km/hr transects. Temporal spacing was chosen instead of distance spacing of the data after Garmin recommended this to avoid any lags due to the data logger's internal computer calculating distances (personal communication with Garmin, 2002).

Data Modeling

Data were first imported to the GIS and inspected for errors. At speeds above 35 km/hr, transducer function was impaired resulting in either null data or erroneously shallow depths. The data points collected at speeds above 35 km/hr were identified using the speed attribute of the data, and subsequently deleted from the data set. Visual inspection was used to identify soundings recorded when the boat changed directions or speeds drastically, such as at the end of a transect. Under these circumstances, the angle of the transducer was not vertical. Thus, recorded depths were greater than actual depths.

Once these problematic data were removed, the residual data were modeled using several interpolation techniques at a cell size of 10 m: inverse distance weighted (IDW), polynomial, radial basis functions (RBFs), and kriging. Each interpolation method was used with the default settings to provide a baseline set of models. High quality color aerial photography acquired at a 1:24,000 scale provided a qualitative tool to determine whether the edges of subaqueous features such as the channels, holes, bars, and seagrass flats were correctly reproduced.

Once it was determined which methods produced superior results, the parameters of these methods were optimized to produce the best possible model. Within each method, Root Mean Square Error (RMSE) was used to choose the best model. Among methods, models were compared based on fitting of edge features to the aerial photograph, RMSE, presence of gross over and under predictions, and interpolation noise. The "best" technique was chosen to be the one that minimized all these parameters.

Interpolation Noise Analysis

Qualitative Assessments of Interpolation Noise: Interpolation noise was visually inspected for a 5 m DEM and a 30 m to visualize the effect of cell size on the DEM. Additionally, a transect bridging two flats across a deep channel was established (Figure 4-2). For the previously determined best DEM at two cell sizes, 15 m and 60 m, the slope was calculated. The elevation and slope values of the 15 m and 60 m DEM that occurred along the transect were plotted to visualize the effect of cell size on the elevation model.

Quantitative assessment of interpolation noise, the scale ratio: The scale ratio was a metric created to measure the relationship between interpolation noise and cell size. The scale ratio was defined as using Equation 4-1.

$$SR = D / C \qquad (4\text{-}1)$$

Variables:

SR = Scale Ratio
D = Distance to nearest data point used in the interpolation
C = Cell size of the DEM

This ratio represents the minimum distances from data points at which artifacts occur at a DEM cell size. Fifty artifacts were identified in the 15 m and 10 m versions of the DEM. Along each artifact, several points were digitized within a GIS environment. The distance between these artifact points and the nearest bathymetric data point was

Figure 4-2. Location of a transect (yellow line) used to compare slopes of DEM at different cell sizes.

calculated (Figure 4-3). This scale ratio was then applied to the bathymetric data set to determine a DEM cell size that would strike a balance between maximizing DEM resolution and minimizing the number of artifacts in the DEM. This final DEM was used as a basemap in Chapter 5.

Results and Discussion

Data Acquisition

All intersections where the boat was moving at a constant velocity were identical in measured depth once corrected for tide. Additionally, transects that were proximate to visual landmarks were inspected within the GIS and proved to be of sufficient accuracy at the 1:20,000 scale. The consistency of this instrument both in the horizontal and vertical directions appeared to be adequate for collecting bathymetry at the 1:20,000 scale. This represents a technological advancement for subaqueous soil survey as it greatly enhances the efficiency, with respect to both time and cost, of collecting bathymetric data.

Finer scale work (e.g., 1:2,000) would likely be better suited for traditional surveying or other more precise methods such as LIDAR. Considering the size of the study area, the spacing of the transects, and the scale of mapping, the accuracy this equipment provided was adequate.

Determining the Best Method for Creating a Digital Elevation Model from Transect Data

The RMSE of all models were compiled to determine which model was the most accurate throughout the study area (Table 4-1). Several models had low RMSE but did not visually appear to be good models. One such model was the Inverse Distance Weighted 2nd Power (Figure 4-4). A “bullseye” effect was noticeable at finer scales. This was expected, due to the nature of the model.

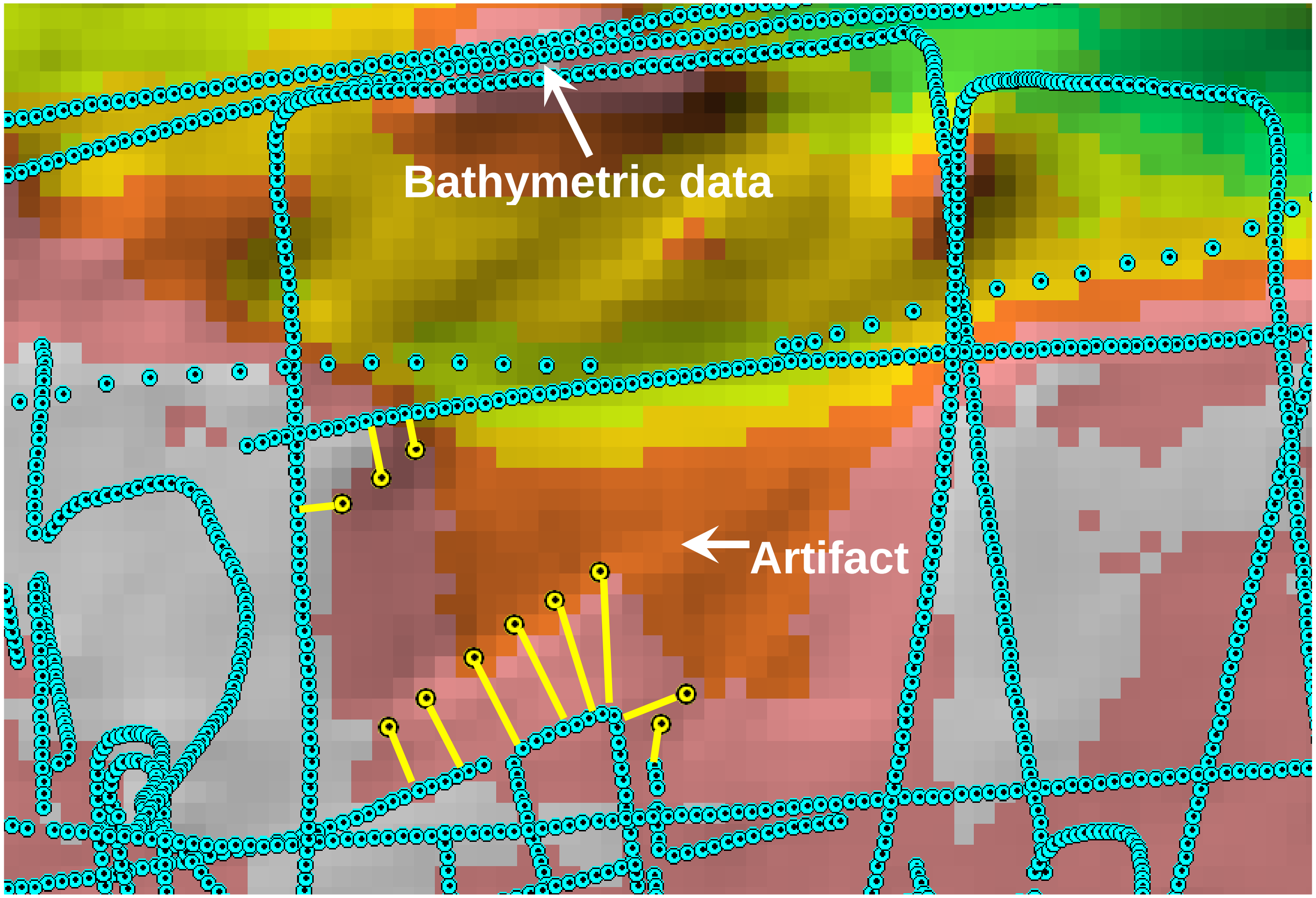


Figure 4-3. Example of an artifact used in the interpolation noise analysis. Typically, these artifacts are present where data are spaced far apart relative to the cell size. The blue dots represent the bathymetric data used as the elevation source for the interpolation. The interpolation method used was Universal Kriging. The yellow dots represent locations along the artifact where the distance to the nearest input data point was measured. The yellow lines represent the vectors of shortest path from the artifact to the input data.

Table 4-1. Error statistics for several combinations of interpolation techniques and parameters. Judging by lowest root mean square error, the universal kriging model with a 0^{th} order, 50% local trend removed was the best. It, like many other models, had a mean of the residuals equal to zero. Other models are inverse distance weighted (IDW), local polynomial (LP), radial basis funcitions completely regularized spline (RBF - CRS), radial basis funcitions spline with tension (RBF - SWT), ordinary kriging (OK), and universal kriging (UK).

Model	Mean of Residuals	Root Mean Square Error
IDW - 1st Power	0.00	1.00
IDW - 2nd Power	0.00	0.64
LP - 0th order - 100% local	-0.02	0.99
LP - 0th order - 75% local	0.01	0.95
LP - 0th order - 50% local	0.00	1.26
LP - 0th order - 25% local	0.45	3.11
LP - 1st order - 100% local	2.30	350.90
LP - 1st order - 75% local	0.01	0.84
LP - 1st order - 50% local	-0.04	1.48
LP - 1st order - 25% local	-0.51	2.96
LP - 2nd order - 100% local	0.22	47.71
LP - 2nd order - 75% local	-0.01	0.88
LP - 2nd order - 50% local	0.00	1.38
LP - 2nd order - 25% local	0.10	2.83
OK	0.00	0.76
RBF - CRS	0.00	3.75
RBF - SWT	0.01	1.43
UK - 0th order, 75% local	0.01	1.23
UK - 0th order, 50% local	0.00	0.48

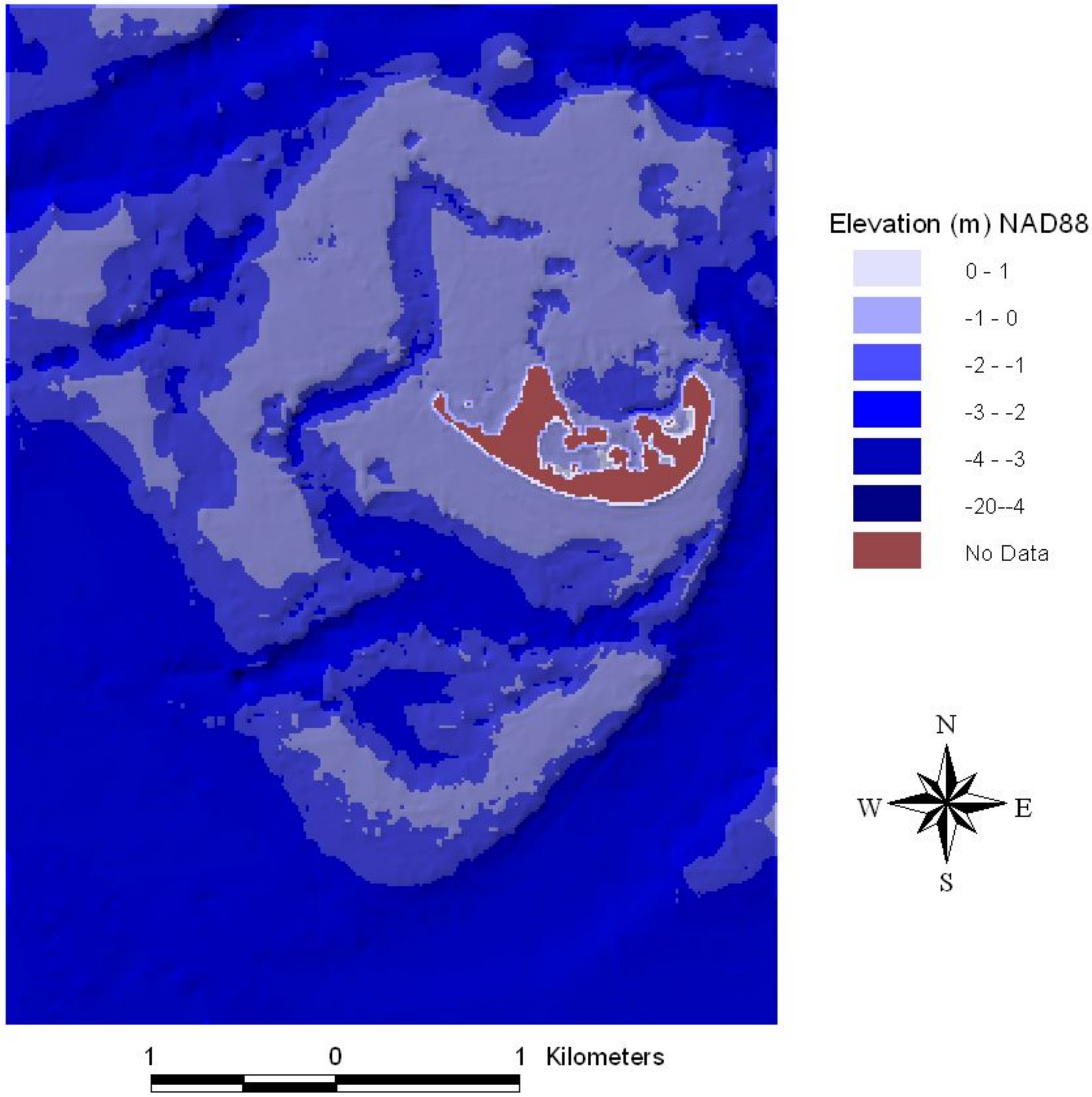


Figure 4-4. Digital elevation model calculated using the Inverse Distance Weighted method, with a power of 2.

Some models, such as the 50% local polynomials (LP), simplified the landscape (Figure 4-5) by generally displaying only the major landscape features such as the channels and flats. Others, such as 25% LP greatly over-generalized the landscape (Figure 4-6). Based on these three models, it appears that a trade-off exists between crispness of the model and unwanted surface texture. Originally, it was not planned to calculate a Universal Kriging (UK) model with a 50% local polynomial removed. However, visual observations of the 50% LP model suggested that removing this trend might enhance the UK model. The result was the lowest RMSE among all the models (Table 4-1). Visually, this model appeared to offer a great deal of cripnesss, but does suffer somewhat form unwanted surface texture (Figure 4-7).

Using the Best Model

Since it was desired to use the “best” model, the UK-50% model was chosen by virtue of its low RMS. Additionally, it appeared to strike a visual balance between crispness of the landscape features and surface noise. The model was exported in three cell sizes: 15 m, 30 m, and 60 m. The 30m cell size is generally appropriate for 1:24,000 scale investigations. Many GIS users wish to work with smaller cell sizes because of the additional spatial information small cell sizes deliver. To determine whether information is lost at larger cell sizes, Figures 4-8 and 4-9 can be visually compared to Figure 4-7. The 30 m model appears coarser, but still allows for adequate representation of the subaqueous landscape. The 60 m model is even coarser, but at this resolution, some landscape information is lost. The 15 m model does not appear to add any additional, useful information about the landscape. Additionally, Figure 4-10 shows that the subaqueous landform features likely to be of interest in a subaqueous soil survey are visible at even a 60 m scale. The 15 m model in Figure 4-10 does not appear to offer any

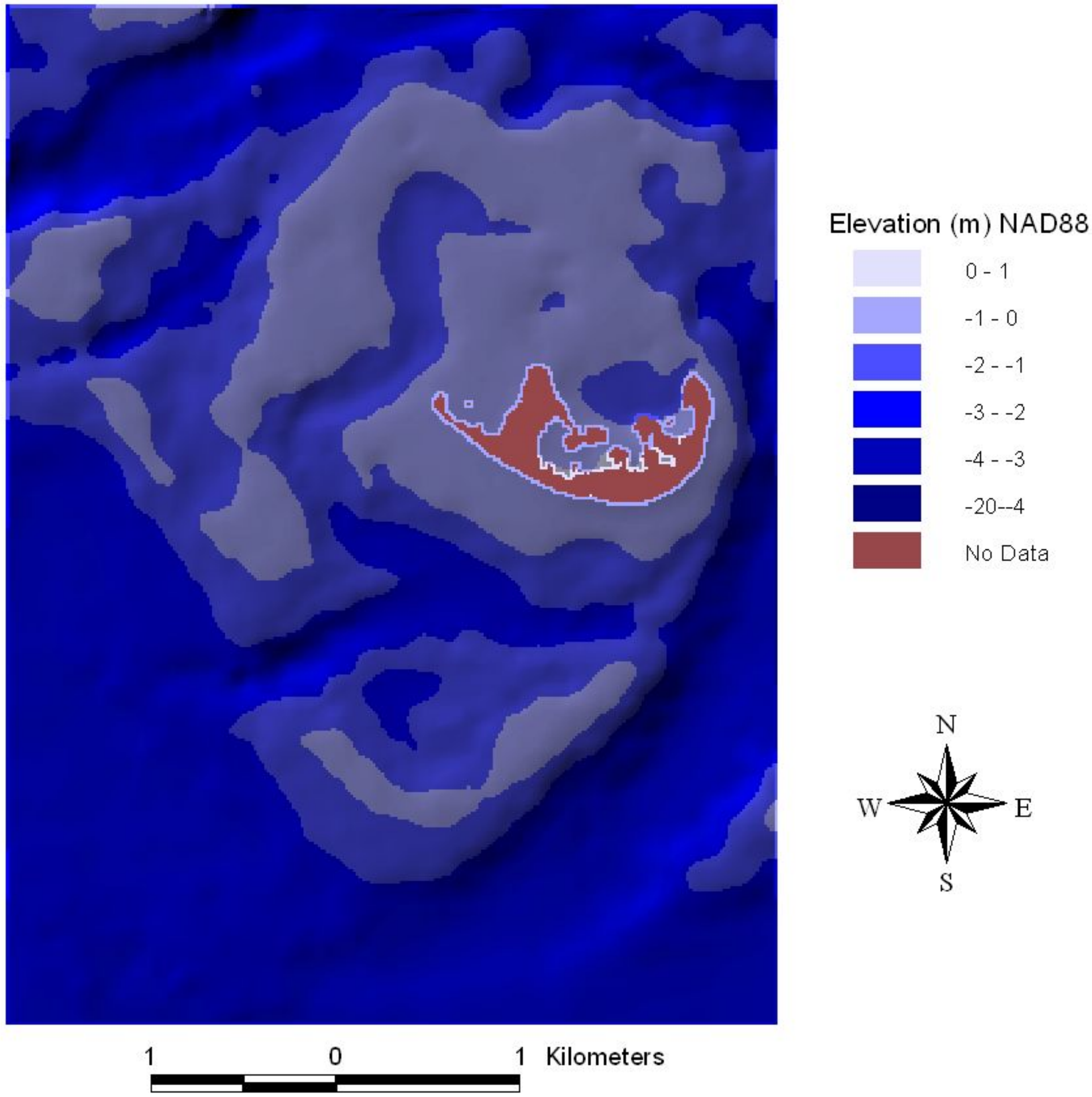


Figure 4-5. Smoothed landscape that results from modeling with a medium-size search neighborhood (50% local).

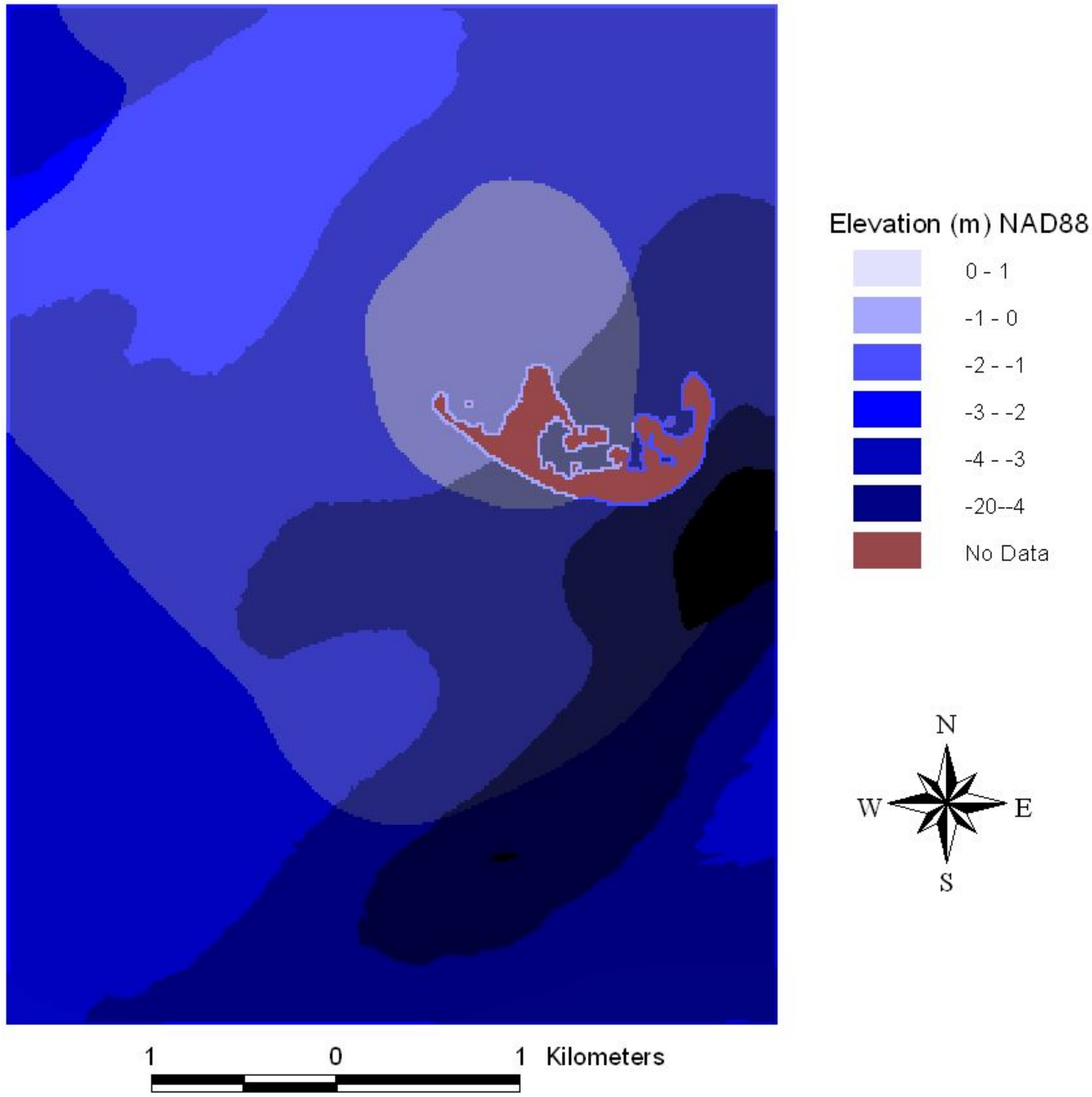


Figure 4-6. Over-generalized landscape that results from too large of a search neighborhood when employing the local polynomial techniques.

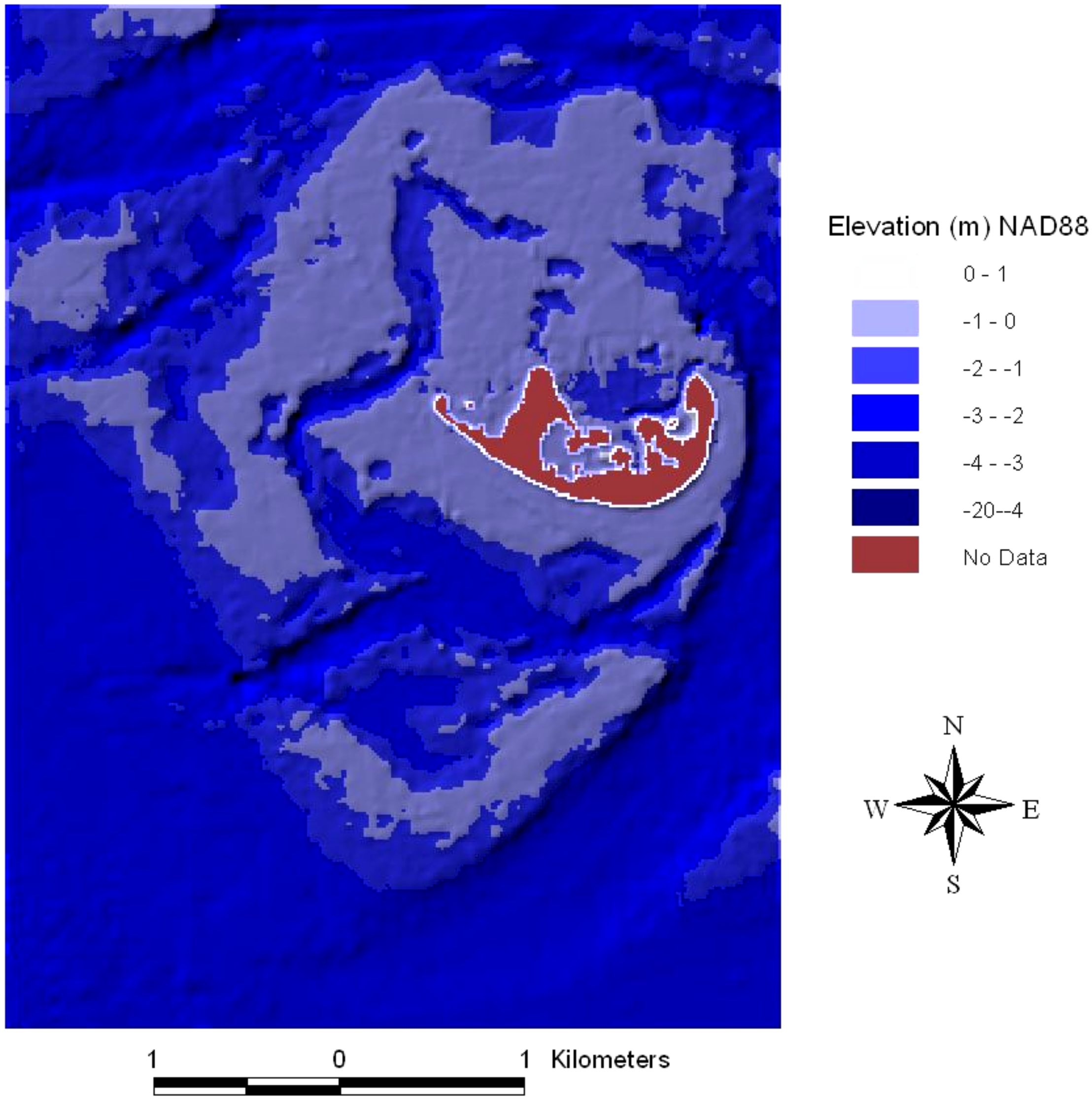


Figure 4-7. Digital elevation model using Universal Kriging with a 50% local polynomial removed prior to Kriging. The cell size is 15m.

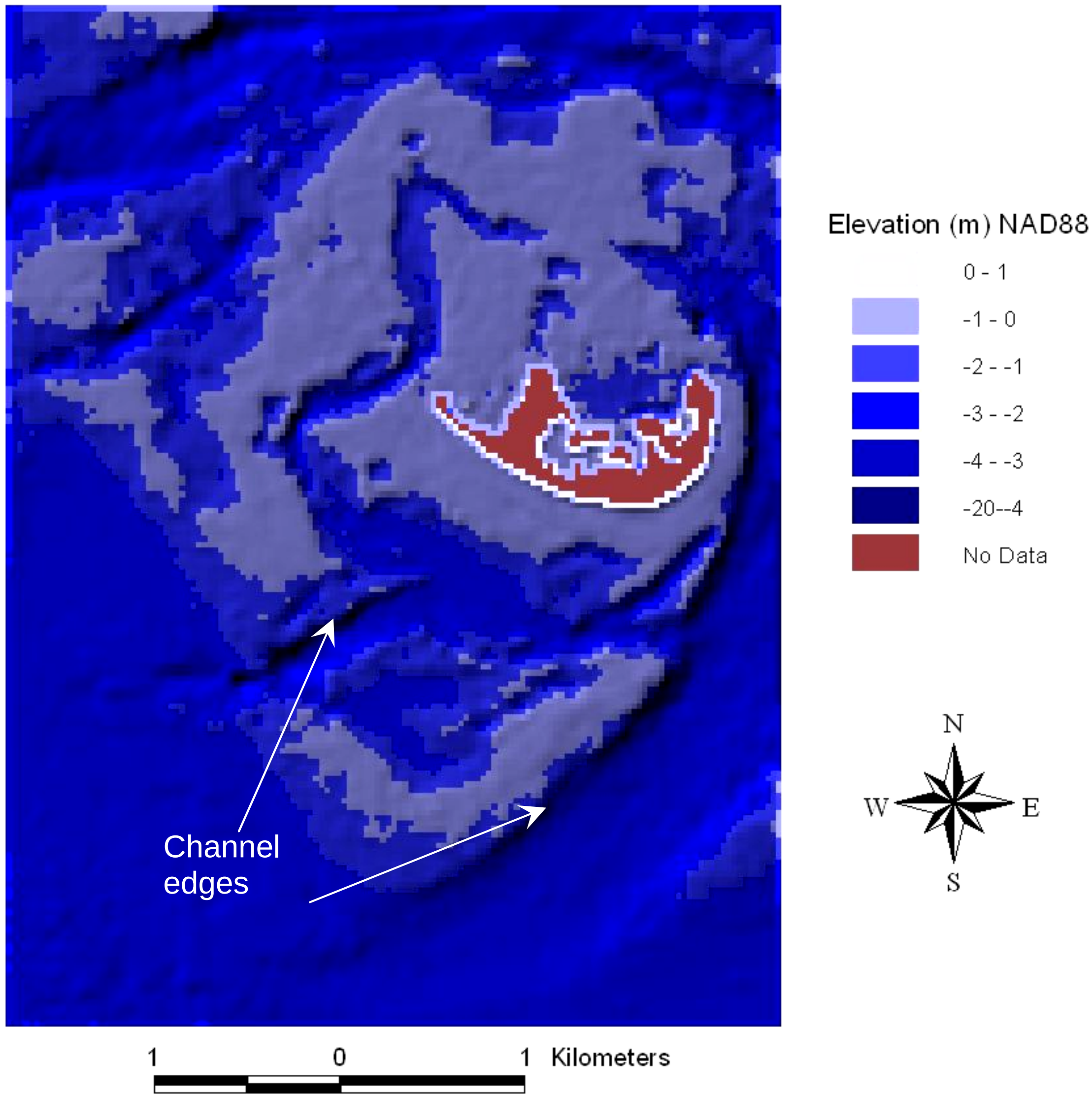


Figure 4-8. Digital elevation model using universal kriging (50% local polynomical trend removed) and a cell size of 30 m. Notice the crispness offered along the edges of the channels and the overall low amount of noise or texture across the study area.

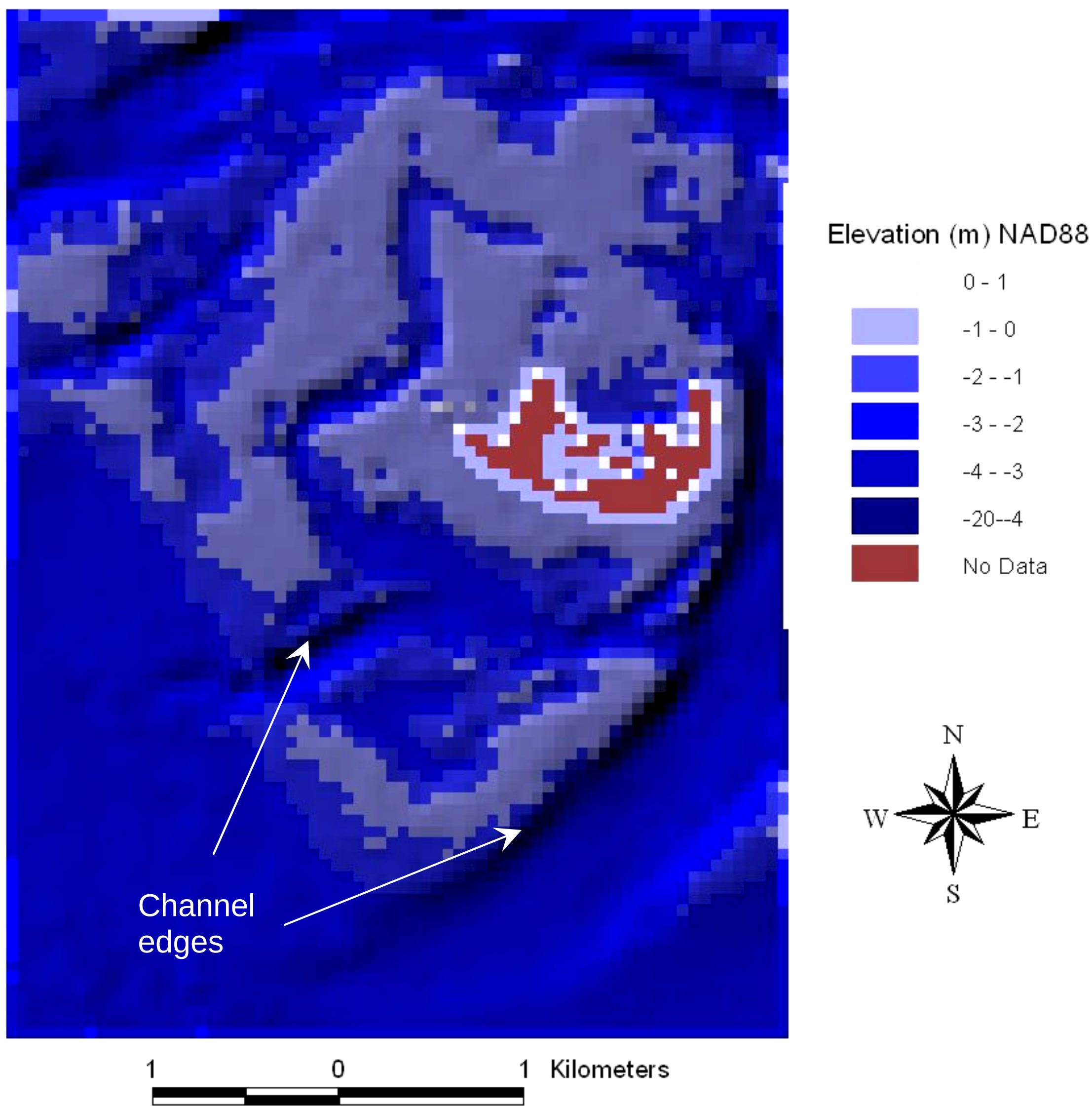


Figure 4-9. Digital elevation model using universal kriging (50% local polynomial removed) and a cell size of 60 m. Notice the crispness offered along the edges of the channels and the absence of noise or texture across the study area.

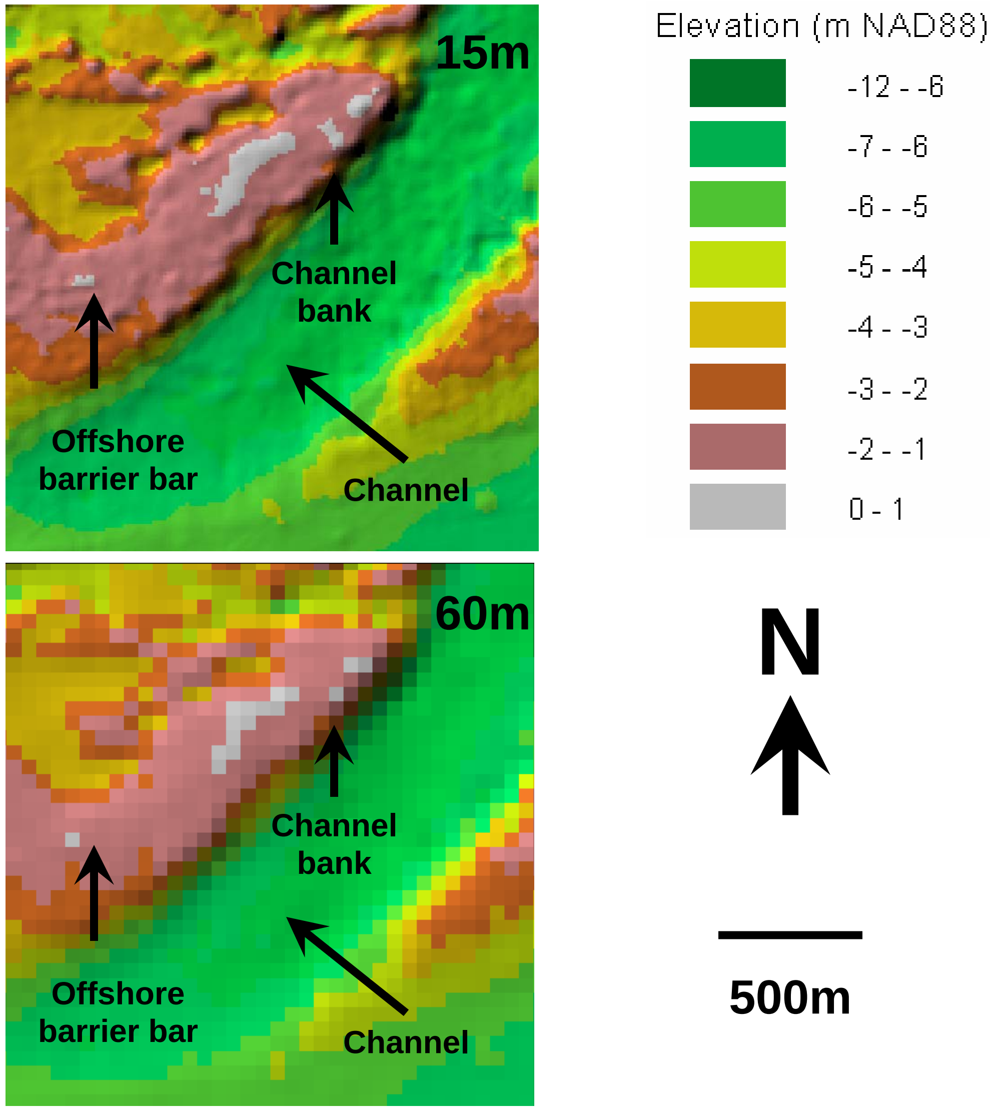


Figure 4-10. Visual comparison of two digital elevations model, 15 m and 60 m cell sizes, both created using the same bathymetric data set and identical parameter settings of universal kriging. Both models have a hillshade applied in order to highlight subtle spatial patterns in variations of elevation. The source data for the interpolation were collected along transects that were spaced approximately 200 m apart. The fine-scale surface undulations apparent in the 15 m are likely artifacts of the interpolation method used. These are not visible in the 60 m model. Both models allow for visual identification of several subaqueous landforms: channel, channel bank, and offshore barrier bar. The additional crispness of the 15 m model does not assist in the identification or delineation of these landforms

additional, useful information about the landscape. A surface roughness is apparent in the 15 m model. This roughness is not visible in the 60 m model.

Interpolation Noise Analysis

Qualitative Assessments of Interpolation Noise: The 15 m model in Figure 4-10 was interpolated at a fine scale relative to the spacing of the data. The result was a texture or roughness across the landscape. This roughness can be seen when applying a hillshade to any DEM. Visualization in 3-D enhances this effect (Figure 4-11).

More than just an aesthetical consideration, this roughness represents quantitative anomolies in the DEM. These are actual fluctuations in predicted value, in this case elevation. At finer scales, these fluctuations can be reported via the numerous cells. At coarser scales, these fluctuations occur spatially within the confines of a cell, thus they are averaged out.

The “up and down” nature of this surface texture creates a repeating pattern of long slopes and short slopes on an otherwise gently sloping surface. Calculating slope can be a quantitative method of identifying areas that have these interpolation artifacts (Figure 4-12). Ignoring these artifacts does not just create a visually rough DEM, it results in the erroneous derivation of surface properties. (Figure 4-13).

What can be learned from these examples is that while “finer” cell size models contain more spatial information, much of that information is likely misleading due to increased topographic noise. “Coarser” cell models, while they contain less spatial information, can communicate a clearer picture of the landscape. “Coarse” and “fine” are relative terms. Thus, the choice of cell size is also relative. It is the spacing of the input data used to generate the DEM relative to the cell size of the DEM that determines whether the model is “coarse” or “fine.”

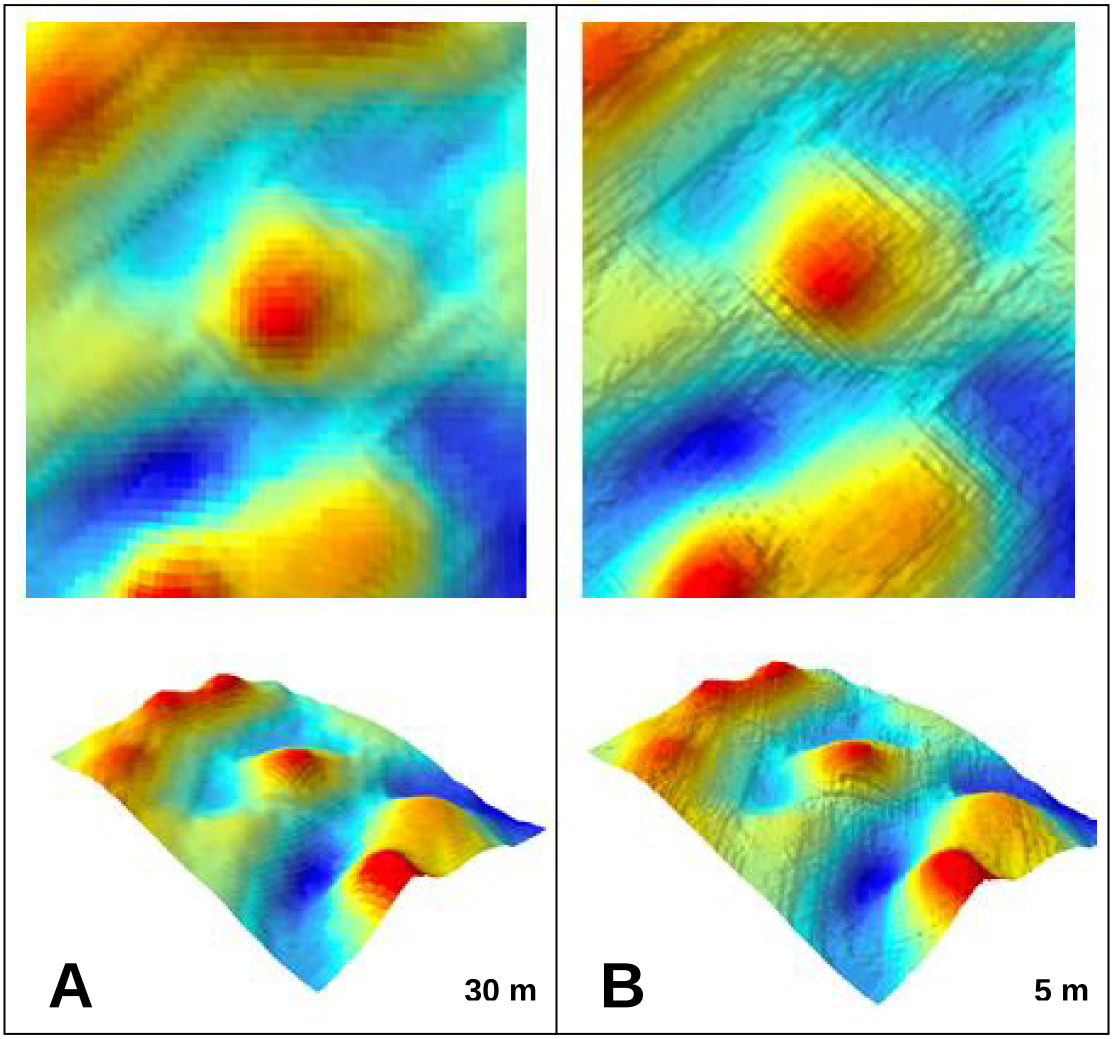


Figure 4-11. Three-dimensional view of two digital elevation models (DEM) of identical origin, but different cell sizes: 30 m (A) and 5 m (B). The 30 m DEM appears smooth while the 5 m appears rough. The input data used to generate these DEMs were spatially dense enough to support depiction of such fine scale topographic variability. Therefore, the 5 m model communicates the same coarse scale topographic variability and falsely communicates fine scale surface noise.

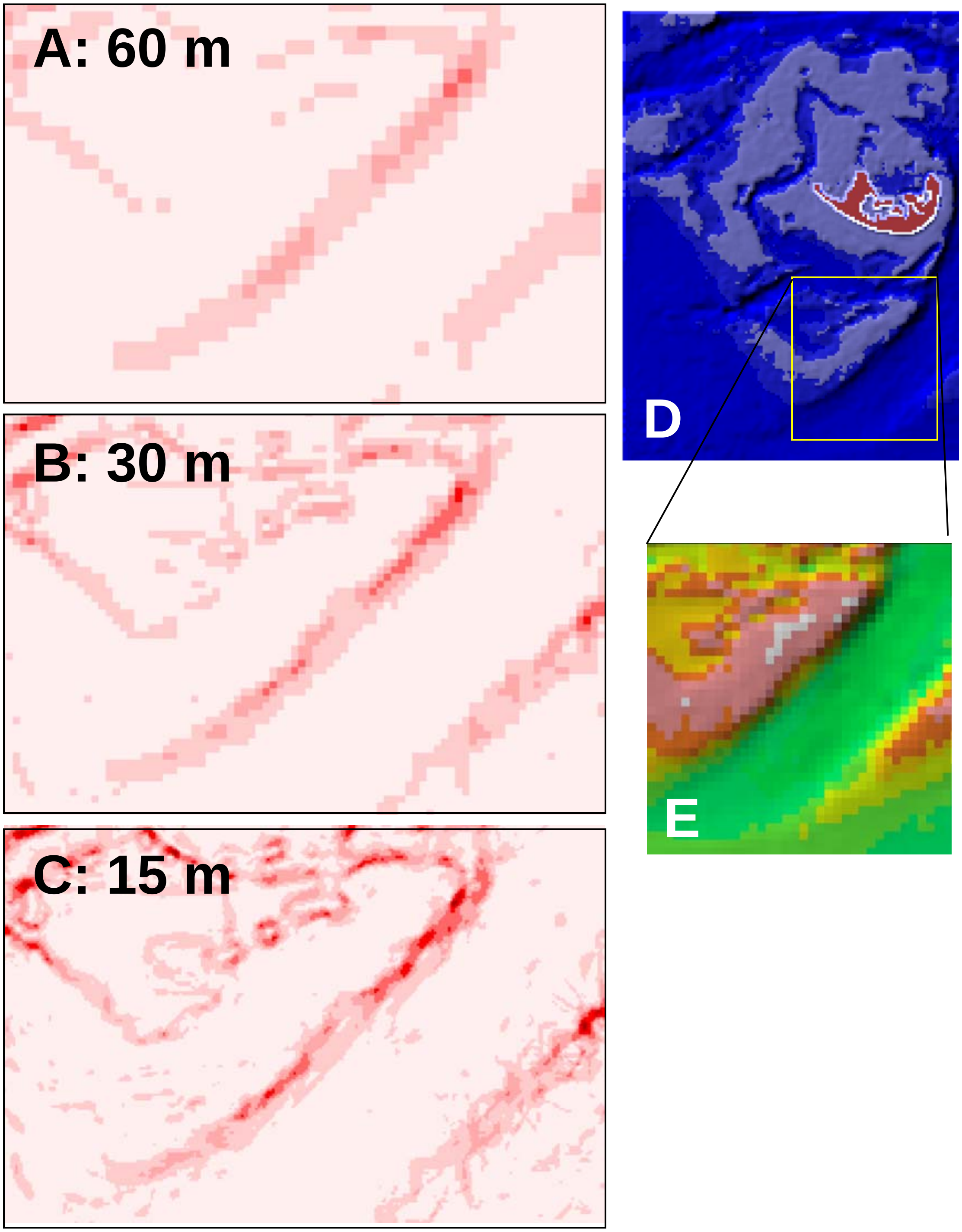


Figure 4-12. Slope maps calculated from three digital elevation models using different cell sizes. It is evident that the 60 m slope map does the best to identify the general areas of long and short slopes. The increased resolution of the 30 m and 15 m models only add confusion. The 60 m model is better for calculating slopes. The location A, B, and C are shown in D, and E.

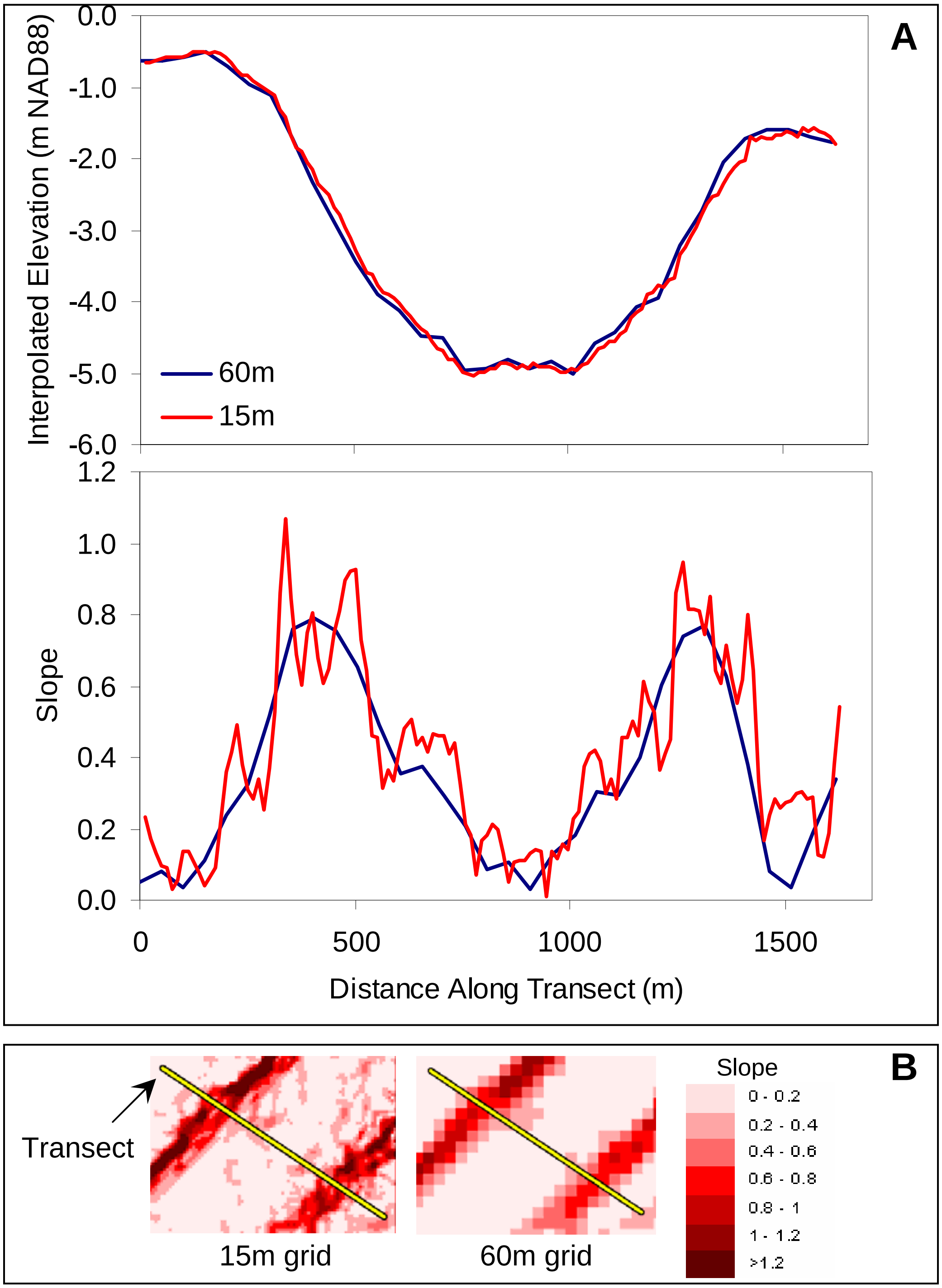


Figure 4-13. Cross-section of a channel modeled using universal kriging at a 60 m cell size and a 15 m cell size. Note the erratic nature of the elevation model (top graph in A) at the 15 m cell size which is highlighted by calculating slope (bottom graph in B). These graphs were based on a transect of elevation data (yellow line in B). Slope units are in percent.

Quantitative Assessment of Interpolation Noise, the Scale Ratio:

The distributions of ratios were similar for both the 15 m and 10 m grids (Figure 4-14). Average and standard deviations of ratios were calculated for both cell sizes (Table 4-2). The smallest data spacing that should typically result in artifacts was defined as the average minus one standard deviation. For both models, this ratio was similar (Table 4-2). The lowest of the two ratios, 4.2 was selected as the threshold scale ratio. This ratio was then rounded down to 4 so that it would conceptually match a cell of a DEM. Based on these results, artifacts should begin to occur at distances greater than 4 cells away from the source data.

In the case of the bathymetry collected along transects spaced in a grid-like pattern, which is a typical scenario, Equation 4-1 can be solved for cell size (C). The distance (D) can then be re-defined as one half the transect spacing. The transect spacing, in areas where artifacts are to be avoided, is therefore the maximum distance between transects. Using the previously determined scale ratio of 4, the calculated cell size becomes the minimum cell size (C_{min}) that avoids most interpolation artifacts (Equation 4-2).

$$C_{min} = (0.5 * TS) / SR \quad (4\text{-}2)$$

Variables:

C_{min} = Minimum cell size of the DEM that will avoid most interpolation artifacts.

TS = Transect spacing. The maximum distance between transects

SR = Scale Ratio

For the shallow landscapes of interest in the study area, TS = 250 m (Figure 4-15). Applying Equation 4-2 to the study area, $C_{min} = (0.5 * 250) / 4 = 31.25$. Therefore, the minimum cell size that should avoid interpolation artifacts in the shallow portions of the study area is 31.25. Usually, DEMs are saved in cell sizes in multiples of 5 (e.g., 15 m,

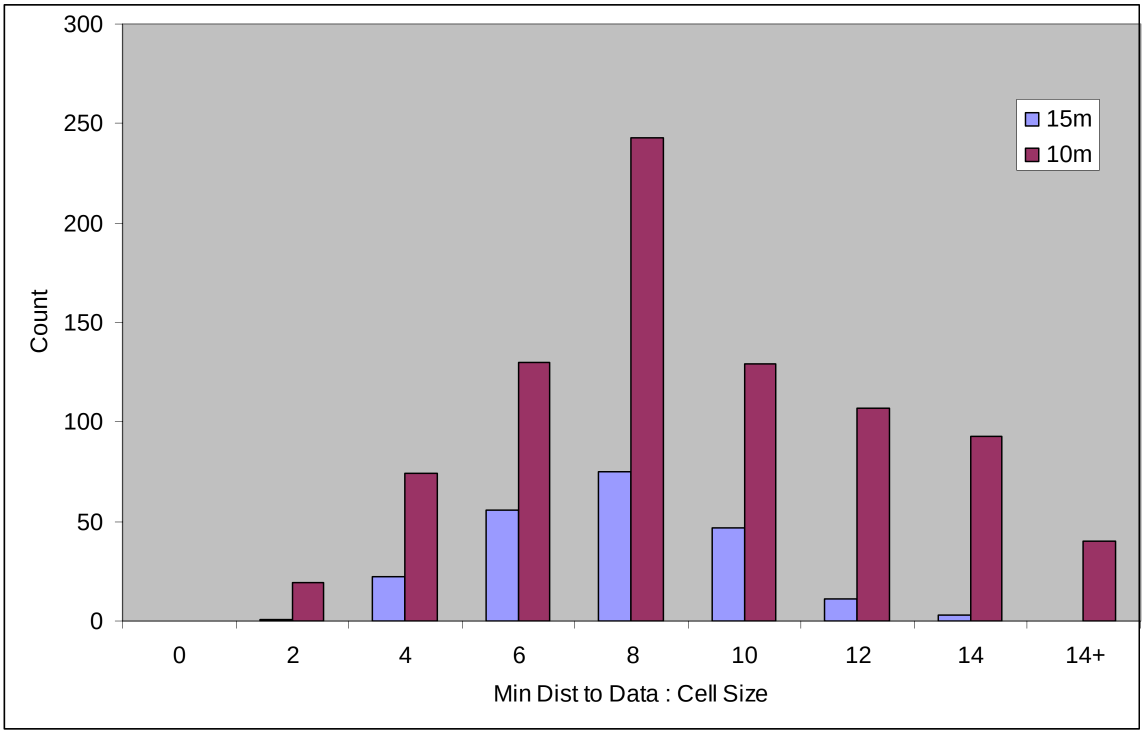


Figure 4-14. Histogram of rations comparing the minimum distance from an artifact to a data point to the cell size. For both cell sizes, the average ratio was the same. This is strong evidence that this ratio will work for a wide range of cell sizes.

Table 4-2. Statistics for the population of distance: Cell size ratios.

Grid Cell Size (m)	Average Ratio	Average Ratio - 1 standard deviation
10	8.1	4.5
15	6.4	4.2

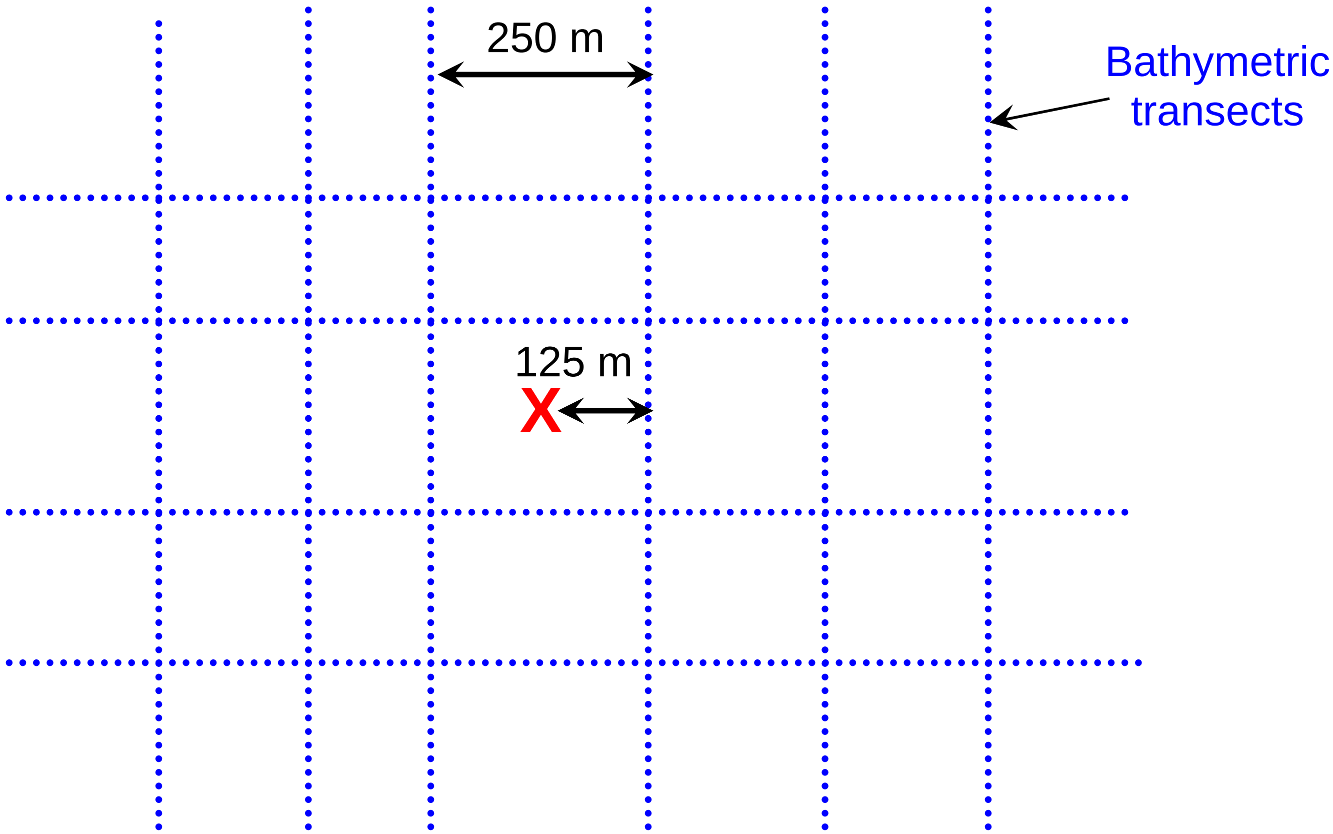


Figure 4-15. General spatial structure of bathymetry collected within the study area. Typically, the largest spacing between transects is 250 m. Therefore, the furthest position from a neighboring bathymetric point is halfway between two transects. In this case, that position results in: shortest distance to nearest bathymetric point = 125 m. Using the equation, Scale Ratio = Distance to Nearest Bathymetric Point / DEM Cell Size, the size can be calculated to be 31.25. Therefore, the smallest cell size DEM that would avoid the occurrence of interpolation artifacts is 31.25.

30 m, 35 m, etc.). Therefore, a 30m cell size was chosen as the acceptable balance between DEM resolution and smoothness. A visual inspection of the DEM at the 15 m, 30 m, and 60 m sizes confirms this assessment (Figure 4-16).

Conclusions

Recent advances in consumer grade GPS and sounding equipment allow for the acquisition of adequate positional and bathymetric data at speeds of 35 km/hr. This greatly reduces the time required to adequately collect bathymetric data compared to traditional, high precision sounding and GPS equipment. Given the increased efficiency, it therefore possible to collect much more data in a given study area using the same resources.

Many spatial interpolation methods are available in contemporary GIS packages. It is advisable to test many methods on a given dataset. For these data, Universal Kriging with a 50% local polynomial removed offered the best combination of model accuracy (low RMS) and model smoothness. Therefore, Universal Kriging should be considered when modeling similar data.

At small cell sizes, surface roughness was noticeably greater than at larger cell sizes. When considering the relationship between the roughness features, called artifacts, and the cell size of the DEM, a Scale Ratio of 4 was calculated. When applied to bathymetric data that are collected along a regularly spaced grid of transects, the cell size of the DEM should be about 1/8 the distance between transects. At cell sizes greater than this, landscape resolution is compromised. At cell sizes smaller than this, interpolation artifacts occur. This analysis was based on the threshold scale ratio (4.2) calculated from the Universal Kriging model. As previously demonstrated, some models such as Local Polynomial are smoother by nature. More research need is needed to determine the

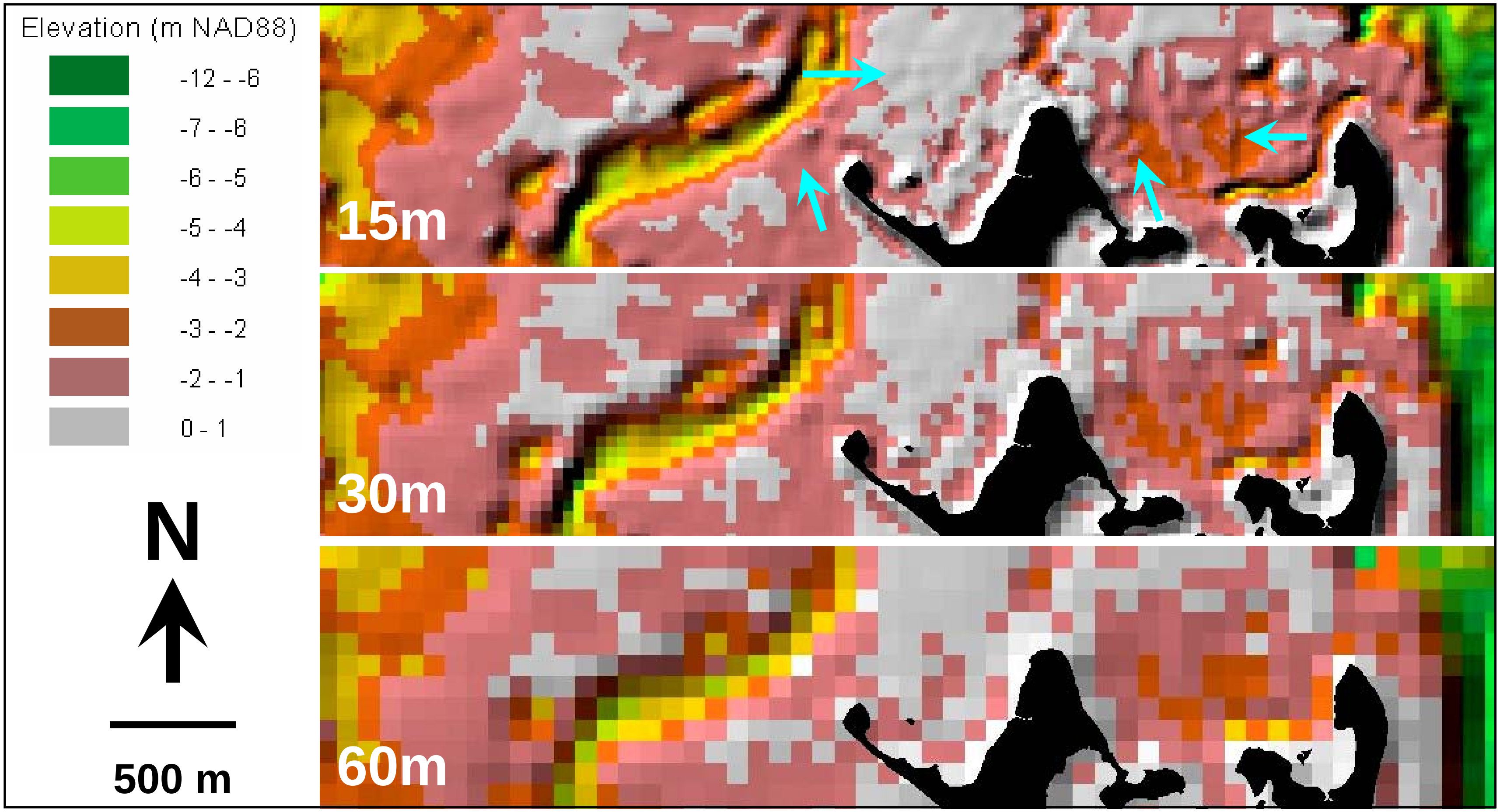


Figure 4-16. Comparison of a digital elevation models (DEMs) created using Universal Kriging at three cell sizes: 15 m, 30 m and 60 m. Source data were bathymetry obtained on a grid of transects. For most of the area shown, transects were not spaced apart further than 300 m. To avoid surface artifacts, the cell size should be 8.4 times smaller than the transect spacing. Therefore, cell size of approximately 30 m should offer the crispest view of the landscape without artifacts. Visually, the 30 m DEM does appear to offer this. The 15 m DEM does offer more landscape detail than either the 30 m or 60 m, but some artifacts are visible. Blue arrows indicate some of these artifacts. The black area represents the Seahorse Key island.

nature of threshold scale ratios for the other interpolation methods. Additionally, the spatial structure of the data may affect interpolation artifacts. Randomly, stratified random, and regular grid are data spatial distributions that need to be investigated using the scale ration approach. Despite this lack of information, the general threshold scale ration of 4 can be used for the planning of future bathymetry collection and modeling. For subaqueous soil survey, these findings could be used to better estimate the necessary resources for developing subaqueous bathymetric base maps.

CHAPTER 5
SUBAQUEOUS SOIL RESOURCE INVENTORY OF A NEARSHORE SUBTROPICAL ESTUARY

Evolution of Soil Survey in the United States

Historical Soil Survey

Soil survey in the United States has evolved from the geological "balance sheet" approaches of the early 1900s. Milton Whitney started the national Soil Survey program in the United States Department of Agriculture (USDA) (Soil Survey Staff, 1993). The early program focused on soil survey for the purpose of agriculture with geological bias. Curtis F. Marbut was the leader of the program that brought soil survey to the United States.

Early soil surveys focused on inventorying the land for the benefit of agriculture. The support of plant growth has always been a central theme in most concepts of soil (Chapter 2) and plant growth for food purposes is vital to society. It is not surprising that historically, soil surveys have focused on agricultural use.

Contemporary Soil Survey

Contemporary soil surveys in the United States have three main functions: 1) interpret the soil properties; 2) classify the soils; and 3) map the extent of the soils. The scale of any particular survey must be at a resolution sufficient to allow soils to be mapped, interpreted, and classified according to its intended use. Thus the use of the soil survey is important to consider.

The initial scale of soil surveys in the United States was 1:63,360, where one inch equals one mile. Soil maps at this scale could be considered general soil association maps. Little detail is provided in these maps. Today, the USDA soil surveys are usually published at scales near 1:20,000. At this scale the smallest area that can be accurately mapped is 1.6 ha (Soil Survey Staff, 1993). Most terrestrial areas of the United States have a published soil survey. Today, most counties in Florida have a completed soil survey (Figure 5-1).

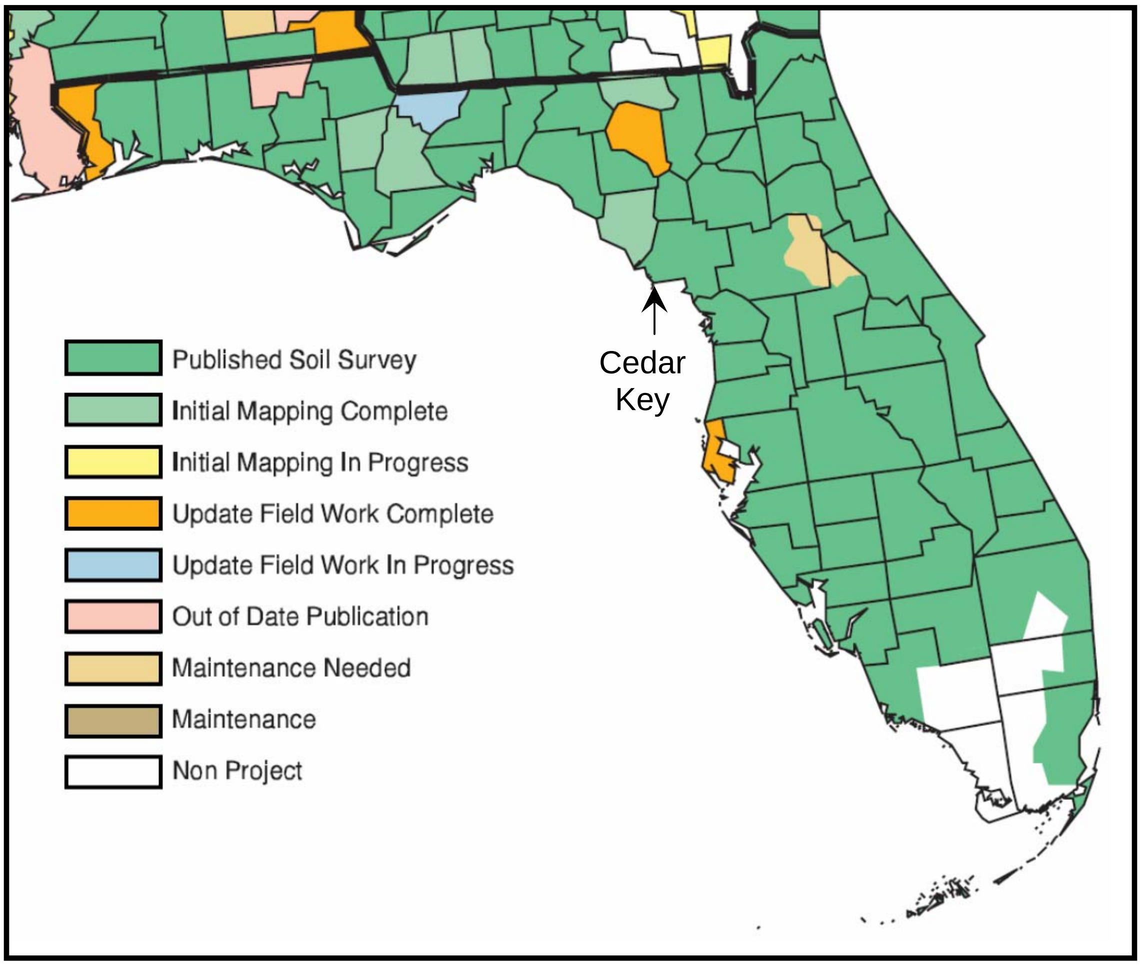


Figure 5-1. Status of county soil surveys in Florida, 2005. Reproduced from the United States Department of Agriculture's 2005 status of soil survey map (http://www.ncgc.nrcs.usda.gov/products/soil-survey/status-maps.html).

The theoretical lower limit of soil has been suggested as the lower limit of biological activity and/or bedrock (Soil Survey Staff, 1975). The general limit of taxonomic and soil survey investigation was originally set at 2 m (Soil Survey Staff, 1975). For taxonomic and survey purposes, soil properties below these depths were not considered, but may be very important in understanding the genesis of the soil. In Florida, because of its climate and dominantly sandy parent materials, soils may have pedogenic horizons to depths of tens of meters (Harris *et al*, 2005).

A knowledge soil property below 2 m is not usually essential for agronomic purposes such as crop production. Furthermore, in many areas of the U.S., the C horizon in the soil is well above a 2 m depth. Consequently, investigations below the C horizons have been considered to be of geological interest. Today there are more non agronomic applications of soil survey (e.g., septic tank suitability, engineering properties, urban and regional planning). Soil properties below 2 m can be of importance in these non agronomic applications. Therefore, this arbitrary 2 m limit may hinder the non agronomic use of the soil survey. Since it is unlikely that subaqueous areas will be farmed, such may be the case with subaqueous soil surveys. However, until a set of applications for subaqueous soil survey are defined, it is difficult to recommend a lower limit of soil investigation for subaqueous survey purposes. Until that time comes, the default of 2 m will likely be adopted by soil scientists mapping subaqueous areas.

Future Soil Survey: The Addition of a Subaqueous Soil Survey Program

Subaqueous soil surveys are in the early stages of development by the USDA-NRCS in the Mid-Atlantic and Northeastern U.S. regions. In 2005, the National Cooperative Soil Survey Program (NCSS) formed an ad-hoc committee charged with defining terminology and methods of investigation specific to subaqueous soils. The purpose of this task force is to, "formulate a plan to incorporate standards of subaqueous soil properties and conditions in the New Soil Survey through National Cooperative Soil Survey partnerships." Specifically, this is to be accomplished by the following items:

1. "Soil properties relevant to assessment of the State of the Nation's Ecosystems and National Resource Inventory should be considered
2. The task force should consider the purpose and strategy of sampling soil and analyzing properties nationally
3. Catalog terms and proposals for techniques and standards for subaqueous soil mapping of incorporation into Soil Survey Handbook"

(http://soils.usda.gov/partnerships/ncss/conferences/national_2005/committees.html)

A new purpose of soil survey is implied when discussing subaqueous soil survey. These areas will likely not be used for terrestrial agriculture. Aquiculture such as clamming is an agricultural use of subaqueous lands. This and other uses would be the focus of a subaqueous soil survey program. For instance, predicting the impacts of channel dredging on adjacent, sensitive seagrasses would require not only an inventory of subaqueous bottom cover, but an assessment of the particle size distribution of soils in the channel. If the particle size distribution of the soils in the channel is too small, then dredging impacts could elevate turbidity levels, negatively impacting seagrasses. Planning future clam leases would also benefit from a subaqueous soil survey, as would ecological modeling of estuaries. These non-traditional, non-terrestrial-agricultural uses of the land will likely be the focus of a subaqueous soil survey program.

Since subaqueous soils occur mainly in protected, shallow areas, it is these areas that will benefit the most from this program. According to general statistics provided by the state of Florida, approximately 29% of Florida's 3700 km of tidal shores are considered beaches (http://www.stateofflorida.com). The remaining 71% of these tidal shores can be assumed to be dominantly low-energy. Florida would greatly benefit from a subaqueous soil survey program. From preservation, restoration, and mitigation perspectives, the detailed knowledge of subaqueous soil properties that a soil survey would provide would be invaluable to Florida as well as other coastal areas of the U.S.

Updating Soil Surveys with Subaqueous Surveys

The Levy County, FL soil survey (Slabaugh *et al*., 1996) is an example of one that would need modification if a subaqueous soil survey program were to be established. Levy County is located along the “Big-Bend” area of Florida’s Gulf coast. The southwestern portion of the county is dominantly salt marsh coastline adjacent to intertidal and subaqueous habitats. An inventory of these habitats may occur if a subaqueous soil survey program is formed. However, some adjustments to soil delineations along the edges to be joined will likely occur. It is also possible, that with a new interest in very-wet lands, that more effort will be placed on mapping the salt marsh areas. Hopefully, subaqueous soil surveys will be considered within the context of existing soil surveys to avoid duplication of effort, overlap of surveys, and mixing of scales. While these details are being discussed within the USDA/NRCS (a program is in the early stages of development), continued research on subaqueous soils will add much needed understanding into the nature, distribution, and formation of the soils to be mapped.

Current Status of Subaqueous Soil Research

Recent pedological explorations have led to an interest in subaqueous pedology of coastal areas along Maryland and Delaware (Demas and Rabenhorst, 1999) and Rhode Island (Bradley and Stolt, 2003). These works have focused specifically on the creation of subaqueous soil surveys. Like terrestrial soil surveys, these efforts investigated soils to a depth of approximately 2 m. These surveys should provide much needed information for those who manage these coastal areas, but also serves as a model for creating subaqueous soil surveys. No subaqueous research is published for other areas of the U.S, although subaqueous soil surveys are underway in Texas. Much of the subaqueous U.S. needs pedological attention to assist the USDA/NRCS's subaqueous soil survey efforts.

The purpose of this research is to produce a soil survey for the nearshore environment near Cedar Key, FL. This is done in an attempt to emphasize the subtropical subaqueous soil/landscape/vegetation relationships and to aid in the establishment of methodologies to construct such surveys.

Objectives

The general objective of the research presented in this chapter is to investigate soil/vegetation/landscape relationships within the study area in order to produce a subaqueous soil survey.

- **Specific objective 1:** Determine mappable patterns in vegetation and landforms.
- **Specific objective 2:** Identify soils associated with those patterns
- **Specific objective 3:** Construct a subtropical subaqueous soil model.
- **Specific objective 4:** Express that model in the form of a subaqueous soil survey, similar to USDA terrestrial county soil surveys.

Accomplishing these objectives will demonstrate the possibilities of subtropical subaqueous pedology, and highlight unique landforms that are present in the Gulf of Mexico.

Material and Methods

A description of the study area is provided in Chapter 1. The soil survey encompasses the entire study area.

Soil Morphology

Soils were described using Dutch and Russian augers. Soil color was determined in the field immediately after sampling by visual comparison to a Munsell® Color Book (Gretag/Macbeth, 2000). Soil textures were determined in the field (Soil Survey Staff, 1993). Percent of soil features such as shells were estimated visually (Soil Survey Staff, 2002). The *n* value was estimated in the field (Soil Survey Staff, 1998).

Laboratory Analyses

Soil samples were collected for laboratory analyses. Bulk soils were air-dried and sieved to remove particles greater than 2 mm. Particle size was determining using the pipette method (Gee and Bauder, 1986). Electrical conductivity and pH were determined using 1:2 soil to water. Some chemical analyses were performed at the University of Florida Analytical Research Lab. These analyses included Mehlich-1 extractable P, K, Ca, Mg, Na, Al, and Fe determined by inductively coupled plasma. Organic matter was determined by weight loss on ignition method (Donkin, 1991). Also determined on selected samples were ^{15}N and ^{13}C using a Costech Model 4010 Elemental Analyzer and Finnigan MAT DeltaPlusXL Mass Spectrometer. The raw data are presented in Appendix 1 (Table A-2).

Additionally, the silt+clay fractions of selected soils were analyzed using X-Ray Diffraction (XRD). A soil supporting *Thalassia* and *Syringodium* was analyzed using XRD before and after treatment with dilute HCl (0.5M) to remove carbonates. A soil supporting *Halodule* was analyzed using XRD with no HCl treatment. The resulting XRD patterns were used to infer the mineralogy of the silt+clay fraction of the soil.

Data Collection

A subaqueous soil survey, like its terrestrial counterpart, is a spatial model of soil-forming factors. Therefore, observing the soils and determining the soil-forming factors related to the soils comprised the initial portion of the survey effort. Relating those factors to the landscape to identify unique combinations of soil-forming factors identifiable by landscape units comprised the second portion of the survey. The final portion of the survey was the delineation of these units using aerial photography. These efforts are outlined as steps in Table 5-1.

Steps 1 to 2: patterns in vegetation, landforms, and soil. The Florida Geological Survey publications for the state of Florida and for Levy County, FL; the geologic spatial data layers publicly available through the Florida Geographic Data Library and the Florida Department of Environmental Protection (FDEP); and the USDA Soil Survey Report for Levy County (Slabaugh *et al.*, 1996) were each consulted to gain a better understanding of local geology. True color 1:24,000 aerial photography flown in 2001 was provided by the Suwannee River Water Management District, Florida Department of Agriculture archived aerial photography housed by the University of Florida's Map and Image Library, and the Landsat imagery were digitized and rectified within a GIS to provide a spatial base map for observing patterns in vegetation and landforms. The terrain model created (Chapter 4) was used in combination with the United States Geological Survey (USGS) 1:24,000 and 1:100,000 scale topographic maps and the National Oceanographic and Atmospheric Administration (NOAA) nautical charts to assist in visualizing the spatial distribution of landforms within the study area.

Table 5-1. List and approach of the steps necessary to create the initial soil survey.

Step	Approach
1.	Observe patterns in vegetation and landforms using aerial photography, digital elevation models, and field observations.
2.	Observe patterns in soil properties via field observations as related to the vegetation and landform patterns.
3.	Superimpose patterns of soils, vegetation, and landscape on the local geology to develop a conceptual soil/landscape model.
4.	Describe and define the soil map units.
5.	Create a physical representation of the conceptual soil/landscape model by spatially delineating aerial photography into units that represent the various landforms and associated soils.
6.	Validate the spatial model and soil map units by randomly selecting locations for testing.
7.	If necessary, refine the conceptual and/or spatial model.
8.	Based on the finalized delineations, choose the locations for modal pedon description.
9.	Finalize the soil/landscape model by populating each map unit with a soil identifier and soil description based on the modal pedon.
10.	Distribute the finalized soil/landscape model as a subaqueous soil survey in digital and analog format to the target audience.

A basic understanding of the vegetation patterns within the study area was obtained from the study reported in Chapter 3. A Normalized Difference in Vegetation Index (NDVI) was calculated from the Landsat imagery to provide a quantitative assessment of the vegetation throughout the study area. This information was then used to interpret the tone, color, and contrast of the aerial photography for the purpose of inferring vegetative and landscape patterns. After analysis of the imagery was complete, the general distribution of vegetation at a scale of 1:20,000 was identified.

Steps 3 to 7: creation and validation of soil models. A conceptual soil/landscape model was created to explain the observed patterns of soil associated with vegetation and landscape, all within the context of the local geology. True color aerial photography was delineated into landscape units (hereto referred to as map units) at a scale of 1:20,000. Map units were created to effectively capture unique combinations of four terrestrial soil-forming factors: parent material, biota, topography, and time. Because of the size of the study area, climate, the fifth soil-forming factor, was considered constant for the area. Two additional soil-forming factors: 1) flow regime and 2) water column attributes were incorporated into map unit design and delineation.

Map units were delineated by hand on 1:20,000 reprints of the 2001 true color aerial photography. Although the goal was a digital model, the extra step of delineating by hand on paper photographs allowed for delineations to be made both in the field as well as in the office. Furthermore, the ever-present temptation to "zoom-in" that occurs when delineating on a computer was removed from this initial mapping effort. Delineations were made only at the specified scale: 1:20,000. Once the analog mapping was complete, it was converted to digital via digitizing in a GIS environment with the geo-referenced 2001 aerial photography as the basemap. The GIS software used was ESRI's ArcView 3.2 and the digital format was an ESRI proprietary vector format of a polygon shapefile. During the digitization processes, map-scale was held constant at 1:20,000. This ensured that the lines initially drawn by hand on the paper aerial photographs were preserved in the digital model.

A spatially random point generator available within the GIS was used to generate the positional coordinates of five locations within each map unit type for model validation (Figure 5-2). At each of these validation points, the soil was described to 2 m. Where delineations did not result in soil morphological differences, the delineations were removed and combined with other map units in ArcView. Once the delineations were finalized, one representative location for each map unit type was chosen for detailed morphological description. The pedons selected at these representative locations were the modal pedons and used to describe each map unit.

Steps 8 to 9: completion of the soil/landscape model and distribution as a subaqueous soil survey. The digital soil/landscape model was completed within ArcView by relating map unit names, modal pedon descriptions, and modal pedon taxonomies to the spatial data. The final product, a subaqueous soil survey, consisted of a shapefile with associated polygon attribute table containing the map unit identification (MUID). Supplemental tables containing the modal pedon descriptive data, which also contained MUID for database relating within the GIS were also part of the final digital product. In the near future, these digital files will be placed on a University of Florida World Wide Web site (http://pedology.ifas.ufl.edu), with the intent of encouraging distribution of the survey. An analog form of the survey is included in Appendix B of

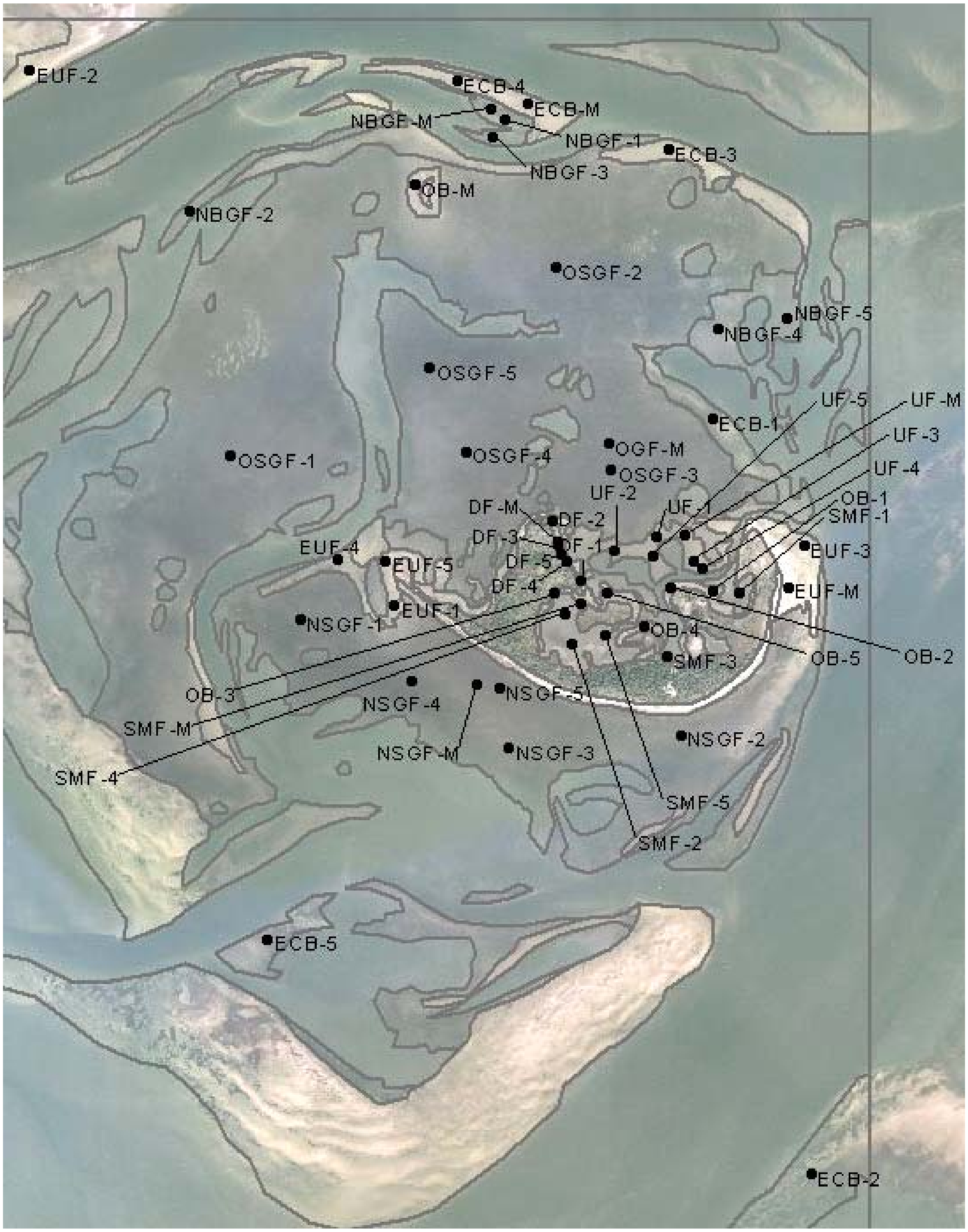


Figure 5-2. Locations of validation and modal soil sampling locations for all landscape units. The basemap is a 1:24,000 true color aerial photograph (Source: Suwannee River Water Management District). The contrast has been reduced and tone lightened to allow viewing of sample locations and labels along with landscape unit delineations (gray lines). The name of each point consists of a series of letters denoting the landscape unit and a sample number (see Table 5-2 for explanation of abbreviations).

this document in the form of map tiles and data tables. Additionally, a 1:20,000 scale poster of the survey was printed and archived along with the printed attribute tables. Thus, a multifaceted approach of distributing the soil survey via analog and digital formats was designed to facilitate delivery of the survey to the target audience (i.e. those who wish to understand how and why to create a subaqueous soil survey).

Results and Discussion

Spatial Distribution of Vegetation and Landforms

The aquatic portion of the study area is about 25% shallow (< 1 m deep at Mean Lower Low Water (MLLW): green areas in Figure 5-3) and 75% deep (> 1 m deep at MLLW: blue areas in Figure 5-3). The immediate areas surrounding Seahorse Key were shallow flats. The area immediately north of the island was a low energy cove salt marsh. The area immediately north-west of the island was another cove, but it appeared to have more wave energy and tidal exchange. This cove was vegetated. The area immediately south of the island was a shallow vegetated flat. The area immediately east of the island was a flat with vegetated and unvegetated areas. The wave energy in the immediate south and east appeared higher than in the coves of the immediate north.

In all these areas, except the salt marsh cove, *Halodule* was the dominant seagrass in the shallowest vegetated areas. A mixed stand of *Thalassia* and *Syringodium* occurred in the deeper vegetated areas of the northwestern cove. *Thalassia* occurred in the deeper vegetated areas of the southern flat. Patches of either *Thalassia* or *Halodule* were present in shallow and deep areas of the eastern flat. However, one very shallow, depressional area of *Thalassia* was present. The elevation of this patch was similar to adjacent *Halodule* patches. This was assumed to be an artifact since *Thalassia* was not identified at this elevation anywhere else in the study area. It was observed, at MLLW, that the

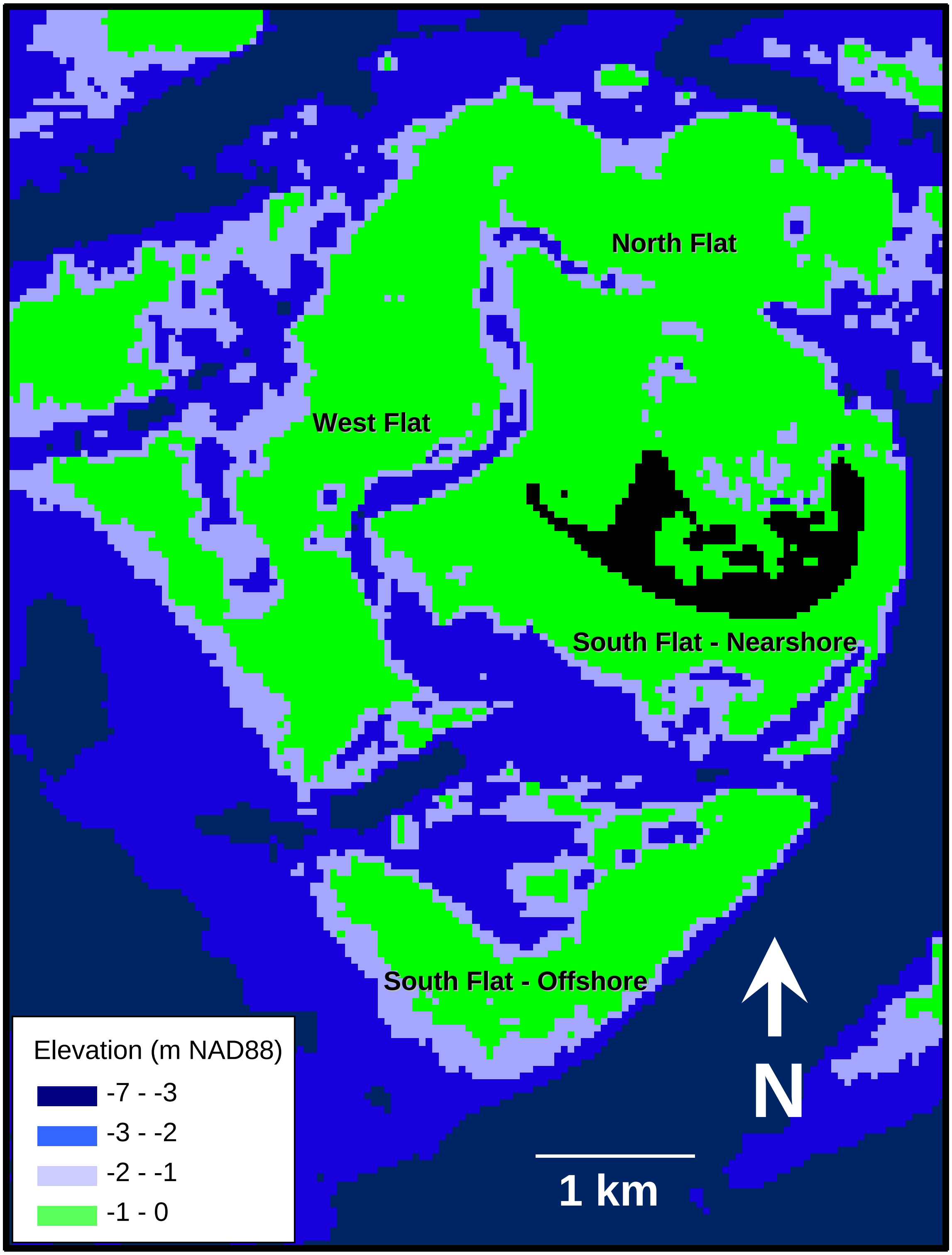


Figure 5-3. Subaqueous topography of the study area. The green areas are shallow (< 1 m deep at Mean Lower Low Water). The black area is upland. Elevation units are in meters relative to the 1988 North American Datum (NAD 88).

depression held water at all tidal cycles. It is likely that this depression is suitable habitat for *Thalassia* by virtue of its hydrology.

Away from the island were vegetated flats. To the north and to the west these flats were bounded by channels of deep water. The flats were punctuated by holes of deep water. Near the edges of these flats, where channels were present, bars were built up. The tops of most bars were unvegetated. The channel side of the bars was unvegetated but the inside of the bar, the portion adjacent to the flat, was vegetated with *Halodule* and *Thalassia*. The flats were vegetated with a mixed stand of *Thalassia* and *Syringodium*. In the north and west flats, vegetation was ubiquitous. No patchy vegetation was observed.

In contrast, the southern flat that occurred away from the shore was only slightly vegetated. Patches of *Halodule* were present throughout the bar. The bar had a rippled topography suggesting frequent disturbance from wave energy. Wave action was observed to be much greater on this flat than in any of the other portions of the study area.

The study area was conceptually divided into several classes of landforms: uplands, bars, coves, deep water, erosional beaches, and flats (Figure 5-4). The flats were dominantly vegetated with mixed stands of *Thalassia* and *Syringodium*. The distribution of seagrass can be seen in the aerial photography (Figure 5-4 and 5-5) as dark gray and brown areas. Unvegetated areas can be seen as areas of either white or light brown (Figure 5-5).

The Flats

Initial flats classification: To better understand the nature of vegetative and soil distributions, the flats were divided into two classes based on position relative to

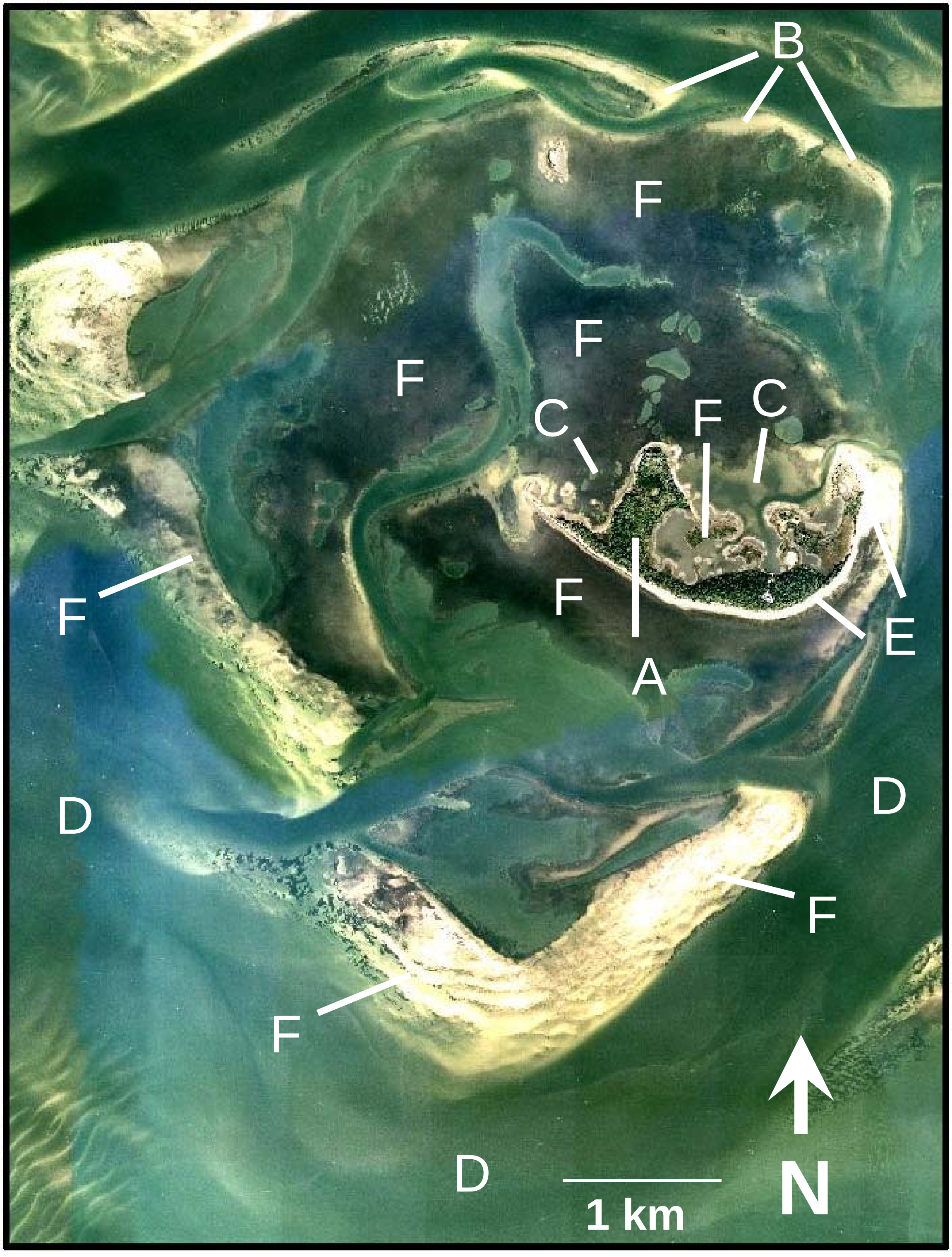


Figure 5-4. General locations of several types of landforms: Uplands (A), Bars (B), Coves (C), Deep Water (D), Erosional Beaches (E), and Flats (F). Landforms B, C, D, and F are subaqueous. Basemap imagery provided by the Suwannee River Water Management District.

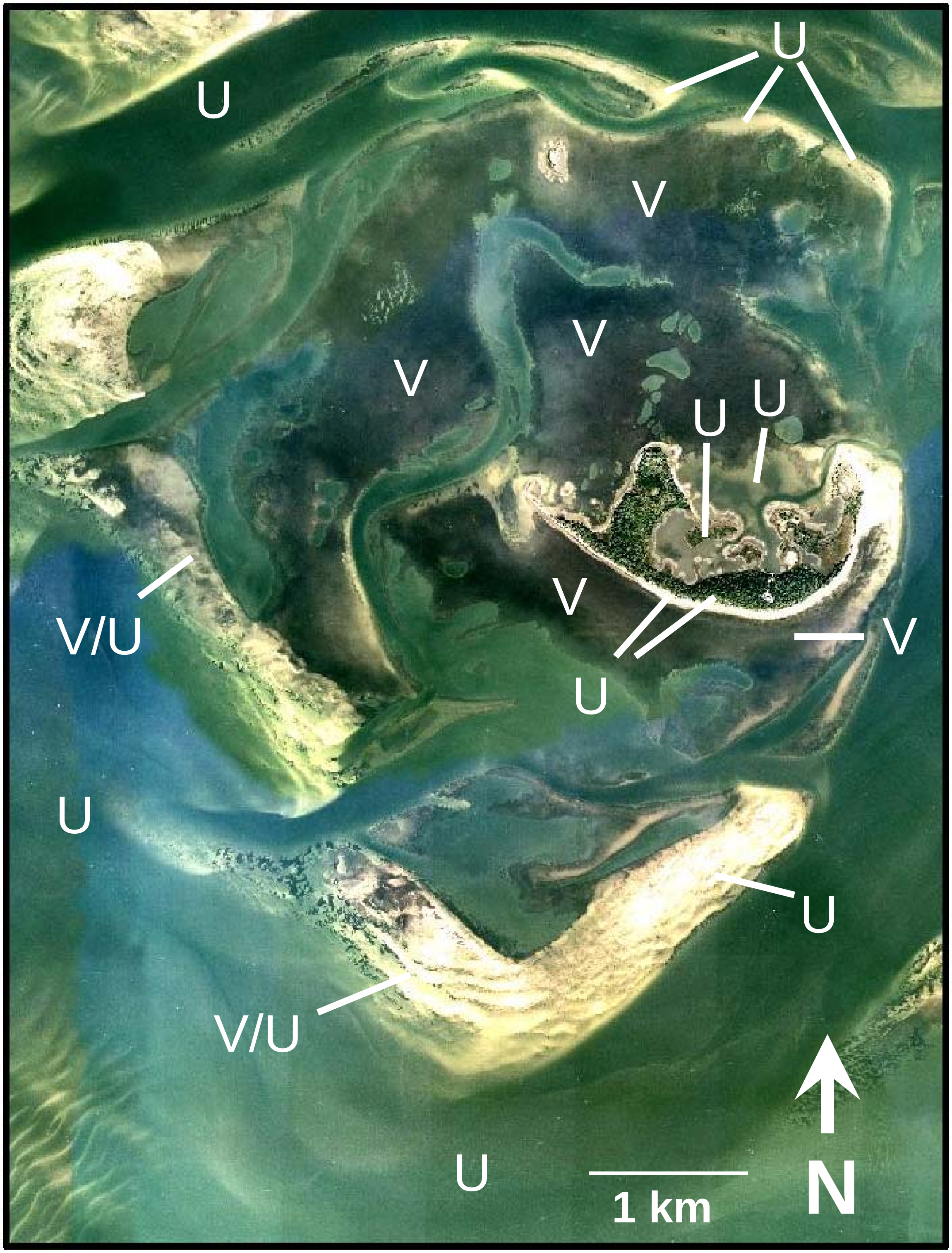


Figure 5-5. Identification of vegetated and unvegetated portions of the study area. Dark areas are mostly vegetated with seagrasses (V) while light and deep water areas are unvegetated (U). Some areas are mixed (V/U). Basemap imagery provided by the Suwannee River Water Management District.

Seahorse Key: nearshore and offshore (Figure 5-6). Nearshore flats were those within 500 m of the south and east shores of Seahorse Key. The north shore was a salt marsh. In this low energy area, wave action was negligible (Figure 5-7a). In the nearshore flats wave action was greater. Wave induced soil erosion was observed to move soil from the uplands through the beach and on to the flats (Figure 5-7b). The remaining flats were classified as offshore flats (Figure 5-6). These flats were generally more than 500 m away from the erosional shores of Seahorse Key. Therefore, the soil properties of the offshore flats were assumed to be much less dependent on the soil properties of the island.

The nearshore flats were unvegetated in the shallowest areas near the beach. Slightly deeper areas were vegetated with *Halodule*. The remaining portions of the nearshore flats were vegetated with *Thalassia* or a mixed stand of *Thalassia* and *Syringodium* (Figure 5-8).

The offshore flats were unvegetated in the shallowest areas, which were the bars near the channels. Deeper areas that graded into the channel were unvegetated. The deeper portions that graded into a flat were vegetated with *Halodule* in the shallower portions which transitioned into *Thalassia* and a mixed stand of *Thalassia* and *Syingodium* (Figure 5-9). The north flat terminated at the salt marsh cove of Seahorse Key. In this cove, terrestrial and wetland vegetation growing right up to the edge of the water along with lack of beach provided evidence that upland soil erosion to the flats was minimal (Figure 5-7a).

Soil/vegetation relationships on the flats: Previously documented upper-pedon/vegetation relationships (Chapter 3) suggested the soils supporting *Thalassia* and

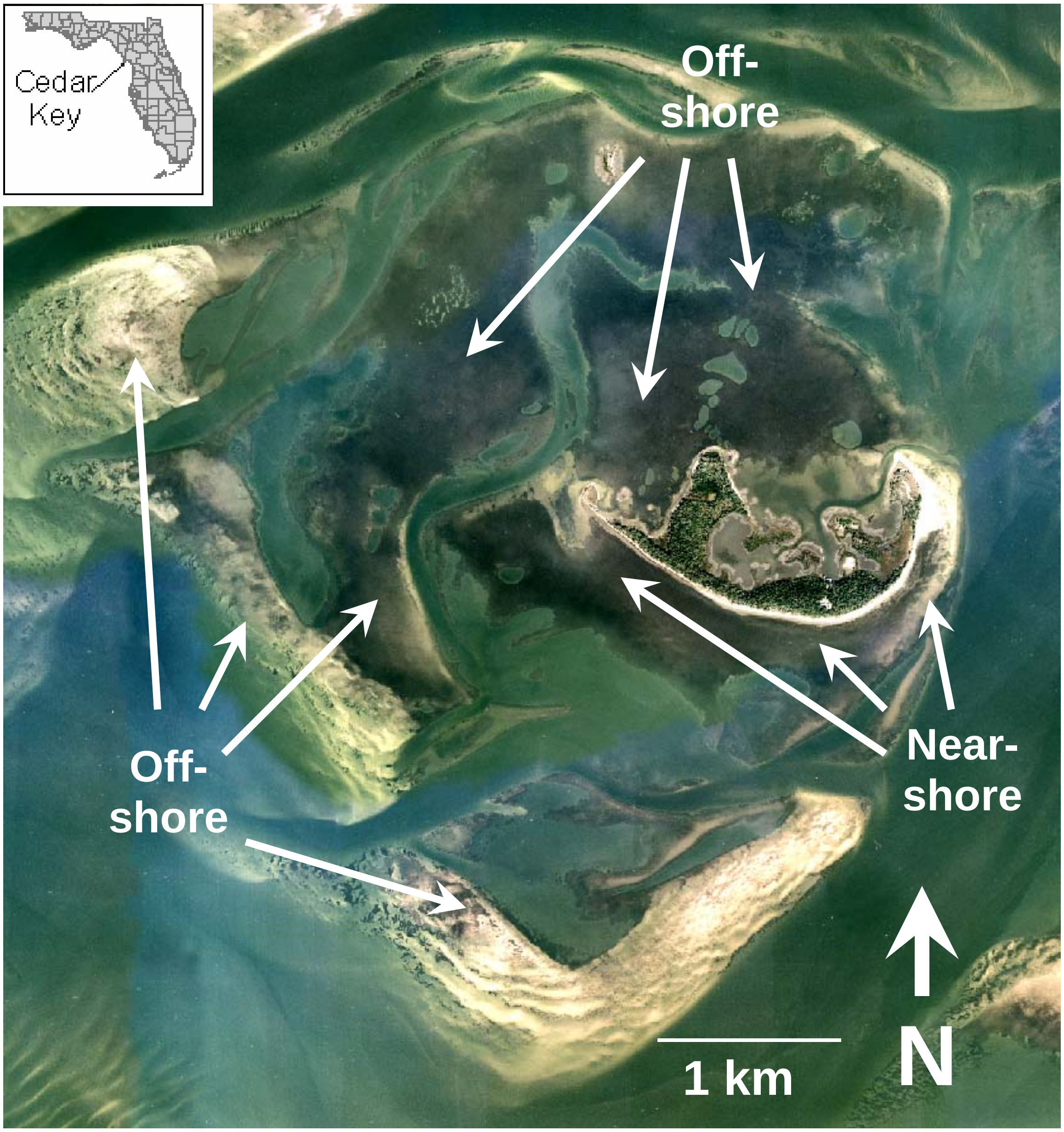


Figure 5-6. Location of nearshore and offshore flats in close proximity to Seahorse Key, FL. The offshore landscapes are those that are not under the direct influence of land either in the form of protection from wind or from the deposit of terrestrial erosional material. Nearshore landscapes are those occurring close to land and are thus influenced by the proximity. Basemap imagery provided by the Suwannee River Water Management District.

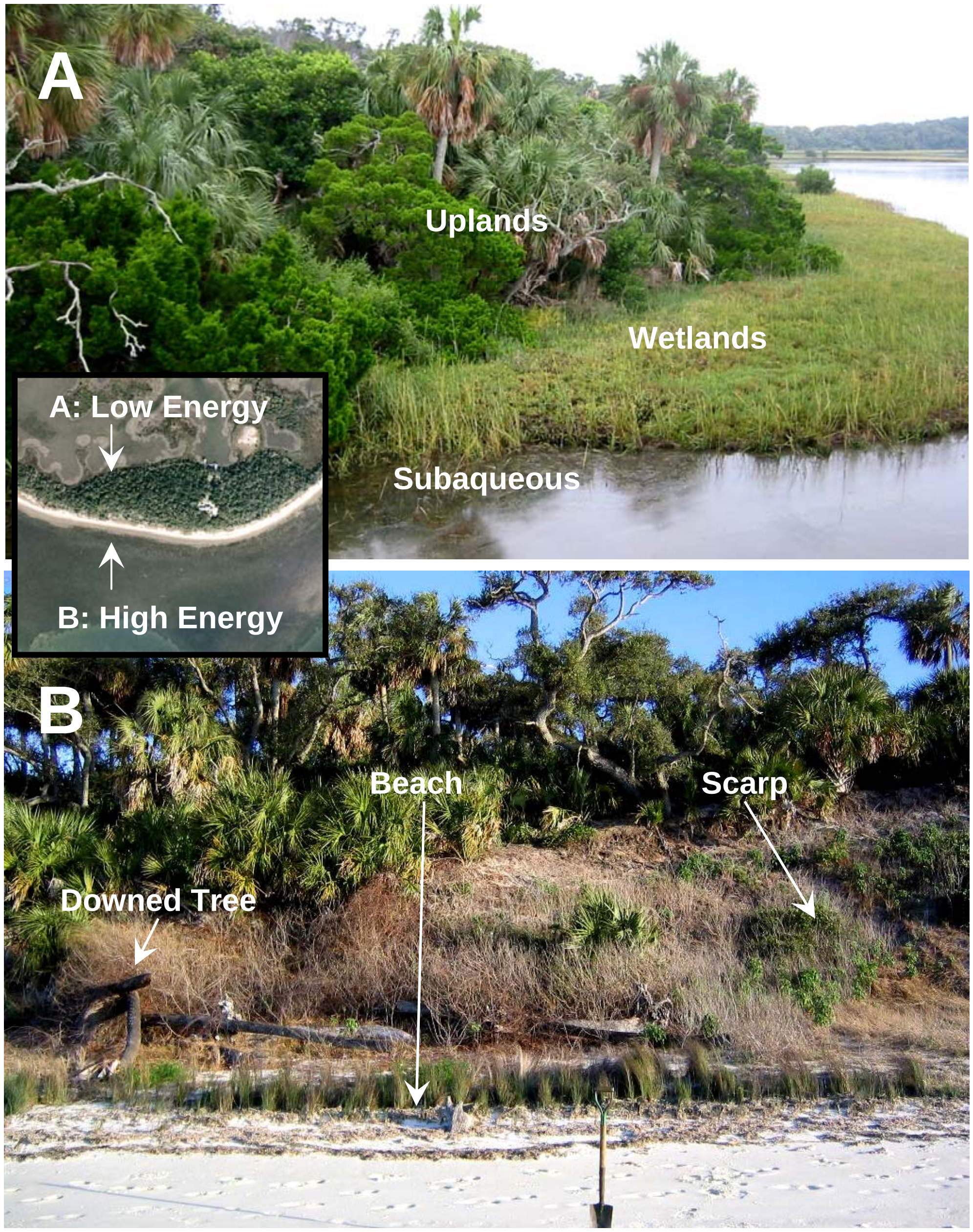


Figure 5-7. Low energy shore (A) vs. high energy shore (B), Seahorse Key, FL. Along the low energy shore, are the merging of upland, wetland, and subaqueous habitats within a very close proximity to each other. Typical of most salt marshes, very little wave energy is present near the shore under normal circumstances. In contrast, the high energy shore is characterized by a beach that slowly erodes via wave action on each high tide (B). It also receives a large supply of sand from the eroded uplands above (see scarp in B). Notice the downed trees indicating the severity of the erosion that has taken place in the past. Erosion has probably occurred along the low energy shore in A

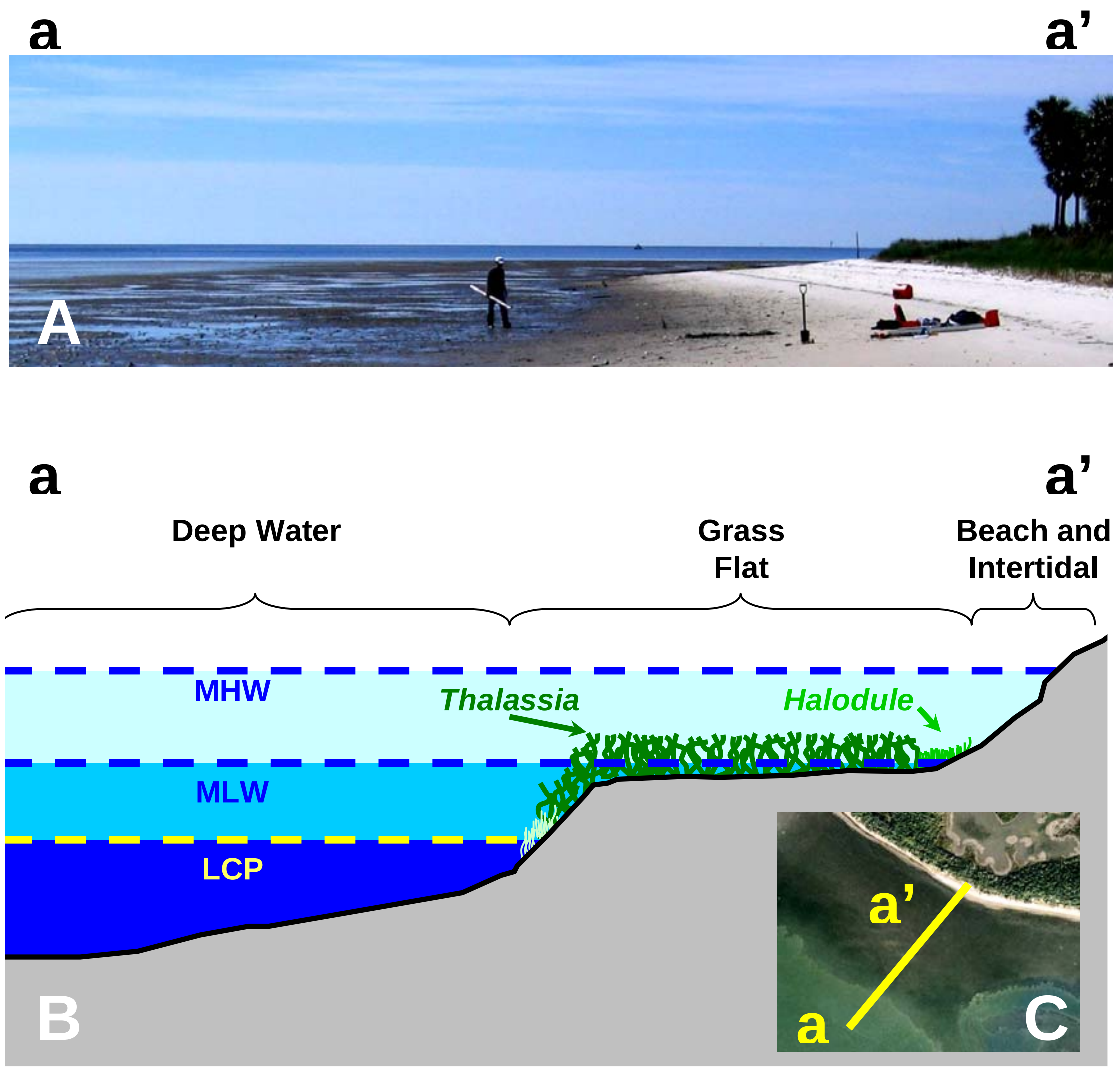


Figure 5-8. An erosional beach that grades into a nearshore grass flat. The transect of a to a’ is shown from a perspective view (A), a cross section view (B), and an aerial view (C). The conceptual landscape cross-section represents the landscape from a to a’. An extensive grass flat is the transition from the erosional beach to deeper water. On this grassflat, SAV grades from *Halodule* to *Thalassia*. Mean high water (MHW), mean low water (MLW), and the hypothetical light compensation point (LCP) are displayed in B.

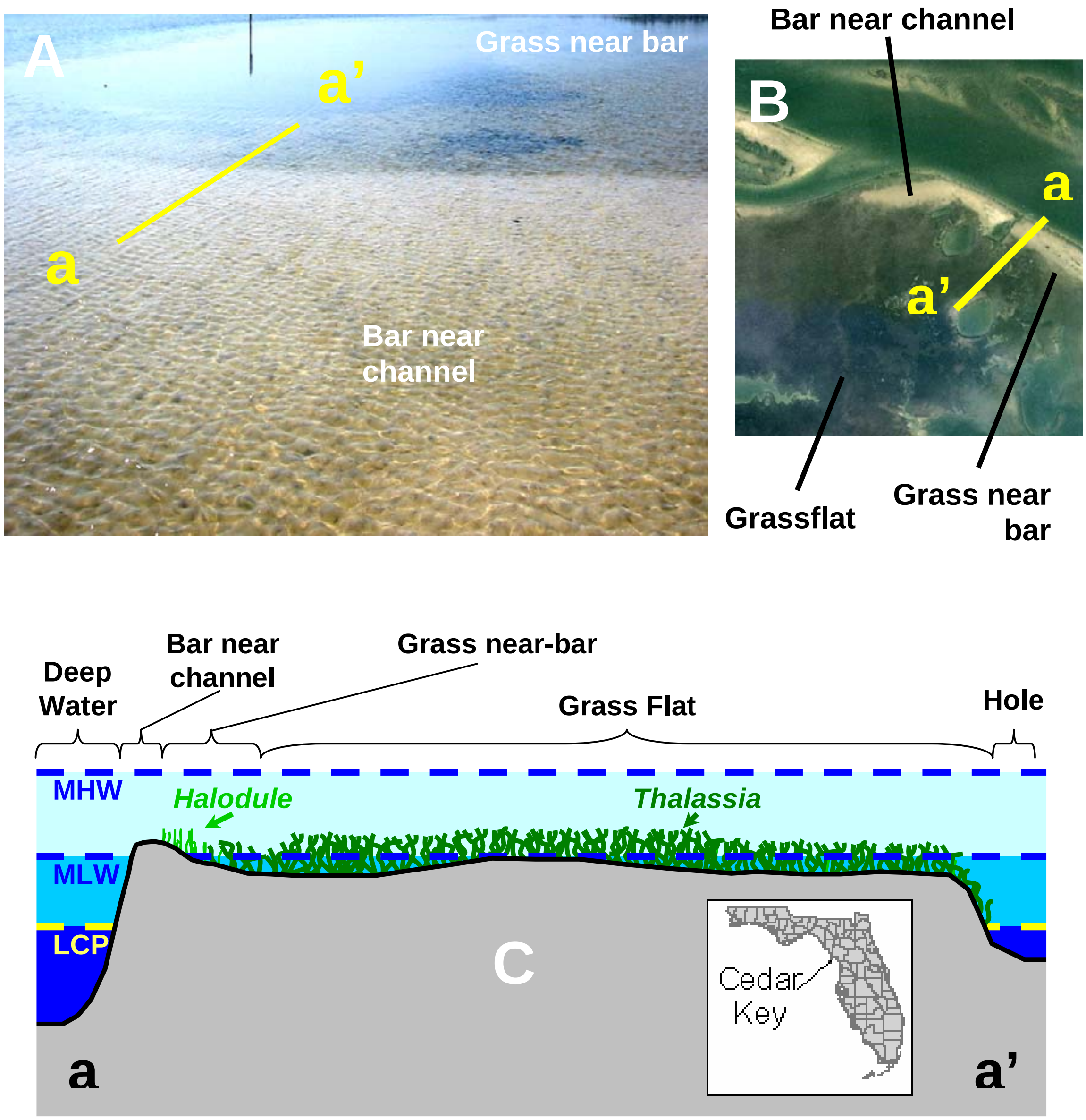


Figure 5-9. An offshore subaqueous landscape near Cedar Key, FL. Transect a-a' is shown from a perspective view (A), an aerial view (B), and a cross-section view (C). Submerged aquatic vegetation (SAV) grows within a narrow depth range of 1 m below mean low water (MLW) and 20 cm above MLW. Mean high water (MHW) is 1 m above MLW. At the edge of the channels, an unvegetated bar is usually built up. On the other (protected) side of the bar, *Halodule wrightii* typically grows in the shallow portions and *Thalassia testudinum* in the slightly deeper portions. Away from the bar, *Thalassia testudinum* is often mixed with *Syringodium filiforme*, both of which densely cover the soil at all depths up to the light compensation point, which is encountered in deeper water.

Soil/vegetation relationships on the flats: Previously documented upper-pedon/vegetation relationships (Chapter 3) suggested the soils supporting *Thalassia* and *Syringodium* to the north of Seahorse Key were higher in OM and silt and darker in color than soils in other areas. This is could be due to the lack of inputs high in sand to the soil from erosional areas such as the beaches of Seahorse Key or the edges of channels.

Energy on the flats: On high tides, it was observed that wave heights on the offshore flats north of Seahorse Key were less than half of those occurring in the deep waters of the channels and three fourths the size of the waves occurring on the nearshore grass flats south of Seahorse Key. From these observations, it was inferred that the offshore grass flats represent a relatively low energy environment.

This low energy probably facilitates the deposition of suspended fine particles and inhibits erosion of soil onto or off of the flats. Even during times of high winds (e.g., > 5 m/s) and choppy waves in the channel, the water on the flats was much calmer than adjacent deep waters. In fact, it was almost stagnant at tides below MLW.

In the winter, tides 0.5 m below MLLW frequently occur exposing the flats to sheet flow and channel flow on falling tides. The sheet flow occurred on the smooth portions of the flats. Channel flow occurred along shallow trenches caused by motor boats plowing the seagrass bed (prop-scars). This channel erosion on winter low tides could be a mechanism for the persistence of prop-scars. Although some erosion of soil within the flat and from the flat to deeper water was observed during the winter low tides, these offshore flats are inferred to be low-energy, stable areas. Mineral and organic inputs to this soil are likely aquatic in nature. Based on observations presented in Chapter 3, soils in these areas should be consistently dark (e.g., 5Y 2.5/1) with relatively high amounts of

OM (e.g., 3 to 6%) within the upper-pedon. Since these areas have been vegetated for a relatively long time (see grass flat in Figure 3-29a and b), substantial trapping of fine particles and OM has likely occurred during that period. Therefore, the deep soil horizons should look similar to the surficial horizons if either mixing or accretion occurred.

On the south side of Seahorse Key, the soil (THAL-2) had poly-value matrix colors with low OM and silt contents. This finding coincides with observations that the south shore grass flats are a relatively high energy system subject due to wave action. The erosional inputs of the island probably do not extend beyond the nearshore flats. Thus, the nearshore flats are areas with poly-value matrices and moderate amounts (1 to 3%) of OM. Because erosion was observed onto these flats, it was inferred that the nearshore flats were younger in age and built up quicker than the offshore flats. Therefore, the soil colors at depths greater than 30 cm were predicted to be poly-value unless a buried horizon (most likely an Ab horizon) was present. This Ab horizon would, therefore, be indicative of the environmental (e.g., vegetation) conditions prior to erosional deposition. Also, previously documented in Chapter 3 were the properties of unvegetated soils. Soils that did not support vegetation did not have appreciable amounts of silt, clay, organic matter, or dark colors.

Low-energy, unvegetated coves are unique due to the distinct intersection of soil-forming factors in these areas. In the cove areas, parent materials may be more dominantly aquatic because the low energy cannot transport sand. The absence of vegetation would mean that the effect of vegetation as a trapping mechanism and as an input of OM would not exist. Because of their proximity to the shore, the soils may not have been subaqueous for as long as the exposed soils. Therefore, these soils may have been terrestrial in previous times.

Some offshore flats areas appeared to be exposed to high wave energies. On the north of Seahorse Key, this was mainly along the edges of the channels. South and west of Seahorse Key, the majority of the flats were observed to be under high wave energies. This may explain the patchy appearance of the flats (U/V portions of Figure 5-6).

Drowned Soils

In some aquatic portions of the study area, subaqueous soil formation was negligible as evident by the preservation of terrestrial soil morphologies. In these areas, terrestrial soils had been “drowned” by rising sea levels (Figure 5-10). A drowned soil is defined here as a soil that has been exposed to rising water, but has undergone minimal burial as a result of that water. In a situation where rising water enhances sedimentation and/or erosion onto a soil, the soil is then buried. Soils in portions of the study area were inferred to have been drowned by rising sea-levels because a degrading spodic horizon that was present just below the surface (Figure 5-11).

Spodic horizons are diagnostic subsurface horizons. *Soil Taxonomy* (Soil Survey Staff, 1999) defines a spodic horizon as a “subsurface horizon underlying an O, A, Ap, or E horizon. A spodic horizon must have 85% of spodic materials in a layer 2.5 cm or more thick that is not part of any Ap horizon.” A spodic horizon is dominated by active amorphous materials that are illuvial and have OM and Al with or without Fe. Most importantly, the soil must have a pH of 5.9 (1:1 water) or less, and organic carbon content of 0.6% or more. The pH criteria were undoubtedly established to identify the Al associated with the OM in the spodic. In a terrestrial soil, a pH less than 5.9 as determined by 1:1 soil:water does occur in the presence of spodic materials. However, the high pH of seawater due to the high concentration of carbonates buffers the pH of drowned spodic materials. It may be possible to avoid this by obtaining an undisturbed core of a spodic horizons and flushing with de-ionized water. In this study, however, soils were not flushed, therefore pH measurements of drowned spodic horizons were similar to other subaqueous soils (Table A-2).

Commonly associated with spodic horizons are albic horizons. Although the soils of beaches with and without spodic horizons were not sampled for color analysis, it was visually noted that beaches with drowned spodic horizons were brighter (higher in value, lower in chroma) than those without drowned spodic horizons. It is reasonable to assume that beaches in the areas with drowned spodic horizons are exposed or re-worked albic horizons. Labeling using the current structure of *Soil Taxonomy* requires knowledge of the degree of re-working that has taken place. When these horizons form as part of a Spodosol, they were E horizons. Rising sea-levels and the resultant wave action has re-worked these E horizons to an unknown degree. If disturbance is minimal, these horizons should continue to be labeled E. If they have been completely re-worked, they should be labeled C. For this portion of the study area (Figure 10), they were labeled CE to denote a belief that some of the E horizon remains, but that a majority of the soil has been locally re-worked.

A transect of soil borings (yellow and black lines in Figure 5-10) were made to determine the lateral and continuous nature of the spodic horizon. This transect was from the upland flatwoods to the drowned soil. The drowned spodic horizon was verified to be laterally continuous with the terrestrial spodic horizon. Furthermore, the color of the drowned spodic horizon was similar (7.5YR 2.5/1) to the terrestrial spodic horizon.

Several chemical analyses are necessary to determine if this horizon classifies as a spodic horizon. When chemical analyses are not available, it is necessary to depend on field identification of a spodic horizon. As a consequence, a simple field test to determine if a soil has a drowned spodic horizon was developed.

Field test for determining the presence of a drowned Spodic horzion: Due to rising sea levels (Ross *et al*, 1994; Williams *et al.*, 1999) and the extent of flatwoods along the Gulf Coast of Florida, drowned flatwoods are likely to occur in this area of Florida (Figures 5-10 and 5-11). Lawrence (1974) studied the Gulf Coast near Panama City, FL. His research documented the existence of submerged "hardpan" material under several meters of gulf water.

A simple test that differentiates between subaqueous soil material and spodic soil material is needed to facilitate field identification of these horizons (Figure 5-12). It was noted that 7.5YR 2.5/1 colored solution was leaching out of the shore on low tide. This leachate was emanating from the spodic horizon just beneath the soil surface. Following this observation, it was hypothesized that the spodic materials from the horizon would cloud and stain the water column if a ped was placed in the water and crushed. The clouding likely occurs because of the elevated clay content in spodic horizons while the staining likely occurs because of the organic acids (fulvics and humics) present in spodic horizons.

The procedure to test if the subaqueous soil material is a drowned spodic horizon is as follows:

1. Obtain ped from the horizon in question and from an A horizon that is not suspected to be spodic.
2. Determine color of peds. Soils with colors of red or yellow-red hues and dark values (e.g., 7.5YR 3/1) should be suspected to be spodic.

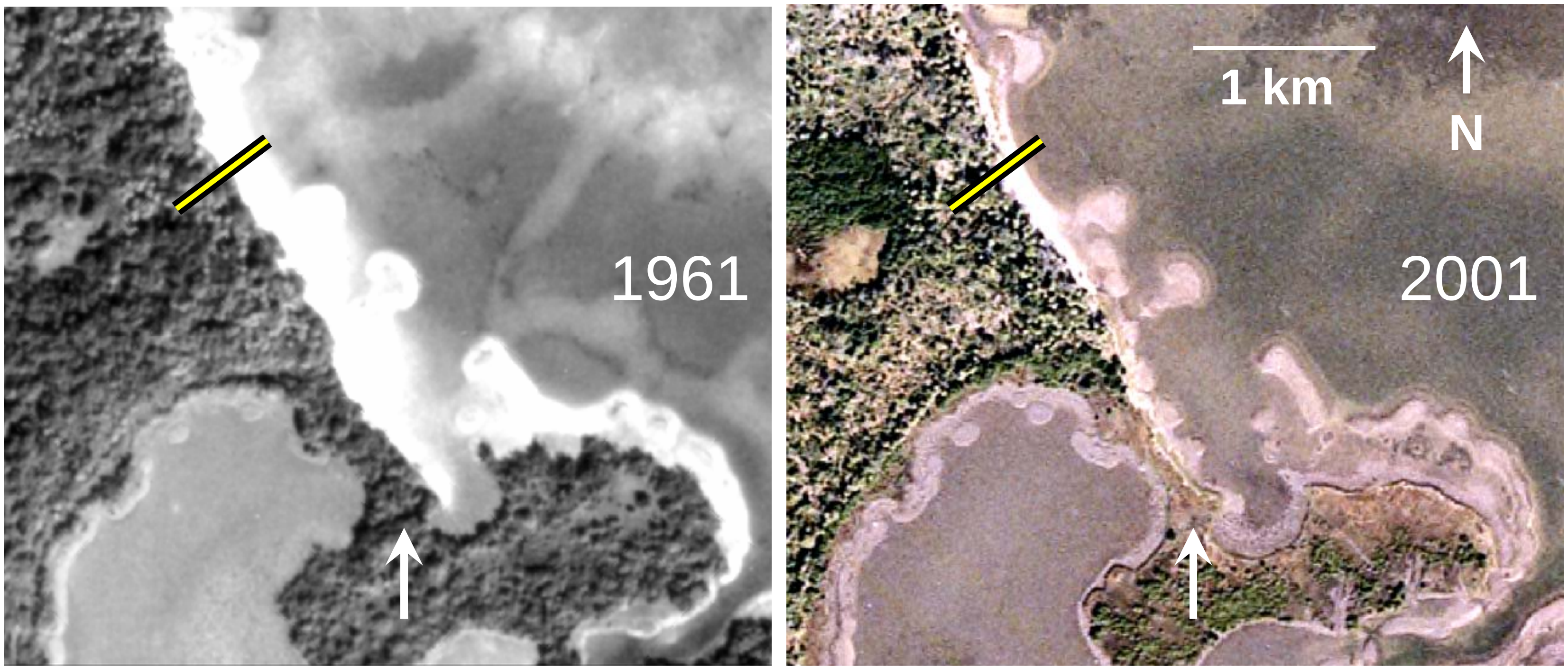


Figure 5-10. Coastal forest retreat over a forty year period: 1961 to 2001. The white arrow points to an isthmus that was forested in 1961 but was a salt marsh in 2001. The yellow and black line is the location of a transect of soil borings to confirm the continuity of the terrestrial spodic horizon with the subaqueous spodic horizon.

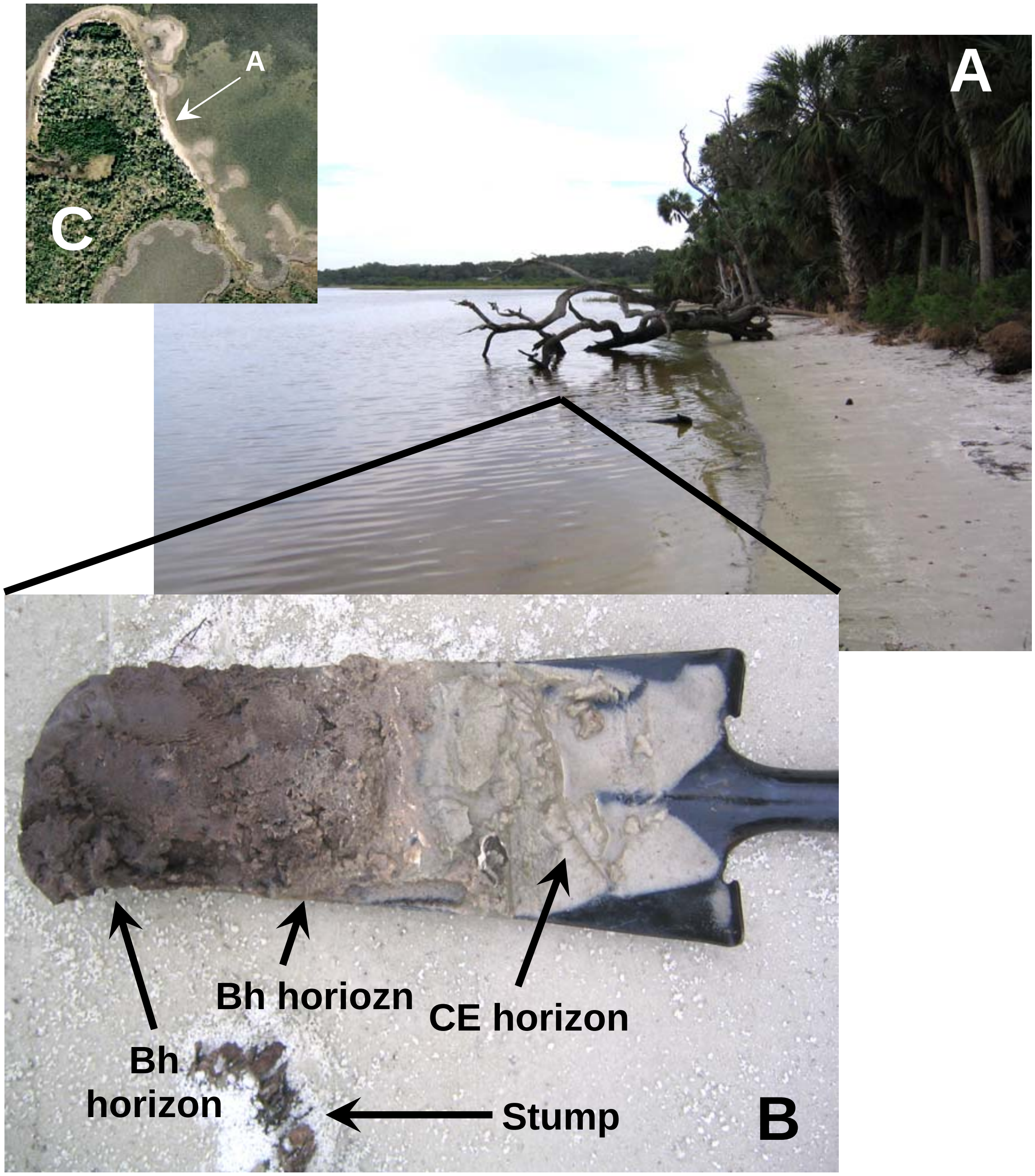


Figure 5-11. Sample of a soil that occurs on a beach that is, in fact, a drowned flatwoods. This soil was a Spodosol at one time. The dark, reddish-brown colors (7.5YR 2.5/1) of the Bh horizon in (B) are diagnostic of terrestrial spodic horizons. In Florida, spodic horizons such as these dominantly form under hydrologic conditions that occur in the poorly-drained flatwoods landscapes (a highly fluctuating water table). This morphology is evidence that areas now under water were once forested. To the side of the shovel is the stump of a tree that likely fell when it died from rising sea levels. The location of the drowned flatwoods soil relative to the island is shown in (C). The CE horizon is not recognized by in *Soil Taxonomy* (Soil Survey Staff, 1999). It is used here to denote a re-worked E horizon.

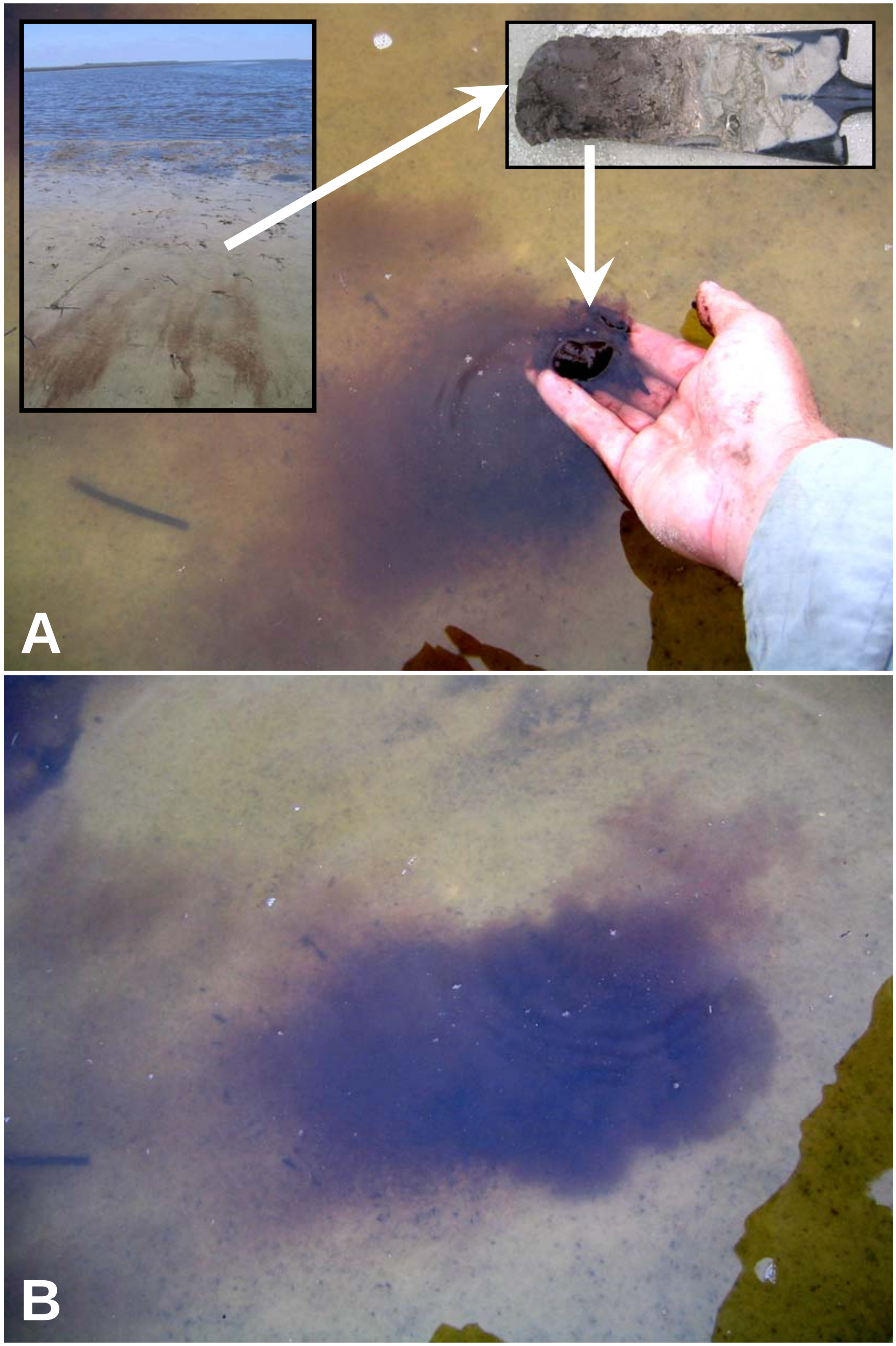


Figure 5-12. Field test to determine if material is spodic. Place soil ped into water (A). It spodic materials are present, the clay and organic acids in the spodic material will cloud the water creating a reddish-brown stain (B).

3. Are the soils sandy? If not, the clay content may be too high for the test to be accurate. If the soils are a loamy sand or coarser, place peds in water and crush between thumb and forefinger.

4. The spodic ped should cloud the water for a significantly longer amount of time than the non spodic ped (e.g., less than 10 seconds for the non spodic, 20 to 40 seconds for the spodic).

5. Repeat test several times to obtain a repeatable result.

Drowned spodic horizons were frequently encountered throughout course of the study. Each time a soil with a reddish hue was encountered, the test determined the material was spodic. Although no known subaqueous podzoliziation occurs, subaqueous soils can theoretically contain high amounts of clay. These soils, unlike the subaqueous A horizons at occurring near Cedar Key, FL would likely cloud the water if clay content was above a few percent. The reddish-brown stain in the water would likely not occur, however, unless the soil contained spodic materials (fulvic and humic acids). This field test for differentiating drowned spodic horizons from subaqueous A horizons needs to be tested in areas outside Cedar Key, FL before it can be more generally applied.

Buried Soils

Terrestrial horizons are not the only horizons that can be buried or drowned. In Chapter 3, it was documented that Ab horizons occur in areas where vegetation has undergone change from dense to sparse or no cover. All soils associated with *Halodule*, should be suspected to have Ab horizons. This is because *Halodule* grows in soils slightly higher in elevation than those that support *Thalassia* and/or *Syringodium*. Burial of soils vegetated with *Thalassia* and/or *Syringodium* would create a habitat suitable for *Halodule* if the resultant soil elevation is not too high (see Chapter 3 for a discussion of soil elevations). Generally, these soils occur on bars vegetated with *Halodule*. Therefore, the inference can be made that the bar had built on top of seagrass flat and then *Halodule* colonized the bar. A typical example of this phenomenon is shown in Figure 5-13.

General Subaqueous Soil-forming Factors

Flow regime (energy): Flow regime is a new soil-forming factor proposed by Demas and Rabenhorst (2001) for subaqueous soils. They described “flow regime” as the energy of the water in which the soils form. They mainly referred to the “shaping” of the subaqueous terrain through the build up of bars under high energy environments. Along the low energy areas of the Gulf Coast of Florida the converse situation is equally important.

Low energy environments provide an opportunity for the settling of fine particles. On shallow vegetated flats, low energies are not likely to carry sand-sized or larger particles. Areas of dense vegetation could enhance the low energy nature of the flat by baffling water flow, thus encouraging the settling of the fine particles.

Climate: The subtropical climate allows for the growth of Caribbean species of seagrasses. Given the relationships between seagrasses and soils documented in Chapter 3 and in this chapter, climate has an effect on soil properties. This study did not investigate areas outside Cedar Key, FL, therefore the effects of climate on soil properties are beyond the scope of this study.

Relief (bathymetry or elevation): The elevation of the soil was related to vegetative cover. Therefore, elevation was related to soil properties of the upper-pedon. The flats were vegetated at most elevations except for the shallowest portions. The soil properties of the upper-pedon varied accordingly.

Biota: Another soil-forming factor, biota, includes both vegetation and animals. Generally, benthic invertebrates will burrow deep in less reduced soils (Valiela, 1995).

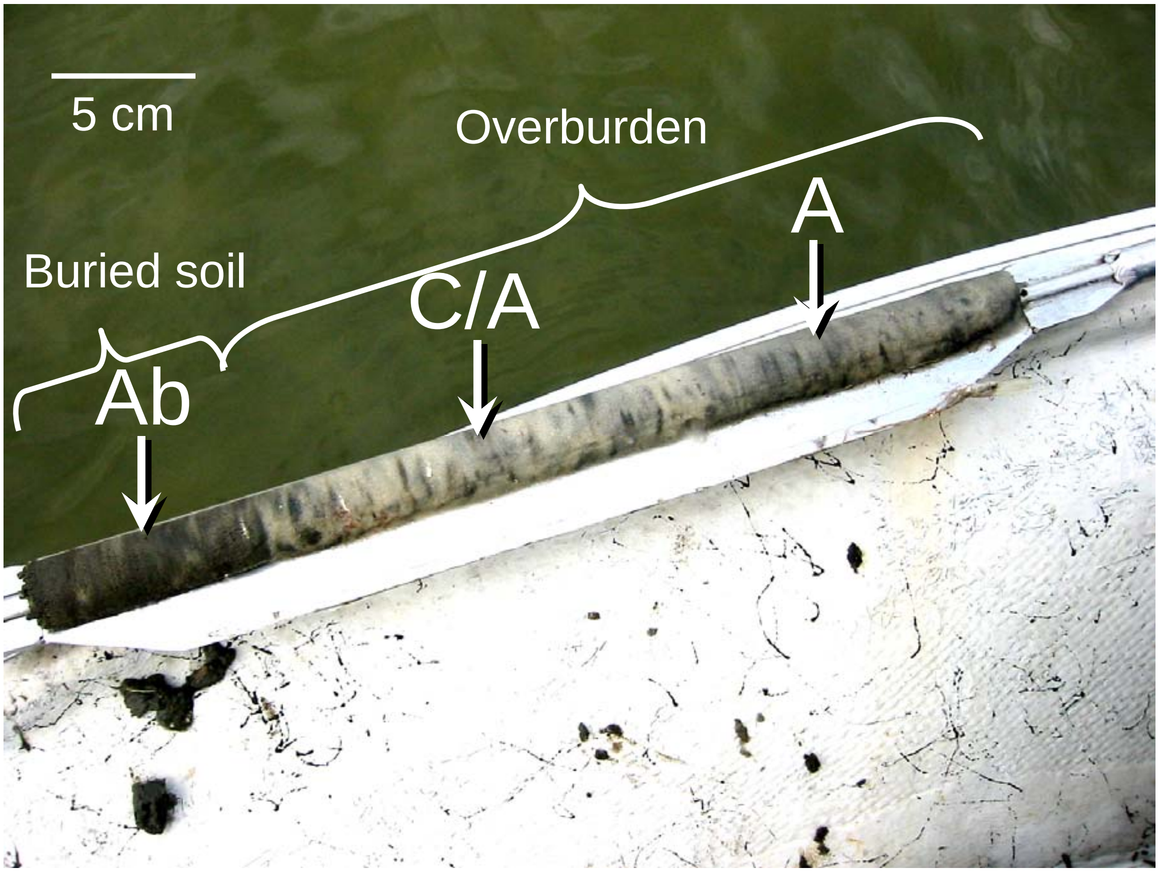


Figure 5-13. Buried A horizon from an area near Seahorse Key, FL currently supporting *Halodule wrightii*. The presence of dark soil material that appears similar to that occurring under dense beds of *Thalassia testudinum* suggests this area was once heavily vegetated. Early loss of the *Thalassia* could have been caused by sedimentation. Alternativly, the overburden could have resulted from the lack of dense vegetation to trap other fine particles and add organic matter to the soil.

Shallow nearshore areas that are unvegetated are likely more oxygenated due to exposure at low tide and contained large soil pores that allow free water flow. Therefore, these areas should have evidence of bioturbation leading to poly-value matrices. Additionally, the high energy of these areas on high tide could remove fine particles that may have settled at low water. Thus, removing most of the detrital OM inputs to the soil. Bioturbation in these areas would probably not be masked by large OM inputs. Consequently, the poly-value nature of the soil would be preserved.

Parent material: Parent material is another soil-forming factor that significantly influences the soil properties throughout the study area. The dominant sand-size mineralogy of the parent material of Levy County terrestrial soils (Slabaugh, 1996) is quartz. Except for sand-sized shell fragments, the sand fraction in the subaqueous soils is also overwhelmingly quartz (see Chapter 3 for a discussion of soil components).

X-ray diffraction of a soil supporting *Thalassia* and *Syringodium* and a soil supporting *Halodule* revealed the nature of the silt and clay sized soil components. The identification of carbonates (Calcite, Dolomite, and Aragonite) in the untreated soil and the lack of these peaks in the treated soil suggested that these minerals are components of the soil. Additionally, these peaks were absent in an XRD profile of a nearshore soil supporting *Halodule*, suggesting these components are not present in these soils (Figure 5-14).

Iron oxide and kaolinitic coatings were present on the terrestrial soils (e.g., Orsino series) and are evident in the subaqueous soils as noted by the color of unvegetated soils (10YR 7/4) and by XRD analysis (Figure 5-14). Also, noticeable in the XRD analysis were carbonates such as calcite, aragonite, and dolomite. These were present in an

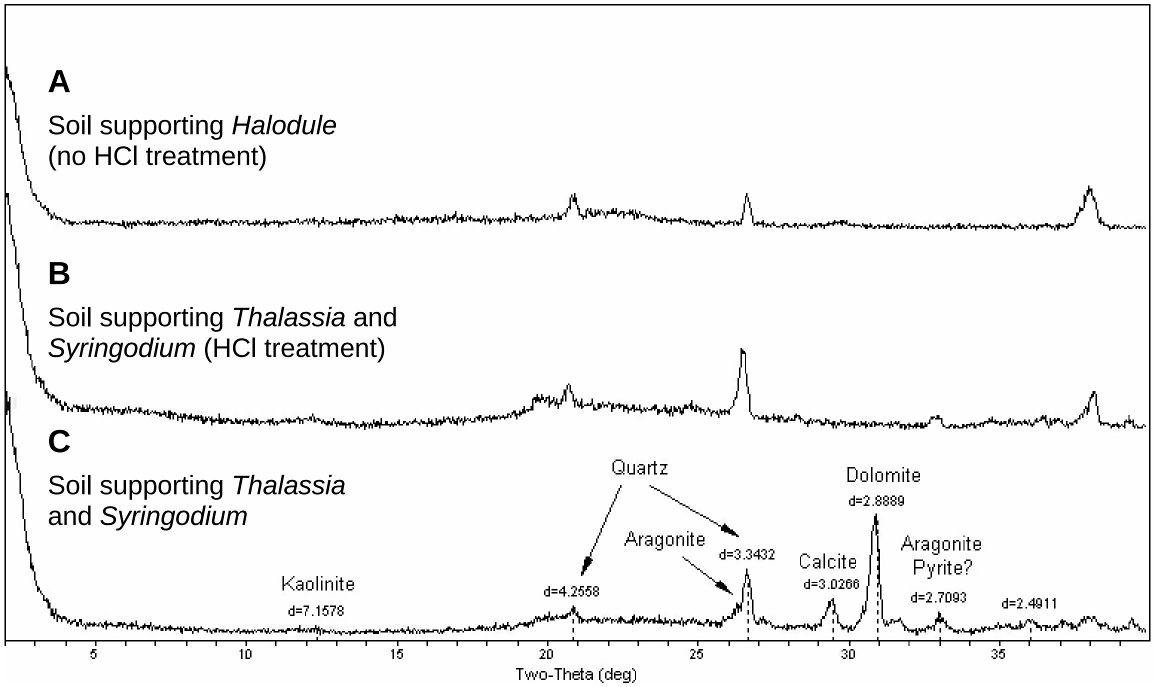


Figure 5-14. X-Ray Diffraction (XRD) patterns of the combined silt and clay size fractions from the rooting zone of two vegetated subaqueous soils. Pattern A represents a soil that occurred near a bar supporting *Halodule wrightii*. Patterns B (carbonates removed) and C (carbonates not removed) represent a soil that occurred on an offshore grassflat supporting a mixed stand of *Thalassia testudinum* and *Syringodium filiforme*. Prior to the XRD analysis for pattern B, the sample was treated with excess 1N HCl to remove carbonates. The d-spacing of each the peaks allowed for the identification of the following minerals: kaolinite, quartz, aragonite, calcite, dolomite. Additionally, it is possible that pyrite is present. Neiher the calcite, dolomite, nor Aragonite peaks are present in pattern B, further supporting their identification from the XRD patterns. In pattern A, those carbonate minerals are also not present.

offshore vegetated soil but not in a nearshore vegetated soil. This suggests that the parent material in the offshore areas was of aquatic origin. The absence of carbonates along with the direct observations of terrestrial soil erosion suggests the parent material of these nearshore areas is terrestrial in nature.

Time: Time on both a geological scale (millions of years) and a historical scale (100s of years), is an important factor in soil formation. Historical air photo analysis shows that some offshore areas near bars and some nearshore areas near erosional beaches have only been recently vegetated (Figure 3-29 a and b). The soil morphologies in these areas are probably much less well-expressed and could be inferred as light (values 6-8) matrix colors and only slightly poly-value. Other areas such as much of the offshore vegetated flats have been vegetated for at least the last 40 years (Figure 3-29 a and b). In Chapter 3, the soils of these areas were reported to be dark in color, and high in OM and silt contents. These soils could be inferred to be more developed. Some areas of these nearshore flats occur in high energy environments and are temporally unstable (Figure 3-29 c and d). It could be inferred that the morphologies of these soils are similar to those in unvegetated and recently (< 40 years) vegetated areas.

Landscape Units

The study area was conceptually divided into landscape units (Table 5-2) that isolated unique combinations of subaqueous the soil-forming factors. Each landscape unit was assigned a map unit identification (MUID) number and was hypothesized to have soils unique to that unit. Once established, these units were delineated throughout the study area on the 2001 true color aerial photography reprinted at a scale of 1:20,000. Those delineations were then re-digitized in a GIS (Figure 5-15). The randomly selected validation points were distributed throughout most of the study area (Figure 5-2) and

Table 5-2. Landscape units present within the study area. Each landscape unit was assigned a unique map unit identifier (MUID).

MUID	Landscape Unit	Abbreviation
1	Erosional Unvegetated Flat / Near Channel Bar Complex	EUF/NCB
2	Deep Water	DW
3	Edge of Channel Bar	ECB
4	Erosional Beach	EB
5	Erosional Unvegetated Flat	EUF
7	Near Bar Grassflat	NBG
8	Drownded Flatwoods	DF
9	Nearshore Grassflat	NSG
10	Offshore Grassflat	OFGF
11	Oyster Bar	OB
12	Saltmarsh	SM
13	Saltmarsh Flat	SMF
14	Unvegetated Flat	UF
15	Uplands	U

Figure 5-15. Spatial landscape model. Each number on the model represents a landscape unit type. The original scale of the model is 1:20,000. This figure appears approximately 1:28,000. Some map units are indistinguishable at thid scale. The legend of landscape unit name and associated MUID is in Table 5-2.

generally, the soil morphologies within map units were consistent. The within map unit variability appeared low for most map units. One exception was Map Unit 13 (Salt marsh flats). After devising the map unit numbering scheme, it was decided that Map Unit 6, a barrier bar was better described by Map Unit 1 (Erosional unvegetated flat/Near channel bar complex), thus all areas identified as Map Unit 6 were changed to Map Unit 1.

Map Unit 1, Erosional Unvegetated Flat / Near Channel Bar Complex: Areas classified as Map Unit 1 are areas of intermingled Map Units 5 and 7. At the 1:20,000 map scale, these intermingled areas were too small to be delineated individually. Thus they were collectively delineated as Map Unit 1. Map Unit 1 occurs away from shore. While terrestrial soil erosion to the subaqueous soil was not inferred, the re-working of subaqueous soil due to wave action was directly observed. The dominant process occurring in these units was the burial of *Halodule* by wave action. Subsequently, some areas support *Halodule* and other areas do not. Buried A horizons were frequently observed in the unvegetated areas. Since burial of the vegetation was considered to be more frequent than occurs along the channel bars, Map Unit 1 was viewed as more similar to the erosional unvegetated flat areas (Map Unit 5). Thus Map Unit 1 was considered to be a complex of 80% Map Unit 5 and 20% Map Unit 7. Individual areas of vegetated and unvegetated could not be separated at the scale selected. Individual areas could be shown on a much larger map scale (e.g., 1:5:000).

Map Unit 2, Deep Water: These areas are unvegetated and under deep water. They do not meet the definition of soil by virtue of support for vegetation and were assumed not to display soil morphology. Therefore, no soil observations were made for this map unit.

Map Unit 3, Edge of Channel Bar: These areas occur along the edges of deep water (Figure 5-9). These areas are inferred to be wave deposited sand originating from the deep water. The protected portions of this map unit support *Halodule wrightii*. Soils in Map Unit 3 have poly-value colors in the upper-pedon. These bars likely formed by burial of offshore grass flats (Map Unit 10). The depth to the Ab horizon varies. The depth to the Ab horizon may suggest that some bars may be relatively older (more burial had occurred) than others (Table 5-3).

Map Unit 4, Beaches: Most soil surveys of coastal counties delineate the beaches and thus identify them as beaches map unit. This standard was adopted to facilitate the joining of a subaqueous soil survey with a terrestrial survey. No soil descriptions were made for this map unit.

Map Unit 5, Erosional Unvegetated Flat: As documented in Chapter 3, the upper-pedons of unvegetated areas are consistently devoid of OM and dark colors. In areas that are unvegetated due to the burial of seagrass from unstable beaches, buried A horizons occur. These buried A horizons reflect the past vegetative history of the area. The morphologies of the Ab horizons in Map Unit 5 suggest the previous vegetation was *Halodule* or *Thalassia* (Table 5-4).

Map Unit 6, Barrier Bar: After delineation and digitization of the map delineations, it was decided that barrier bars were best described as a complex of Map Unit 5 and 7: Map Unit 1. Thus all areas initially delineated as Map Unit 6 were re-classified as Map Unit 1. Soil surveys are a work in progress, and missing map units can

Table 5-3. Soil descriptions from Edge of Channel Bar (MUID 3). Textural class abbreviations: loamy sand (LS), sand (S).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
ECB-1	C1	0-2	LS	5Y 3/1	1	shells in medium pieces
	C2	2-45	S	2.5Y 6/1		
	Ab1	45-69	S	2.5Y 2.5/1		
	Ab2	69-200	S	2.5Y 4/1		
ECB-2	C	0-15	S	5Y 5/1		
	Ab	15-200	S	2.5Y 2.5/1		
ECB-3	C1	0-4	LS	5Y 3/1		
	C2	4-85	S	2.5Y 6/1		
	Ab	85-200	S	5Y 2.5/1		
ECB-4	C1	0-8	S	5Y 5/1		
	C2	8-35	S	2.5Y 6/1		
	C3	35-72	S	2.5Y 7/1		
	Ab	72-200	S	2.5Y 2.5/1		
ECB-5	C	0-61	S	5Y 5/1		
	Ab	61-200	S	5Y 3/1		

Table 5-4. Soil descriptions of soils in the Erosional Unvegetated Flats (MUID 5). Textural class abbreviations: loam (L), sand (S).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
EUF-1	C	0-31	S	5Y 6/2	2	
	Ab	31-39	S	2.5Y 2.5/2		
	Ab/C	39-200	S	5Y 4/2	20	10% 5Y 7/2
EUF-2	C	0-78	S	10YR 6/2		
	Ab	78-200	L	5Y 5/1		
EUF-3	C1	0-42	S	5Y 6/3		
	C2	42-200	S	5Y 5/1		
EUF-4	C	0-22	S	5Y 7/2	2	
	Ab	22-39	S	2.5Y 2.5/2		
	Ab/C	39-200	S	5Y 3/2	10	20% 5Y 5/2
EUF-5	C	0-18	S	5Y 7/2	2	
	Ab	18-57	S	2.5Y 2.5/2		
	Ab/C	57-200	S	2.5Y 3/2	5	20% 5Y 5/2

be frequently found in published surveys. For example, Map Unit 20 does not appear in the Levy County Soil Survey (Slabaugh *et al*., 1996).

The practice of preserving the existing map unit numbering scheme rather than re-numbering to maintain a consecutive numbering scheme is deliberate. The reason for doing so is mainly to eliminate confusion as soil surveys are updated. Consider again the Levy County Soil Survey (Slabaugh *et al*., 1996). Map Unit 20 in the Levy County Soil Survey does not exist and the highest map unit number is 78. When updated, if a new map unit is added to the survey, it will be designated Map Unit 79 instead of Map Unit 20. This maintains a consistency between old and new surveys.

Map Unit 7, Near Bar Grassflat: The portions of either nearshore or offshore grass flats occuring near the bars of Map Unit 3 are dominantly *Halodule* and occasionally monotypic *Thalassia*. Because these areas are adjacent to the bars and channels, some wash-over of sand from Map Unit 3 to Map Unit 7 has occurred. The resultant buried A horizons present in all these soils suggests that before wash-over, either nearshore or offshore grass flats were present (Table 5-5).

Map Unit 8, Drowned Flatwoods: This map unit occupies the same landscape position as Map Unit 4, but occurs on the north side of the island in the salt marsh cove. These areas are unvegetated. A degrading spodic horizon was present in all soils observed in this map unit (Table 5-6). These horizons were confirmed to be spodic using the previously mentioned field test. Since they were documented to be laterally continuous with terrestrial Spodosols in the adjacent uplands, it was inferred that soils in this map unit were once upland flatwoods. The degrading spodic was also observed in some of the soils in Map Unit 9 and Map Unit 11. A shell midden was observed on the

Table 5-5. Soil descriptions for soils occurring on the Near Bar Grassflat landscape units (MUID 7). Textural class abbreviations: loamy sand (LS), sand (S).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
NBGF-1	C/A	0-18	S	2.5Y 6/4		20% 2.5Y 2.5/1
	C	18-34	S	2.5Y 6/4		
	Ab	34-200	LS	2.5Y 2.5/1	5	
NBGF-2	C/A	0-28	S	2.5Y 7/4		5% 2.5Y 2.5/1
	C	28-44	S	2.5Y 7/4		
	Ab	44-200	S	2.5Y 2.5/1		
NBGF-3	C/A	0-22	S	2.5Y 5/3		15% 2.5Y 2.5/1
	C	22-53	S	2.5Y 5/3		
	Ab	53-200	LS	2.5Y 2.5/1	2	
NBGF-4	C/A	0-15	S	2.5Y 6/3		20% 2.5Y 2.5/1
	C	15-62	S	2.5Y 6/3		
	Ab	62-200	LS	2.5Y 2.5/1	5	
NBGF-5	C/A	0-25	S	2.5Y 6/4		10% 2.5Y 2.5/1
	C	25-59	S	2.5Y 6/4		
	Ab	59-200	LS	2.5Y 2.5/1	10	

Table 5-6. Soil descriptions for the Drowned Flatwoods map unit (MUID 8). Textural class abbreviations: sand (S).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
DF-1	C	0-18	S	5Y 7/2	25	Shell fragment from adjacent midden
	Bw	18-31	S	7.5YR 6/3		
	Bh	31-82	S	7.5YR 2.5/2		
DF-2	C	0-21	S	5Y 7/2	25	Shell fragment from adjacent midden
	Bw	21-29	S	7.5YR 6/3		
	Bh	29-110	S	7.5YR 2.5/2		
DF-3	C	0-35	S	5Y 7/2	25	Shell fragment from adjacent midden
	Bw	35-45	S	7.5YR 6/3		
	Bh	45-105	S	7.5YR 2.5/2		
DF-4	C	0-12	S	5Y 7/2	25	Shell fragment from adjacent midden
	Bw	12-24	S	7.5YR 6/3		
	Bh	24-97	S	7.5YR 2.5/2		
DF-5	C	0-17	S	5Y 7/2	25	Shell fragment from adjacent midden
	Bw	17-26	S	7.5YR 6/3		
	Bh	26-89	S	7.5YR 2.5/2		

terrestrial Spodosols in the adjacent uplands. These shells were also present in the soils of Map Unit 8.

Map Unit 9, Nearshore Grassflat: Soils in this landscape unit were observed to be vegetated with either *Halodule* or *Thalassia*. The vegetation was zonated according to distance from shore as the depth increased. Nearest the shore, soils were unvegetated. In the next zone, *Halodule* was present. These two zones could not be delineated at 1:20,000. No soils in either of these zones were described, but were observed to have upper-pedons consistent with those described in Chapter 3. The remainder of the map unit has water deep enough to support *Thalassia* while the edges supported *Thalassia* and *Syringodium*.

A drowned and and buried spodic horizon was observed in two of the five soils (NSGF-2 and NSGF-5) described in Map Unit 9 (Table 5-7). These horizons were confirmed to be drowned spodic using the previously mentioned field test. These soils occurred closer to the island and were thus closer to the terrestrial Spodosols.

Map Unit 10, Offshore Grassflat: Areas of this map unit support mixed stands of *Thalassia* and *Syringodium*. In the offshore grass flats, water currents were slow to stagnant at low tide but currents were faster during tidal transition. A flocculent layer was observed in all the soils, but was only a few cm thick. This floc layer could be detrial material either produced in the grass bed or trapped from the water column. The components (e.g., mineralogy, N and C isotopes, etc.) of this material were not determined. It is possible that benthic organisms provide a mechanism for downward movement of this material. Also, it is possible that much of the material is removed due to erosion on low tides (Table 5-8).

Table 5-7. Soil descriptions for the Nearshore Grassflat map unit (MUID 9). Textural class abbreviations: loamy sand (LS), sand (S).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
NSGF-1	C	0-5	LS	2.5Y 6/4		
	A	2-20	S	2.5Y 2.5/1	5	
	A / Cg	20-200	S	2.5Y 2.5/1	5	40% 5Y 5/1
NSGF-2	C	0-2	LS	2.5Y 6/4		
	A	2-32	S	2.5Y 2.5/1	2	
	A / Cg	32-138	S	2.5Y 2.5/1	2	30% 5Y 5/1
	Bhb	138-200	S	7.5YR 2.5/3		
NSGF-3	C	0-2	LS	2.5Y 6/4		
	A	2-20	S	2.5Y 2.5/1		
	A / Cg	20-150	S	2.5Y 2.5/1		20% 5Y 5/1
NSGF-4	C	0-2	LS	2.5Y 6/4		
	A	2-22	S	2.5Y 2.5/1	5	20% 5Y 5/1
	A /Cg	22-200	S	2.5Y 2.5/1		40% 5Y 5/1
NSGF-5	C	0-2	LS	2.5Y 6/4		
	A / Cg	20-150	S	2.5Y 2.5/1	2	20% 5Y 5/1
	Bhb	150-200	S	7.5YR 2.5/3		

Table 5-8. Pedon descriptions from the Offshore Grass Flat map unit (MUID 10). Textural class abbreviations: loamy sand (LS), sand (S), and sandy loam (SL).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
OSGF-1	Al	0-5	LS	5Y 2.5/1		Very low *n* value
	A2	5-17	S	5Y 2.5/1		
	A3	17-22	S	5Y 3/1		
	A4	22-200	S	5Y 3/1	70	
OSGF-2	Al	0-12	LS	2.5Y 2.5/2		
	A2	12-43	LS	2.5Y 3/2	2	
	A / Cg	43-200	LS	2.5Y 3/2	2	2% 2.5Y 5/2 splotches
OSGF-3	A1	0-11	SL	N2/0	2	Very high *n* value
	A2	11-20	LS	5YR 2.5/1	4	
	A3	20-60	LS	5Y 3/1	12	
	A4	60-91	LS	5Y 3/1		
	A5	91-200	SL	5Y 2.5Y/1		
OSGF-4	Al	0-25	LS	2.5Y 2.5/2	5	
	A2	25-200	LS	2.5Y 3/2	5	
OSGF-5	Al	0-15	LS	2.5Y 2.5/2		
	A2	15-89	LS	2.5Y 3/2	1	
	A / Cg	89-200	S	2.5Y 3/2	1	2% 2.5Y 4/2 splotches

A Mollic epipedon is defined in *Soil Taxonomy* (Soil Survey Staff, 1999) as having the following general characteristics (see *Soil Taxonomy* for exact requirements):

- Dark Color: Value of 3 or less (moist) and 5 or less (dry)
- High organic carbon content: > 0.6%
- High base saturation: > 50 %
- Thickness: 10 to 25 cm depending on other soil properties
- *n* value < 0.7.

Although dry colors are not reported in Table 5-8, they typically were on the 5Y and 2.5Y pages with a value of 5 or 4 and a chroma of 1. Organic carbon content can generally be assumed to be half of OM content. The THAL/SYR soils analyzed in Chapter 3 occurred on offshore grass flats. All of these soils had OM contents above 4% Table A-1), therefore it can be assumed that their OC contents were above 0.6%. Base saturation was not measured, however, the extremely high concentrations of bases (Ca, M, and K) measured in all subaqueous soils in this study (Table A-2) coupled with active acidity measurements around pH 8 (Table A-2), support the assumption that base saturation exceeds 50% for all soils. Table 5-8 shows the dark colored A horizons extend well below the 25-cm depth. Although some soils had surface horizons of a high *n* value (OSGF-1 and OSGF-3), most soils had *n* values less than 0.7. Furthermore, these horizons that were of high *n* value were not thick enough to exclude these soils from having a Mollic epipedon. Given this evidence, the soils occuring in offshore grass flats should be considered Mollisols.

While some may consider subaqueous soils to be outside the concept of Mollisols, others may not. One’s concept of a soil taxa is likely formed via one’s experience and training. If much time is spent dealing with the Mollisols of the Midwestern U.S., then certainly the seagrass flats of the Southeastern U.S. is “outside” that experience. On the other hand, if one's experience with Mollisols were exclusive to Florida, then the aquolls that occur in Florida's wetlands may seem more similar to these soils occuring on offshore seagrass flats. Regardless of one's perspective, *Soil Taxonomy* was established to allow the classification of soils based on properties, not concepts of genesis. Guy Smith, the founder of *Soil Taxonomy* explicitly states this in his interviews (Smith, 1986). The soils of these offshore grass flats meet the criteria of a Mollisol and should be classified as such.

Map Unit 11, Oyster Bar: These soils support and occurr underneath oyster bars. This map unit occurs adjacent to Salt Marsh Flats (Map Unit 13). The soils of Map Unit 11 are sandier and have a much lower *n* value than the Salt Marsh Flats. In one of the soils described in this map unit, a buried and degrading spodic horizon was observed. This horizon was confirmed as a spodic horizon using the previously mentioned field test. This soil was proximate to terrestrial Spodosols (Table 5-9).

Map Unit 12, Salt Marsh: Areas of this map unit support typical salt marsh vegetation: *Spartina alterniflora* and *Juncus roemerianus*. These soils were previously mapped as Wulfert (Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfisaprists) in the Levy County Soil Survey (Slabaugh *et al.*, 1996). The boundaries of these map units were re-delineated to be consistent with this subaqueous soil survey. Pedons of this map unit were not described as they were described in the terrestrial soil survey of Levy County.

Map Unit 13, Salt Marsh Flat: Areas of this map unit do not support vegetation. Soils in this landscape map unit occur in the subaqueous areas associated with salt marshes (Table 5-10). The variability of their properties below the upper-pedon is such

Table 5-9. Soil descriptions from an Oyster Bar map unit (MUID 11). Textural class abbreviations: loam (L), loamy sand (LS), sand (S), and sandy loam (SL).

Site No.	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
OB-1	Cl	0-5	S	5Y 3/1	99	C1 Horizon is
	C2	5-52	LS	5Y 3/1	35	mostly shell
	C3	52-220	SL	5Y 2.5/1	50	
OB-2	Cl	0-3	L	5Y 2.5/1	99	C1 Horizon is
	C2	3-75	L	5Y 2.5/1	10	mostly shell
	C3	55-200	LS	2.5Y 2.5/1	30	
OB-3	Cl	0-7	L	2.5Y 2.5/1	99	
	C2	7-100	L	2.5Y 2.5/1	35	
	C3	100-158	LS	2.5Y 2.5/1	35	
	Bw	158-200	S	10YR 4/1		
OB-4	Cl	0-5	L	5Y 2.5/1	99	C1 Horizon is
	C2	5-24	L	5Y 2.5/1	10	mostly shell
	C3	24-112	LS	2.5Y 2.5/1	30	
	C4	112-200	LS	2.5Y 2.5/1	10	
OB-5	C1	0-7	LS	5Y 3/1	80	C1 Horizon is
	C2	7-45	S	5Y 3/1	20	mostly shell
	C/Bhb	45-60	S	5Y 3/1		40% 7.5YR
	Bhb1	60-69	S	7.5YR 3/1		
	Bhb2	69-101	S	10YR 2/2		
	Bhb3	101-109	S	5YR 3/1		

Table 5-10. Soil descriptions from the Salt Marsh Flat map unit (MUID 13). Textural class abbreviations: loam (L), loamy sand (LS), sand (S), and sandy loam (SL).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
SMF-1	Cl	0-10	L	5Y 3/1		Very high *n* value
	C2	10-41	LS	2.5Y 2.5/1		
	C3	41-80	LS	2.5 Y 2.5/1	10	
	C4	80-104	SL	5Y 2.5/1	25	
	C5	104-200	LS	5Y 2.5/1	10	
SMF-2	Cl	0-8	L	5Y 3/1		Very high *n* value
	C2	8-200	L	2.5Y 2.5/1		Very high *n* value
SMF-3	Cl	0-12	L	5Y 3/1		Very high *n* value
	C2	12-200	L	2.5Y 2.5/1		Very high *n* value
SMF-4	Cl	0-14	L	2.5 Y 2.5/1		Very high *n* value
	C2	14-153	LS	5Y 2.5/1		
	Bh1b	143-171	S	7.5YR 2.5/1		
	Bh2b	171-200	S	7.5YR 2.5/3		
SMF-5	Cl	0-25	L	2.5 Y 2.5/1		Very high *n* value
	C2	25-200	L	2.5 Y 2.5/1	5	Very high *n* value

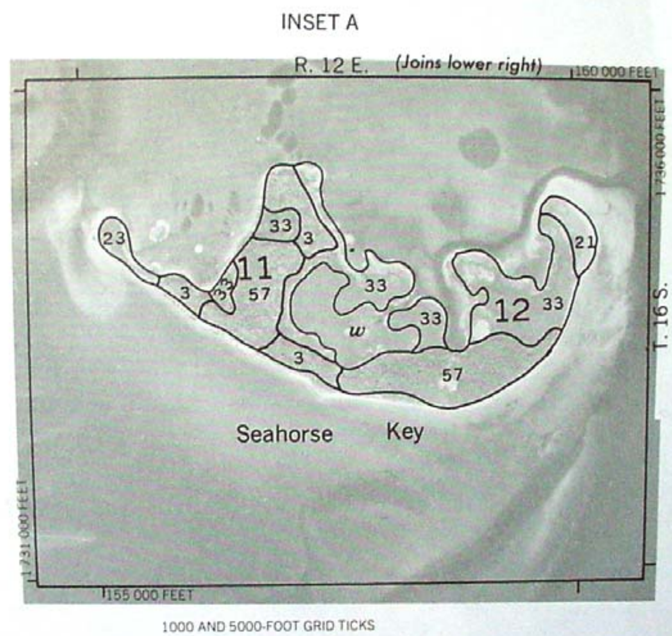
that some soils have a high *n* value (>>0.7) to a depth of 2 m while other soils have a high value in only the upper few cm. This high *n* value material is probably depositional in nature. Therefore, its thickness would be inversely related to the elevation of the previous soil surface. In areas where terrestrial soils have been drowned and left in place instead of eroded down to a lower elevation, the depositional material is thin (e.g., SMF-4). In areas where the paleosol surface was low in elevation, the depositional material is thicker (e.g., SMF-2). This trend is difficult to predict because the presence of a drowned vs. eroded soils is not always straight forward. In the case of SMF-4, the soil was close to other map unit soils that contained buried and/or degrading spodic horizons, thus leading to a prediction that SMF-4 would have a thin depositional layer over a paleosol. Although it is possible to spend the time in SMF map units to improve one's ability to predict the depth to a paleosol, it is not practical for soil survey purposes.

Map Unit 14, Unvegetated Flat: This map unit was of small extent. Because of this, the soils described were located close together (Table 5-11). UF-2 had a 24 cm accumulation of dark and loamy soil material at the surface. It was first thought that this layer was an A horizon. After noting that no evidence of vegetation was present anywhere in the unit, it was designated as a C horizon. Other clues that this might be an A horizon, such as dead roots, were not present in the soil.

Map Unit 15, Upland Soils: Soils within this map unit were previously mapped for the Levy County Soil Survey (Slabaugh *et al*., 1996) and are shown in Figure 5-16. For the purposes of this subaqueous soil survey, they were classified as labeled Map Unit 15, Upland Soils. The boundaries of this map unit were delineated during the subaqueous

Table 5-11. Soil descriptions for the Unvegetated Flat map unit (MUID 14). Textural class abbreviations: loamy sand (LS), sand (S), and loam (L).

Site	Horizon	Depth (cm)	USDA texture class	Matrix color	Shells (%)	Notes
UF-1	C1	0-6	LS	5Y 3/1		
	C2	6-35	S			
	C3	35-200	S			
UF-2	C1	0-5	L	5Y 3/1		
	C2	5-24	LS	5Y 3/1		20% 2.5Y 2/1 splothces
	C3	24-50	S	10YR 4/1		20% 2.5Y 6/1 splothces
	C4	50-80	S	10YR 4/1	2	
	C5	80-200	S	2.5Y 6/1	35	20% 10YR 6/1 mottles
UF-3	C1	0-8	LS	5Y 3/1		
	C2	8-45	S	2.5Y 6/1		
	C3	45-110	S	2.5Y 6/1		
	C4	110-200	S	2.5Y 6/1		
UF-4	C1	0-3	LS	5Y 3/1		
	C2	3-72	S	5Y 6/2		
	C3	72-130	S	2.5Y 6/1		
	C4	130-200	S	2.5Y 1/1		
UF-5	C1	0-20	S	2.5Y 6/2		
	C2	20-200	S	2.5Y 5/1		



Map Unit	Name	Taxonomy
3	Orsino fine sand, 0 to 8 percent slopes:	Hyperthermic, uncoated Spodic Quartzipsamments
21	Pompano fine sand	Silicious, hyperthermic Typic Psammaquents
23	Zolfo fine sand	Sandy, siliceous, hyperthermic Grossarenic Entic Haplohumods
33	Wulfert muck, frequently flooded	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemist
57	Paola fine sand, gently rolling	Hyperthermic, uncoated Spodic Quartzipsamments

Figure 5-16. Portion of the Levy County Soil Survey: Seahorse Key on Inset A from Map Tile 60 (Slabaugh *et al*., 1996). Below the scanned map is compiled information about the soils mapped on Seahorse Key.

survey so that the terrestrial and subaqueous soils would join to form a seamless coverage throughout the study area.

Modal Pedons

The modal pedons for most map units were described to 2 m. These descriptions (Tables 5-12 through 5-20) were formatted similar to those in the USDA soil survey reports. For all subaqueous map units, an appropriate existing series could not be identified, so a new series name was created.

Combinations of Soil-forming Factors

Demas and Rabenhorst (2001) modified the Jenny's (1941) soil equation by replacing relief with bathymetry and flow regime. They also added water column attributes and catastrophic events as factors. Within the study area, flow regime can be conceptualized as water energy. This is a broader view that incorporates currents and wave action. Additionally, geographic

Based on this research, ten unique combinations of the soil-forming factors were documented to form ten soil map units. Below, these combinations are outlined by identifying the soil-forming factors. The factors considered are a combination of Dokuchaev's (Dokuchaev, 1883; Glinka 1927; Jenny 1941), Demas and Rabenhorst's (2001) and a new soil-forming factor. Dokuchaev's factors that are considered are parent material (P), climate (C), vegetation (V), and time (T). Demas and Rabenhorst (2001) proposed the replacement of relief with bathymetry (B) and flow regime. Within the study area, flow regime can be conceptualized as water energy (E). This is a broader view that incorporates water currents and wave action. Demas and Rabenhorst (2001) also suggested that water column attributes be included as a factor, but this factor was not

Table 5-12. Modal pedon description for North Key

Map Unit 3: Edge of Channel Bar.
Proposed Series Name: North Key
Classification: Sandy, siliceous, hyperthermic Typic Fluvaquents

C / A	0-50 cm; mixed dark gray (5Y 4/1) and light olive brown (2.5Y 5/4) fine sand; single grained; loose; no roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
C	50-58 cm; light olive brown (2.5Y 5/3) loamy sand; very fluid; abrupt wavy boundary.
Ab	58-73 cm; black (2.5Y 2.5/1) and very dark gray (2.5Y 3/1) fine sand; weak fine and medium subangular structure; very friable; many fine and medium live roots; 8% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Ab / Cg	73-84 cm; 80% black (2.5Y 2.5/1) and 30% olive gray (5Y 5/2) fine sand; weak fine and medium subangular structure and single grained; very friable to loose; common fine and medium live roots; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / Ab1	84-111 cm; 50% dark grayish brown (2.5Y 4/2), 10% gray (2.5Y 6/1), and 40% very dark gray (2.5Y 3/1) fine sand; single grained; loose; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / Ab2	111-134 cm; 70% gray (2.5Y 6/1) and 30% black (2.5Y 2.5/1) sand; single grained; loose; 1% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg	134-200 cm; 90% gray (2.5Y 6/1), and 10% dark grayish brown (2.5Y 4/2) fine sand; single grained; loose; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.

Table 5-13. Modal pedon description for Hornet

Map Unit 5: Erosional Unvegetated Flat.
Proposed Series Name: Hornet
Classification: Sandy, siliceous, hyperthermic Typic Fluvaquents

C	0-3 cm; pale yellow (2.5Y 7/4) sand; very fluid; abrupt wavy boundary.
Cg	3-40 cm; gray (10YR 6/1) sand; abrupt wavy boundary.
Ab	40-48 cm; black (2.5Y 2.5/1) and very dark gray (2.5Y 3/1) fine sand; common fine and medium live roots; 2% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Ab / Cgb	48-62 cm; 80% black (2.5Y 2.5/1) and 30% olive gray (5Y 5/2) fine sand; weak fine and medium subangular structure and single grained; very friable to loose; common fine and medium live roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cgb / Ab	62-200 cm; 60% dark grayish brown (2.5Y 4/2), 20% gray (2.5Y 6/1), and 20% very dark gray (2.5Y 3/1) fine sand; single grained; loose; 5% shell fragments; dried soil with deionized water pH 8.2.

Table 5-14. Modal pedon description for Nebar

Map Unit 7: Near Bar Grassflat.
Proposed Series Name: Nebar
Classification: Sandy, siliceous, hyperthermic Typic Psammaquents

C	0-3 cm.; light olive brown (2.5Y 5/3) loamy sand; very fluid; abrupt wavy boundary.
A	3-15 cm; 60% dark gray (2.5Y 4/1) and 40% black (2.5Y 2.5/1) organic bodies; fine sand; weak fine and medium subangular structure; very friable; many fine and medium live roots; common vertical and horizontal rhizomes; 2% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / A	15-25 cm; 80% gray (10YR 6/1) and 20% black (2.5Y 2.5/1) fine sand; weak fine and medium subangular structure and single grained; very friable to loose; common fine and medium live and dead roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg1	25-39 cm; 95% gray (10YR 6/1) and 5% black (2.5Y 2.5/1) fine sand; single grained; loose; common fine and medium live and dead roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg2	39-50 cm; 90% gray (10YR 6/1) and 10% black (2.5Y 2.5/1) gravelly fine sand; single grained; loose; common fine and medium live and dead roots; 20% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg3	50-121 cm.; 90% gray (10YR 6/1) and 10% black (2.5Y 2.5/1) fine sand; single grained; loose; 5% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg4	121-200 cm.; 90% gray (10YR 6/1) and 10% black (2.5Y 2.5/1) gravelly fine sand; single grained; loose; 20% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.

Table 5-15. Modal pedon description for Atsena Otie

Map Unit 8: Drowned Flatwoods.
Proposed Series Name: Atsena Otie
Classification: Sandy, siliceous, hyperthermic Spodic Psammaquents

C	0-30 cm; light grey (5Y 7/2) sand; abrupt wavy boundary.
Bw	30-40 cm; pink (7.5YR 7/3) sand; gradual smooth boundary
Bh	40-200 cm; very dark brown (7.5YR 2.5/3) fine sand; weak medium subangular blocky structure; very friable; common black (7.5YR 2.5/1) dead roots; dried soil with deionized water pH 7.2.

Table 5-16. Modal pedon description of Snake Key

Map Unit 9: Nearshore Grassflat.
Proposed Series Name: Snake Key
Classification: Sandy, siliceous, hyperthermic Mollic Psammaquents

C	0-3 cm; light olive brown (2.5Y 5/3) loamy sand; very fluid; abrupt wavy boundary.
A	3-9 cm; black (2.5Y 2.5/1) fine sand; weak fine and medium subangular structure; very friable; common fine and medium live roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
A / Cg	9-23 cm; 70% black (2.5Y 2.5/1) and 30% dark gray (2.5Y 4/1) fine sand; weak fine and medium subangular structure and single grained; very friable to loose; common fine and medium live roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / A1	23 -90 cm; 40% dark gray (2.5Y 4/1), 20% gray (2.5Y 6/1), and 20% very dark gray (2.5Y 3/1) fine sand; single grained; loose; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / A2	90-140 cm; 40% dark gray (2.5Y 4/1), 20% gray (2.5Y 6/1), and 20% very dark gray (2.5Y 3/1) fine sand; single grained; loose; 5% shell fragments; dried soil with deionized water pH 8.2; common black (7.5YR 2.5/1) dead roots; abrupt smooth boundary.
Bhb	140-200 cm; very dark brown (7.5YR 2.5/3) fine sand; weak medium subangular blocky structure; very friable; few shell fragments; common black (7.5YR 2.5/1) dead roots; dried soil with deionized water pH 7.2.

Table 5-17. Modal pedon description for Seahorse Key

Map Unit 10: Offshore Grassflat.
Proposed Series Name: Seahorse Key
Classification: Sandy, siliceous, hyperthermic Cumulic Endoaquolls.

C	0-3 cm; 90% black (2.5Y 2.5/1) and 10% olive gray (5Y 4/2) fine sand; very fluid; abrupt wavy boundary.
A1	3-10 cm; 90% black (5Y 2.5/1) and 10% olive gray (5Y 4/2) loamy sand; weak fine and medium subangular structure; very friable; common fine and medium live roots; 5% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
A2	10-25 cm; 90% black (5Y 2.5/1) and 10% olive gray (5Y 4/2) loamy sand; weak fine and medium subangular structure; very friable; common fine and medium live roots; 10% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
A3	25-61 cm; 90% black (5Y 2.5/1) and 10% olive gray (5Y 4/2) loamy sand; weak fine and medium subangular structure; very friable; common fine and medium dead roots; 5% shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
A / Cg	61-122 cm.; 70% very dark gray (5Y 3/1) and 30% very dark gray (5Y 3/1) loamy sand; weak fine and medium subangular structure and single grained; very friable to loose; few shell fragments; dried soil with deionized water pH 8.2.
Cg	122-200 cm; no sample could be taken; soil material with high *n* value is suspected to occur here.

Table 5-18. Modal pedon description for Reddrum

Map Unit 11: Oyster Bar.
Proposed Series Name: Reddrum
Classification: Sandy, siliceous, hyperthermic Typic Endoaquolls

A	0-6 cm; very dark grey (5Y 3/1) loamy fine sand; horizon is mostly whole or crushed oyster shell; dried soil with deionized water pH 8.2; clear smooth boundary.
A / Cg	6-51 cm; 75% very dark gray (5Y 3/1) and 25% gray (5Y 6/1) fine sand; 20% oyster shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg / Bw	51-65 cm.; 60% black (5Y 2.5/1) and 40% brown (7.5YR 5/3) fine sand; loose; non fluid; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Bhb1	65-90 cm; dark brown (7.5YR 3/2) dried soil with deionized water pH 7.3; gradual smooth boundary.
Bhb2	90-200 cm; dark brown (7.5YR 3/2) dried soil with deionized water pH 7.3.

Table 5-19. Modal pedon description for Shell Mound

Map Unit 13: Salt Marsh Flat.
Proposed Series Name: Shell Mound
Classification: Loamy, siliceous, hyperthermic Sulfic Hydraquents

A1	0-13 cm.; black (N 2.5/0) loamy fine sand; very fluid, soil flows easily between fingers when squeezed leaving a residue of some mineral soil material and organic materials; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
A2	13-23 cm; 95% very dark gray (5Y 3/1) and 5% gray (5Y 6/1) fine sand; very fluid, soil flows easily between fingers when squeezed leaving a residue of some mineral soil material and organic materials; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg	23-56 cm; 70% gray (5Y 6/1) and 30% black (5Y 2.5/1) fine sand; single grained; loose; non fluid; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Ab	56-100 cm; mixed very dark gray (5Y 3/1) and black (2.5Y 2.5/1) fine sand; single grained; loose; non fluid; few shell fragments; dried soil with deionized water pH 8.2; abrupt smooth boundary.
Bh	100- 116 cm; black (7.5YR 2.5/1) fine sand; weak medium subangular blocky structure; very friable; non fluid; few shell fragments; dried soil with deionized water pH 7.2; clear wavy boundary.
Cg / Bw	116-200 cm; gray (10YR 6/1) and olive brown (2.5Y 4/3) fine sand; single grained; loose; non fluid; few shell fragments; dried soil with deionized water pH 8.2.

Table 5-20. Modal pedon description for Lighthouse Point

Map Unit 14: Unvegetated Flat.
Proposed Series Name: Lighthouse Point
Classification: sandy, siliceous, hyperthermic Typic Psammaquents

C / A1	0-8 cm; mixed gray (5Y 5/1) and light olive brown (2.5Y 5/4) fine sand; single grained; loose; no roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
C / A2	8-18 cm; mixed gray (5Y 5/1), light olive brown (2.5Y 5/3), and very dark grayish brown (5Y 3/2) fine sand; single grained; loose; no roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg1	26-66 cm; mixed gray (5Y 5/1), grayish brown (2.5Y 5/2), and very dark grayish brown (5Y 3/2) fine sand; single grained; loose; no live roots; common medium dead roots; few shell fragments; dried soil with deionized water pH 8.2; clear smooth boundary.
Cg2	66-200 cm; mixed dark gray (5Y 4/1), grayish brown (2.5Y 5/2), and very dark grayish brown (5Y 3/2) fine sand; single grained; loose; no live roots; common medium dead roots; few shell fragments; dried soil with deionized water pH 8.2.

considered for Cedar Key. In addition to these factors, geographic position (GP) relative to barrier islands was a new factor considered. The Map Unit soil (S) is conceptually predicted by the Equation 5-1.

$$S = f(P, C, V, B, E, GP, T) \qquad (5\text{-}1)$$

Variables

S	=	soil
f ( )	=	function of ( )
P	=	parent material
C	=	climate
V	=	vegetation
B	=	bathymetry (elevation)
E	=	water energy
GP	=	geographic position relative to land
T	=	time

The combinations of each map unit are listed below in map unit numerical order. Following the list is a short summary repeating the main points of soil genesis for the map unit. For all combinations of soil-forming factors in this study, C is subtropical. Unlike Jenny's (1941) contention that soil-forming factors are independent, some of these are not, such as parent material, geographic position relative to land, and water energy. These variables should become more independent, however, as the size of the study area is expanded. The values given for each of these variables are qualitative and were subjectively determined. They could, in theory, be quantified. Parent material as used here is not the same term as parent material in *Soil Taxonomy*, which as a pre-defined set of classes (e.g., loess or glacial till). Here it is a qualitative description of the particle size and mineralogy of the soil material.

Combination 1: Map Unit 1, Erosional Unvegetated Flat / Grass Near Channel Bar Complex

C = Subtropical
P = Mostly quartz sands from deep water, some shell fragments

V = Mostly unvegetated, some *Halodule*
B = Exposed on MLW
E = High energy on most tidal cycles
GP = Offshore
T = Greater than 40 years old, some portions are younger

This is a map unit that is a complex of Map Units 5 and 7. The concept behind this map unit is that where barrier flats exist, energy is high enough to burry vegetation. This happens catastrophically as it does in an Erosional Unvegetated Flat. About 20% of the area is protected, so pockets of *Halodule* can be found as it is in the Grass Near Channel Bar units. Near Cedar Key, this map unit or a barrier island is probably necessary for the offshore grassflats to exist in their current form.

Combination 2: Map Unit 3, Edge of Channel Bar

C = Subtropical
P = Mostly quartz sands from channel, some shell fragments
V = Mostly unvegetated, some *Halodule*
B = Exposed on MLW
E = Medium energy on most tidal cycles
GP = Offshore, the edges of grass-flats bordered by deep channels
T = Greater than 40 years old

This map unit is a bar that builds up along the edges of Map Unit 10, Offshore Grassflats where bordered by a channel. Wave deposition of sand from the bottom of the channel during times of high energy is the likely cause of this bar. The highest portions are unvegetated and provide protection for Map Unit 7, Grass Near Channel Bar.

Combination 3: Map Unit 5, Erosional Unvegetated Flat

C = Subtropical
P = Mostly quartz sands from nearby land
V = Mostly unvegetated, some *Halodule*, occasionally *Thalassia* in depressions
B = Exposed on MLW
E = Low to medium energy
GP = Near unstable shore
T = Greater than 40 years old, vegetation buried within the past 40 years.

This map unit occurs where a shore has become unstable and eroded onto grasses.

Combination 4: Map Unit 7, Near Bar Grassflat

C = Subtropical
P = Mostly quartz sands from deep water, some shell fragments
V = Mostly vegetated with *Halodule,* some *Thalassia*
B = Exposed on MLW
E = Low energy
GP = Offshore, protected side of bar near channel
T = Greater than 40 years old

This map unit exists on the protected side of the bars that comprise Map Unit 3. The grasses currently growing in these areas, mainly *Halodule*, were likely not the grasses growing before the bar was formed.

Combination 5: Map Unit 8, Drowned Flatwoods

C = Subtropical
P = Mostly quartz sands from drowned Spodosol. Some shells in upper-pedon
V = Unvegetated
B = Exposed on MLW
E = Low energy
GP = Protected shore, drowned shore near contemporary Spodosols
T = Greater than 40 years old, inferred to be as old as the adjacent uplands

This map unit occurs anywhere soils that were once Spodosols are near the shore and energy is not high. The result of sea level rise is that flatwoods have been drowned and coastal forest retreat has and is occurring. These soils were once coastal forests, probably pine flatwoods.

Combination 6: Map Unit 9, Nearshore Grassflat

C = Subtropical
P = Upper-pedon is mostly quartz sands from beach, supplied by eroding uplands; aquatic fine particles that settle
P = Pedon below is either the same or quartz sand from a drowned Spodosol
V = Mostly vegetated with *Thalassia*, *Halodule* occurs in the shallower, nearshore
B = Exposed only at MLLW, but exposed MLW where *Halodule* occurs
E = Low energy
GP = Nearshore, adjacent to beaches

T = Greater than 40 years old

This map unit occurs near beaches that are fed by upland erosion, and provide a slow, constant supply of this sand to the soils within the map unit. The current vegetation grades from *Halodule* in shallow water to *Thalassia* in areas with deeper water. Soils are poly-value in the upper-pedon as a result. Beneath the upper podon is the same soil material unless a buried and degrading spodic horizon is present. This would most likely occur if soils that were once Spodosols were near the shore.

Combination 7: Map Unit 10, Offshore Grassflat

C = Subtropical
P = Quartz sands, probably from channel or deeper water; aquatic fine particles that settle
V = Vegetated with a mixed stand of *Thalassia*, and *Syringodium*
B = Exposed only on MLLW
E = Very low energy
GP = Nearshore, adjacent to beaches
T = Greater than 40 years old

This map unit occurs as flats away from the erosional influence of land. *Thalassia* and *Syringodium* grow on these map units because the energy is low. In this area, the low energy is due partially to the presence of barrier flats and barrier islands, but also due to the gentle slope of this portion of the Gulf of Mexico. Also, these flats are extensive enough that their size creates a zone of shallow water and thus low energy.

Combination 8: Map Unit 11, Oyster Bar

C = Subtropical
P = Upper-pedon is mostly quartz sands from land, oyster shell fragments, aquatic fine particles that settle
P = Pedon below is either the same or quartz sand from a drowned Spodosol
V = Unvegetated
B = Well exposed at MLW
E = Low energy
GP = Nearshore; near salt marshes, flatwoods, and grassflats
T = Greater than 40 years old

This map unit can occur in almost any low energy area near a shore. If a beach is not present, then the energy is likely to be low enough for oyster bars to be present. They can occur in the same areas as Map Unit 8, Drowned Flatwoods and Map Unit 13, Salt Marsh Flats. When near drowned flatwoods, a buried degrading spodic will likely occur at depth. The soil material above will be comprised of quartz sand from the nearby shore, oyster shell fragments, and aquatic particles that settle out. This material comprises the entire pedon when near salt marsh flats.

Combination 9: Map Unit 13, Salt Marsh Flat

C = Subtropical
P = Upper-pedon is mostly quartz sands from land and aquatic fines that settle
P = Pedon below is either the same or quartz sand from a drowned Spodosol
V = Unvegetated
B = Exposed at MLW
E = Very low energy
GP = Nearshore, protected areas of salt marshes
T = Greater than 40 years old

This map unit occurs in the very low energy areas around salt marshes. The dominant process here is the settling of aquatic particles to create a high *n* value soil in the upper pedon. This persists to a depth at which a paleosol is present. If near flatwoods, a buried and degrading spodic horizon is present. Otherwise the upper-pedon extends to a depth of 2 m.

Combination 10: Map Unit 14, Unvegetated Flat

C = Subtropical
P = Mostly quartz sands from closest source
V = Unvegetated
B = Ranges from never exposed to exposed on MLW
E = Low energy
GP = Nearshore, in protected cove
T = Greater than 40 years old

Within the study area, the only unvegetated areas are the barrier bars, the erosional flats, and the soils inside the cove. Those cove soils that are not salt marsh flats, drowned flatwoods, or oyster bars are basically just quartz sand for a depth of 2 m. Generally, these soils have water too deep to support vegetation.

The Subaqueous Soil Survey and its Potential Uses

The final soil survey was completed within ArcView and saved as a spatial data layer format of shapefile with additional attribute tables (Table 5-21, Figure 5-17, Figures B-1 to B-13). For archival purposes, a hard copy of the map was printed at the scale of 1:20,000 in the form of a poster. The map unit attributes were also printed and included with the map. This survey represents the first soil survey of subtropical subaqueous areas. As such, it serves as a model for future surveys in concept, scale, and methodology.

In addition to serving as a model for future subaqueous soil survey efforts, this survey offers useful information about the subaqueous bottom in and around Seahorse Key. For instance, Map Unit 5: Hornet communicates, by virtue of its Ab horizons, that burial of seagrasses has take place in the recent (e.g., < 40 years) past. If historical aerial

Table 5-21. Map unit listing for the subaqueous soil survey.

MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyterthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Nearshore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

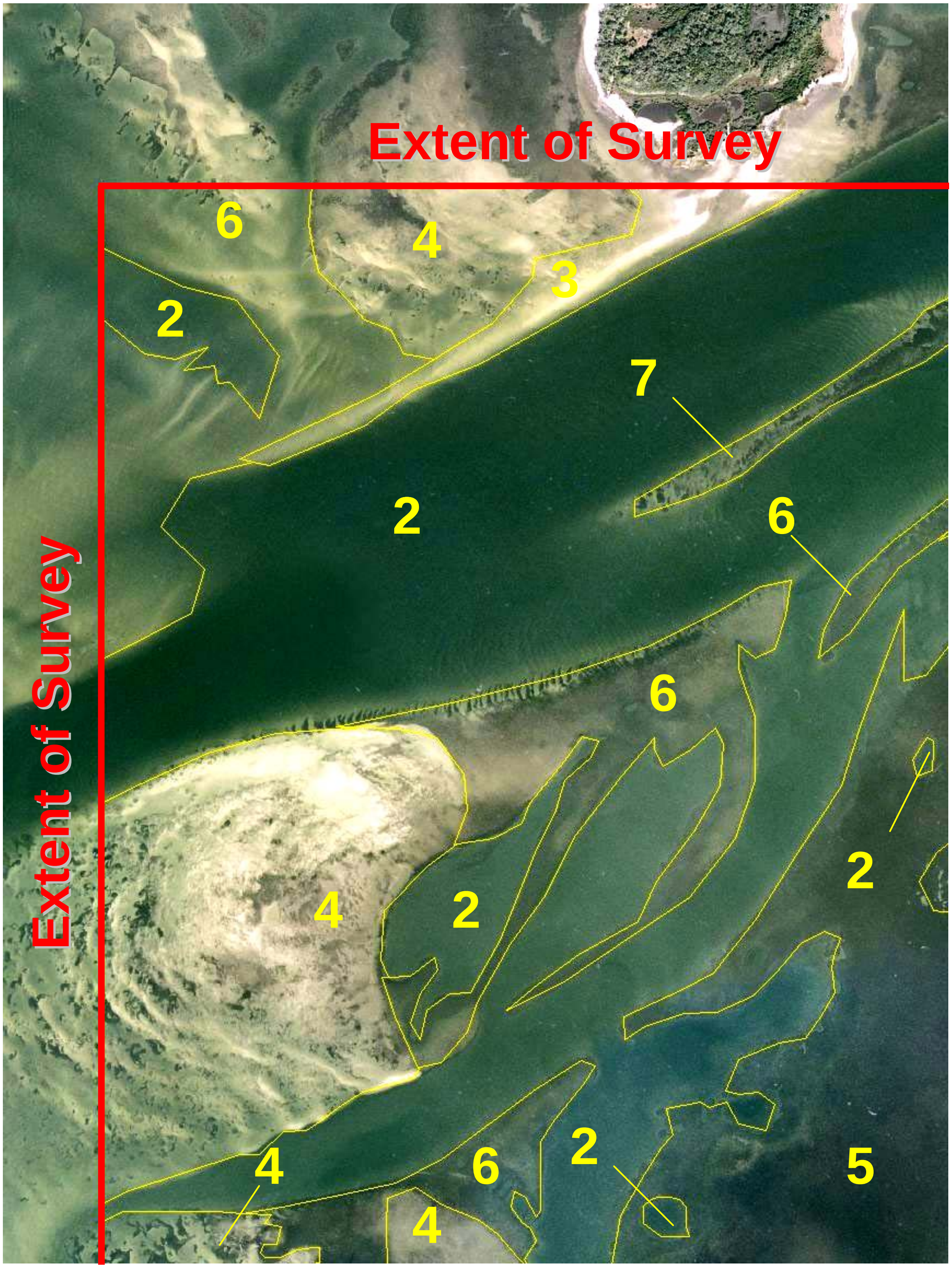


Figure 5-17. The Northwestern corner of the subaqueous soil survey. Note that each delineation has map unit identification number. That number relates to a landscape unit name and modal soil attributes. A complete set of map tiles can be found in Appendix B. The image source is 2001 true color aerial photography acquired from the Suwannee River Water Management District.

photography were not available, as can often be the case, these soils would serve as the only record of this event. Not only does Hornet inform the reader that seagrasses have been lost, but by virtue of the abrupt upper boundary of the Ab, suggests the event may have been a catastrophic burial. The user of this survey would then be aware that such an event had or is taking place, such as an eroding shore line. This information would be invaluable if user was investigating the area as a seagrass mitigation site. Burial would surely be detrimental to planted seagrasses.

Additionally, the user could speculate that if the catastrophic event were stopped (e.g., the shoreline stabilized) then the soil could be excavated to the elevation of the top of the Ab prior to seagrass planting. This would not guarantee success, but it would certainly improve the chances simply due to the additional information that soils provide.

In general, estuarine habitat managers would greatly benefit from the systematic, fine-scale, three dimensional benthic model that a subaqueous soil survey would provide. Whether it's using the soils information to understand the past and forecast the future, inputting the survey into an ecological model, or simply observing the survey to gain insight into the spatial distribution of subaqueous terrain for the planning of activities such as clam leases and dredging, a subaqueous soil survey would be a valuable tool for those who are involved in using and managing estuaries and nearshore coastal habitats.

Summary and Conclusions

Vegetation

The shallow flats are vegetated with dense seagrasses in all but the highest and lowest energy areas. The highest energy areas experienced erosion onto and off of the flats. The lowest energy areas were protected coves dominated by salt marshes. The remainder of the flats and coves were ubiquitously vegetated with seagrasses. Vegetative species seemed to strictly adhere to elevation constraints. Grading from shallow to deep was *Halodule wrightii*, *Thalassia testudinum*, and mixed stands of *Thalassia testudinum* and *Syringodium filiforme*.

Landforms

Flats are the dominant landform in the study area. As mentioned before, these flats were densely vegetated in all but the extremely high or low energy environments. Elevated bars typically occurred on the edges of these flats where channels were present. In both the high energy flats and the bars, burial of seagrasses has occurred. These areas are of minimal extent compared to the vegetated flats. Thus, for a majority of the shallow areas, the landforms appear to be very stable. Also occuring in the study area are drowned upland landforms. Deep water, also a dominant landform, occurred where channels or holes are present.

Soils

Soil morphology was predictable when all soil-forming factors were considered. Although geographic position has not been formally proposed as a soil-forming factor, its consideration allowed for the separation of flats that were inferred to be of different ages: the nearshore (young) and the offshore (old) flats. Accounting for this difference explained upper-pedon morphology (the offshore flats were higher in OM, darker in color, and loamier in texture than the nearshore flats) and morphology deeper in the profile (buried spodic horizons occurred in some nearshore flats). Geographic position thus encompasses the Time soil-forming factor. It also helps explain Energy, as the nearshore flats were slightly higher and appeared to receive more erosional imputs from land than the offshore flats. More research is needed to determine whether geographic position relative to islands or land is an important soil-forming factor in other geographic areas.

Some of the subaqueous soils that occurred in the study area were Entisols, which is similar to the findings of Demas and Rabenhorst (1999) and Bradley and Stolt (2003). Extensive Mollisols occurred in the offshore grassflats, however. This is the first identification of subaqueous Mollisols.

Although these soils occur under the extensive prairie-like seagrass meadows, their acceptance within the pedosphere as Mollisols will likely meet resistance. More research is needed to address the nature and properties of soil organic matter in these subaqueous Mollisols. This will further the understanding of the genesis of these soils. If it can be demonstrated that the OM comes from, at least in part, the seagrasses (e.g., the soils have A horizons at the surface), then these soils will better fit into the concept of the Mollisol. If instead, it can be demonstrated that the OM is similar in amount and composition to other low-energy unvegetated subaqueous areas (e.g., the soils have C horizons at the surface), then the soils will likely be considered by most as Entisols. The fact remains, however, that these soils do meet the taxonomic requirements of a Mollisol.

The Subtropical Subaqueous Soil Survey

This was not the first subaqueous soil survey created. In fact, the approach to creating this survey was modeled after Demas and Rabenhorst's (1999). What was unique about this survey was the open nature of the system, the subtropical climate, and the ubiquitous nature of Caribbean species of seagrasses. The west coast of Florida has many areas that are similarly characterized by expansive, offshore grass flats. The soil/landscape relationships presented here may apply to those areas as well. Also, the approach of creating a subaqueous soil survey can be further refined by additional subaqueous soil surveys.

These results add corroborating evidence that subaqueous bottoms are predictably related to the subaqueous landscape when soil-forming factors are considered. These relationships can be modeled using the conceptual model along with aerial photography, satellite imagery, and digital elevation models to create a soil survey similar in nature to those that exist for terrestrial areas.

The terrestrial approach of using base maps to delineate the land based on field confirmed soil/landscape relationships was applied to the study area to create a subtropical subaqueous soil survey. The approach, just like on land, strikes a unique balance between observing soil, mapping soil, and achieving accuracy and precision. This time-tested approach has thus far demonstrated the best way to map land at scales near 1:20,000 with a reasonable amount of resources. The same appears now to be true for the subaqueous areas near Cedar Key, FL.

Whether the USDA/NRCS pursues a state-wide or nation-wide subaqueous soils mapping effort remains to be seen. Regardless, this survey demonstrates the applicability of the pedological paradigm in subtropical subaqueous areas. More importantly, it calls attention to soil/seagrass relationships. Soils are obviously related to seagrasses. Exactly what the processes are that lead to the poly-value matrices, the OM, and biogenic silica are future research questions pedologists need to address. This is A horizon formation in a submerged environment. It is subaqueous soil genesis.

CHAPTER 6
SYNTHESIS

Subtropical Subaqueous Soils

The subtropical subaqueous soils investigated in this research are different from the temperate soils of the Mid-Atlantic and Northeastern U.S. not only in climate and vegetation, but in landscapes as well. The barrier island/lagoon system of the East coast of the U.S. was not typical of Cedar Key, FL. Instead, the study area was open, yet low enough in energy to support extensive, thick seagrass beds. The unique landforms and soil/vegetation relationships described in this research demonstrate the need for more research on subaqueous soil in the Southeastern US, especially those along the Gulf Coast.

Soil/Vegetation Relationships

The upper parts (0 to 30 cm) of the subaqueous soils investigated in this research were related to the vegetation they supported. The soil morphology consistently reflected the vegetative cover. Seagrasses with high biomass appeared to impart a dark color, caused by increases of soil OM in the upper part of the soil. Low biomass seagrasses appeared to impart a poly-value color on the upper part of the soil. Unvegetated soils appeared to be uniformly light in color in the upper part. The morphologies of the lower parts (30 to 200 cm) of the soil were related to the landform type and setting.

Soil/Landscape Relationships

The landform type (e.g., flat or bar) combined with the setting (position relative to barrier islands) were important to consider because they were related to the soil-forming factors. For the entire study area, the soil was classified by considering seven soil-forming factors: parent material, vegetation, bathymetry, water energy, geographic position relative to land, time, and climate. Because the study area consisted only of soils near Cedar Key, FL, the last soil-forming factor, climate, was considered constant for all soils. As a result of these considerations, ten subaqueous map units were created. These map units were delineated throughout the study area at a scale of 1:20,000. The final product was a subtropical subaqueous soil survey.

Subaqueous soils studied by pedologists thus far (Demas and Rabenhorst, 1999; Bradley and Stolt 2003) exist in systems characterized by long barrier islands protecting lagoons. The soils observed in this investigation were unique because of the extensive, vegetated offshore system of flats that comprised a majority of the landscapes. Additional research of open systems is needed explore the ideas presented herein.

The Pedological Paradigm in a Subaqueous Environment

A paradigm can be divided into three parts: 1) Theory: a set of beliefs or theory used to explain and understand systems, 2) Tools: A set of research tools for observing, measuring, and modeling systems, 3) Approach: together, the theory and the tools help form the approach(s) used for solving a problem or answering questions. This research was presented in an effort to apply/refine the pedological paradigm in a subtropical subaqueous environment. Based on this research, it appears that the pedological paradigm is, in part, applicable in a subtropical subaqueous environment.

Pedological Theory

With the recent expansion of soil research and survey efforts into subaqueous environments it has become clear that some pedological concepts need to be tested and/or refined. The concept of soil, the soil-forming factors, and the master horizon concepts have not been thoroughly tested in aquatic environments. More research is needed to address how each of these important parts of pedological theory can be applied to subaqueous soils.

The concept of soil: The most obvious and fundamental concept in soil science and especially pedology is the assumption or position that the upper portion of the earth is soil. Specifically, soil is considered to be the clastic substrates that comprise the upper portion of the earth's surface which support vegetative growth. This position is highlighted when one is asked the question about an aquatic bottom; is it soil or is it sediment? Answering this question is certainly not a formal requirement for the study of the soil or sediment, but the answer reveals one's direction of research. Pedologists, of course, will generally think of the earth's surface as soil.

The portions of the earth that are underwater have been technically considered soil as long as vegetative support existed or was possible. The recent change of the United States Department of Agriculture's (USDA) definition of soil in *Soil Taxonomy* (Soil Survey Staff 1999), along with the subaqueous pedological research that has occurred since the mid 1990s, signifies a movement towards recognizing such areas as soil.

Soil-forming factors: Another fundamental concept in pedology is the idea that soils are individuals (polypedons) that can be studied and modeled as functions of soil-forming factors. Demas and Rabenhorst (2001) began the refinement of the soil-forming factors concept by replacing some factors and adding others so that subaqueous soils could better be modeled. Additional refinements will likely occur as pedologists continue to study subaqueous soils, especially from a soil genesis point of view.

Subaqueous A horizons: Another fundamental concept in pedology is the idea of A horizons. Most of the terrestrial surface soils are indeed enriched in plant-derived humus and are therefore A horizons. Previous subaqueous pedological research has not tested this concept. Instead, it has been assumed, as it usually is on land, that elevated concentrations of OM at the soil surface signify the presence of A horizons. This concept warrants further investigation of subaqueous environments so that the master horizon designations for subaqueous will soils communicate the soil-forming processes that occur.

Sedimentary materials can be high in OM and that OM can be preserved in the aquatic environment. A depth profile of OM concentration in a sediment can look very similar to a depth profile of OM concentration in a soil with a well developed A horizon.

A similarity between sedimentary and soil OM accumulations is that post-depositional processes create the decrease of carbon with soil/sediment depth. The fundamental difference between the two scenarios is that in soils, rooted vegetation adds the OM, and downward leaching translocates some of the OM to deeper portions of the soil. This is A horizon formation. In the case of sediments, the OM is deposited with the mineral material, not after. This material is initially a C horizon. A master horizon designation other than C would communicate that soil formation has occurred.

Perhaps a subordinate horizon (e.g., lower-case L: "l" indicating the limnic, or aquatic, nature of the soil surface) could be created to designate subaqueous soil surfaces that appear to be A horizons, but are not dominated by plant-derived OM, More research is needed to determine the nature and genesis of OM in subaqueous "A" horizons.

Pedological Tools

The set of pedological tools also needs attention. Sampling, description, and analysis of subaqueous soils has to date, been conducted with the terrestrial set of pedological tools. A notable exception, however, is the use of a vibracore by Demas and Rabenhorst (1999) and the use of acoustical sounding equipment and geographical information systems to create subaqueous basemaps (Demas and Rabenhorst, 1999; Bradley and Stolt, 2002, 2003; Chapter 4 and 5).

Soil Sampling: For observing and sampling soil, soil scientists typically use manually operated tools such as shovels and augers where soil pits are not available or feasible. In a subaqueous environment, soil pits are obviously not feasible. The spade shovel used in Chapter 3 allowed for the efficient and effective retrieval of the upper 30 cm of the soil. The Dutch and Russian augers used in the deeper soil investigations of Chapter 5 were more difficult to utilize. They required tremendous manual effort to retrieve soils at depths greater than 1m. Perhaps sedimentological tools such as the vibracores used by Demas and Rabenhorst (1999) are better suited for subaqueous investigations if available resources and the sampling environment permit the use of this relatively larger, resource consuming equipment.

Soil Description and Analysis: For describing soils, soil scientists use both qualitative and quantitative tools in both the field and laboratory. For soil color, Munsell® colors charts are most often used. These provide an efficient and repeatable measure of soil color. These charts require few resources to acquire and can be employed by most any one in the field or laboratory.

Soil colors reported for terrestrial soils are typically moist color determined in the field. Occasionally, dry colors are reported for epipedon or hydric soil purposes.

Subaqueous soils can be poly value (Chapters 3 and 5) and can rapidly change color (Chapter 3). Despite this, there is no current standard for how long after initial sampling one should wait before coloring the soil. Waiting too long could result in a reported color that is different from the initially observed soil color. In other situations, allowing the soil to re-oxidize before coloring could provide useful information.

For example, it was suggested in Chapter 5 that some of the subaqueous soils received a large input of parent material from nearby eroding terrestrial soil. In these cases, allowing the subaqueous soil to re-oxidize may allow them to revert to a color similar to the nearby parent material source. Why color is reported for subaqueous soils needs to be defined so that standard methods of reporting soil color can be established.

Soil texture is also an important part of soil descriptions. Texture is qualitatively described by textural classes. Placement within a class can be determined by quantitative measurement of soil fractions in the laboratory or by estimation in the field. Neither the standard field nor the standard laboratory methods for determining particle-size distribution have been tested in a subaqueous environment. Instead, previous subaqueous pedology, including this research, has assumed that existing terrestrial techniques provide accurate, repeatable results. Research is needed to test the applicability of these and other standard laboratory techniques for describing and analyzing subaqueous soils.

Soil Survey: The soil survey is another important tool used by soil scientists. Demas and Rabenhorst (1999) were the first to apply the same approach used by the USDA in county-level soil surveys to a subaqueous environment in the Mid-Atlantic U.S. Bradley and Stolt (2003) applied the approach to subaqueous areas in the Northeastern U.S. Chapter 5 applied the approach to subaqueous areas in the Southeastern U.S. As the soil survey approach is applied to more subaqueous areas of the U.S. the approach will continue to be tested and probably refined to better suit new uses for soil survey.

An important part of the soil survey approach is the basemap. In a subaqueous environment, topographic basemaps are often not available, so they must be created. Collecting and modeling bathymetric data to create a digital elevation model (DEM) is currently the method being employed in the subaqueous soil survey efforts. Generation of DEMs is resource intensive, thus more research is needed to determine acceptable levels of input data spacing, acceptable levels of data variability, and appropriate method of modeling those data.

Now that underwater soils are a focus of pedologists, the applicability of pedological tools should be questioned and tested. Testing and refinement of pedological tools will allow for better application of the pedological paradigm to subaqueous environments.

Pedological Approach

The approach of soil science, specifically pedology, begins with a view of the earth's surface as soil. Using time-tested tools and techniques, the earth's surface can be studied at multiple scales for multiple purposes. Often, the fine scale study of the soil focuses on soil processes, which feeds the coarse scale study of soils and landscapes. Findings from the coarse-scale soil investigations pose new questions for the fine-scale research, and so on.

In subaqueous soil science, the coarse-scale research has begun in the Northeast, Mid-Atlantic, and now Southeastern U.S. Reciprocal fine-scale research of soil-forming processes is needed so that subaqueous soil genesis is better understood. This will allow for better landscape-level subaqueous soil investigations. The pedological approach is based on the assumption that soils and landscapes are related. In a subaqueous environment, this assumption must also assume subaqueous landscapes are stable enough for soils to develop. The definition of soil includes any areas that support or could support the growth of rooted plants. Should unstable subaqueous landscapes that periodically support seagrass growth be considered soil also? If so, should they be studied with the same approach as that used for soil survey?

Overall Conclusions

Subaqueous pedology signifies recognition by pedologists that underwater areas are soil if the support for vegetation is possible. This concept is not new, as soils have always been considered the support for vegetation. This support has traditionally been understood to be both physical and nutritional. Aquatic bottoms provide this function for rooted plants as well. These plants are submerged aquatic vegetation (SAV).

In a marine environment, which has been the focus of subaqueous research thus far, SAV is in the form of seagrasses. Seagrasses exist throughout the world and their existence has been documented to be very important to marine systems as both primary producers and as engineers of ecosystems. Subaqueous pedology that focuses on seagrasses should add to our understanding of seagrass habitats. Hopefully, subaqueous pedology will contribute to the protection of seagrass ecosystems via better understanding of the soils in which they are rooted.

As subaqueous pedology continues, changes to the pedological paradigm will probably continue so that the best theory, tools, and approaches are applied to the study of subaqueous soils.

APPENDIX A
SOIL CHARACTERIZATION DATA

Table A-1. Organic matter (OM) contents and particle size distributions for sites located in four vegetation cover classes: unvegetated (UNVEG), *Halodule wrightii* (HAL), *Thalassia testudinum* (THAL), and *Thalassia / Syringodium filiforme* mixed stand (THAL/SYR). Geographic coordinates are referenced to the WGS 84 datum. Numbers in ( ) are standard deviations.

Site	Organic Matter % by LOI	Particle Size Distribution %			Soil Color Moist Rubbed			Site Coordinates WGS 84	
		Clay	Silt	Sand	Hue	Value	Chroma	Latitude	Longitude
UNVEG-1	0.4 (0.2)	0.2 (0.0)	1.2 (0.2)	98.6 (0.2)	2.5Y	7	1	-83.07511	29.10050
UNVEG-2	0.5 (0.3)	0.2 (0.0)	2.5 (0.3)	97.4 (0.3)	5Y	7	1	-83.06071	29.09924
UNVEG-3	0.4 (0.2)	0.2 (0.0)	2.1 (0.7)	97.7 (0.7)	2.5Y	7	1	-83.06054	29.10087
UNVEG-4	0.7 (0.4)	0.1 (0.0)	1.8 (1.2)	98.1 (1.2)	5Y	6	1	-83.07487	29.10106
UNVEG-5	0.6 (0.3)	0.1 (0.0)	4.0 (0.4)	95.9 (0.4)	5Y	7	1	-83.07662	29.10113
HAL-1	2.4 (1.8)	0.2 (0.0)	6.0 (0.7)	93.8 (0.7)	5Y	5	2	-83.06070	29.09888
HAL-2	2.3 (1.6)	0.2 (0.0)	6.2 (1.8)	93.6 (1.8)	2.5Y	5	2	-83.07486	29.10112
HAL-3	2.1 (1.0)	0.2 (0.0)	6.0 (2.2)	93.8 (2.2)	2.5Y	4	3	-83.07580	29.09989
HAL-4	1.9 (0.9)	0.2 (0.0)	5.4 (0.5)	94.4 (0.5)	2.5Y	5	2	-83.06363	29.10651
HAL-5	1.9 (1.2)	0.2 (0.0)	5.6 (0.8)	94.2 (0.8)	2.5Y	4	3	-83.06471	29.10244
THAL-1	3.3 (0.4)	0.3 (0.1)	11.5 (0.9)	88.2 (0.9)	5Y	2.5	1	-83.07357	29.10078
THAL-2	3.5 (0.6)	0.2 (0.0)	8.0 (0.5)	91.8 (0.5)	2.5Y	3	1	-83.06744	29.09427
THAL-3	3.7 (0.5)	0.2 (0.0)	10.9 (0.7)	88.9 (0.7)	2.5Y	2.5	2	-83.06920	29.10426
THAL-4	2.7 (0.1)	0.2 (0.0)	8.9 (0.7)	90.9 (0.7)	2.5Y	3	1	-83.07498	29.10180
THAL-5	3.1 (0.6)	0.2 (0.0)	8.2 (1.1)	91.6 (1.1)	5Y	2.5	1	-83.06864	29.10337
THAL/SYR-1	5.2 (0.3)	0.2 (0.0)	14.4 (1.5)	85.4 (1.5)	5Y	2.5	1	-83.06804	29.10686
THAL/SYR-2	4.6 (0.7	0.2 (0.0)	13.2 (0.5)	86.6 (0.5)	2.5Y	2.5	2	-83.06320	29.10453
THAL/SYR-3	6.2 (1.8)	0.3 (0.1)	12.1 (0.7)	87.5 (0.7)	2.5Y	2.5	2	-83.06940	29.10660
THAL/SYR-4	5.2 (2.4	0.2 (0.0)	13.8 (0.6)	85.9 (0.6)	2.5Y	3	1	-83.07538	29.10357
THAL/SYR-5	4.2 (1.1)	0.2 (0.0)	11.3 (0.7)	88.5 (0.7)	5Y	2.5	1	-83.06648	29.10403

Table A-2. Soil physical and chemical data for selected locations. Geographic coordinates are referenced to the WGS 84 datum.

Sample	Cover Class	% Cover	Sample Interval (in)	pH	EC	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	%OM
101	TS	100	0-6	8.33	11.74	1.60	418.80	7640.00	830.00	0.00	0.00	4068.00	6.04
102	TS	100	6-12	8.38	10.23	1.92	363.20	7712.00	739.60	0.00	0.00	3712.00	None
103	TS	100	12-18	8.38	9.39	2.90	369.20	7616.00	732.80	0.00	0.00	3832.00	5.68
104	TS	100	0-6	None	None	2.78	460.40	7492.00	922.00	0.66	0.00	4552.00	4.43
105	TS	100	6-12	8.33	8.96	5.89	382.00	6712.00	782.00	5.84	3.53	36.12	5.77
106	TS	100	12-18	8.33	8.98	6.84	362.00	6836.00	742.00	6.18	3.67	4000.00	5.39
107	TS	100	0-6	8.22	10.90	3.95	481.20	7304.00	1115.20	1.82	0.00	7144.00	6.16
108	TS	100	6-12	8.30	8.38	10.87	371.60	7228.00	789.20	11.72	21.00	3596.00	4.41
109	TS	100	12-18	8.35	9.03	12.16	376.00	7456.00	774.40	13.39	27.16	3480.00	3.11
110	TS	100	0-6	8.09	9.99	12.82	432.00	7148.00	943.20	15.77	31.52	3948.00	7.08
111	TS	100	6-12	8.19	8.83	9.54	422.80	6376.00	894.00	11.53	14.60	95.68	6.80
112	TS	100	12-18	8.22	7.80	11.82	397.60	6640.00	869.60	10.39	14.40	108.84	4.59
113	TS	75	0-6	8.27	9.28	36.32	430.40	6484.00	907.60	39.56	94.12	3696.00	2.65
114	TS	75	6-12	8.28	8.40	6.99	416.00	7236.00	903.60	8.97	4.97	3756.00	4.18
115	TS	75	12-18	None	None	26.32	364.80	6184.00	720.00	29.92	81.80	4152.00	3.75
116	T	50	0-6	8.23	10.00	21.08	482.00	6936.00	1203.60	20.56	48.36	4552.00	3.86
117	T	50	6-12	8.28	7.59	53.16	318.80	4668.00	847.60	51.92	106.08	3736.00	3.38
118	T	50	12-18	8.29	9.16	14.34	435.60	7156.00	1206.40	14.61	19.53	4664.00	2.63
119	NONE	0	0-6	8.36	5.29	34.56	148.76	456.00	354.00	19.20	13.25	2324.00	0.31
120	NONE	0	6-12	8.61	5.19	16.76	159.60	1376.80	430.80	27.56	28.44	2512.00	0.54
121	NONE	0	12-18	8.17	7.39	33.20	279.20	2548.00	734.40	49.00	77.36	3464.00	1.90

Table A-2 continued.

Sample	% Clay	% Silt	% Sand	Sand Fraction					$d^{15}N$	$d^{13}C$	Longitude	Latitude
				% VC	% C	% M	% F	% VF				
101	None	None	None	None	None	None	None	None	None	None	29.110395	-83.064985
102	None	None	None	None	None	None	None	None	None	None	29.110395	-83.064985
103	None	None	None	None	None	None	None	None	None	None	29.110395	-83.064985
104	0.24	15.09	84.67	1.18	4.49	39.59	48.90	5.84	None	None	29.106855	-83.068040
105	0.25	14.87	84.88	0.75	3.53	37.18	51.79	6.74	None	None	29.106855	-83.068040
106	0.26	13.18	86.55	3.84	0.50	38.13	51.62	5.92	None	None	29.106855	-83.068040
107	0.27	16.09	83.64	1.10	2.82	35.34	55.14	5.60	None	None	29.104532	-83.063199
108	0.25	12.63	87.12	1.19	2.89	32.09	56.93	6.89	None	None	29.104532	-83.063199
109	0.22	10.74	89.04	0.13	1.98	32.12	59.07	6.69	None	None	29.104532	-83.063199
110	0.36	11.88	87.76	0.00	2.78	32.04	57.20	7.98	None	None	29.106596	-83.069396
111	0.23	12.66	87.11	0.22	2.11	29.11	59.37	9.18	None	None	29.106596	-83.069396
112	0.36	11.88	87.76	0.00	2.78	32.04	57.20	7.98	None	None	29.106596	-83.069396
113	0.22	9.82	89.97	0.23	3.78	44.15	47.80	4.04	None	None	29.103862	-83.071112
114	0.27	13.15	86.57	1.20	4.55	40.57	49.27	4.41	None	None	29.103862	-83.071112
115	0.26	12.01	87.73	0.42	4.24	45.28	46.87	3.19	None	None	29.103862	-83.071112
116	None	None	None	None	None	None	None	None	None	None	29.100779	-83.073570
117	0.25	11.51	88.24	0.00	2.95	34.27	54.85	7.93	None	None	29.100779	-83.073570
118	None	None	None	None	None	None	None	None	None	None	29.100779	-83.073570
119	0.16	1.56	98.28	0.00	4.07	45.26	50.51	0.16	None	None	29.100503	-83.075113
120	0.17	0.85	98.98	0.95	7.56	39.68	50.96	0.84	None	None	29.100503	-83.075113
121	0.19	6.57	93.23	0.42	4.20	41.27	51.53	2.57	None	None	29.100503	-83.075113

Table A-2 continued.

Sample	Cover Class	% Cover	Sample Interval (in)	pH	EC	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	%OM
122	TS	100	0-6	8.18	9.68	4.79	474.00	7196.00	954.40	2.24	0.00	5616.00	4.11
123	TS	100	6-12	8.23	8.46	9.93	390.40	7272.00	802.80	11.07	17.20	3492.00	5.88
124	TS	100	12-18	8.21	9.26	10.00	505.60	7068.00	1121.60	7.11	6.50	6516.00	5.64
125	TS	100	0-6	None	None	28.08	572.00	6184.00	1368.80	39.72	102.56	6964.00	4.33
126	TS	100	6-11	7.67	8.31	32.32	317.60	1149.60	771.20	69.72	109.96	3876.00	3.76
127	TS	100	11-14	7.57	7.40	21.00	286.80	692.80	722.00	54.28	74.72	3564.00	2.31
128	TS	100	14-18	None	None	17.35	247.20	924.80	608.80	49.96	59.08	3428.00	1.08
129	T	100	0-6	8.09	8.39	35.80	360.40	2048.00	779.60	73.16	98.44	4288.00	3.44
130	T	100	6-12	7.97	7.83	29.16	315.60	1567.60	811.60	61.36	95.44	3740.00	4.09
131	T	100	12-18	7.60	7.26	28.32	323.20	805.60	848.00	54.96	76.92	4216.00	2.99
132	H	50	0-2	7.75	8.62	100.84	439.60	2492.00	1112.00	83.96	104.48	3404.00	4.53
133	H	50	2-10	8.38	6.57	90.96	238.00	1649.60	576.80	47.40	43.92	3496.00	0.92
134	H	50	10-13	8.33	8.92	94.92	213.20	2660.00	589.20	42.88	59.40	2976.00	None
135	H	50	13-18	8.22	6.71	61.80	232.80	2408.00	666.40	45.96	67.60	3044.00	1.78
136	NONE	0	0-6	8.54	5.50	80.52	162.20	958.80	415.60	30.64	25.08	2500.00	0.66
137	NONE	0	6-12	8.58	5.02	53.92	109.24	515.60	302.00	18.19	14.41	1757.20	0.30
138	NONE	0	12-15	8.52	5.14	127.44	157.24	917.20	402.40	21.76	20.72	2544.00	0.40
139	NONE	0	15-20	8.28	6.28	99.12	214.00	2764.00	607.60	50.48	67.08	2664.00	2.18
140	NONE	0	0-5	8.11	5.45	26.88	196.52	1422.80	404.80	47.92	23.96	2336.00	0.76
141	NONE	0	5-12	8.18	7.86	16.27	438.40	6928.00	1128.00	15.60	22.96	3880.00	4.26
142	NONE	0	12-18	8.24	7.65	14.85	308.80	6752.00	653.20	13.05	18.66	3000.00	3.75

Table A-2 continued.

Sample	% Clay	% Silt	% Sand	Sand Fraction					d15N	d13C	Longitude	Latitude
				% VC	% C	% M	% F	% VF				
122	0.24	14.40	85.36	1.73	4.26	34.21	55.48	4.31	None	None	29.103574	-83.075380
123	0.24	12.96	86.80	1.52	3.78	32.90	56.64	5.16	None	None	29.103574	-83.075380
124	0.21	14.11	85.68	0.56	2.85	30.86	59.34	6.40	None	None	29.103574	-83.075380
125	0.23	11.19	88.57	0.25	4.05	32.61	58.35	4.74	None	None	29.095164	-83.071505
126	0.22	8.70	91.08	0.22	5.09	36.19	56.61	1.89	None	None	29.095164	-83.071505
127	0.23	9.51	90.27	0.13	5.76	37.84	56.10	0.17	None	None	29.095164	-83.071505
128	0.05	7.18	92.78	0.16	5.65	41.26	52.82	0.11	None	None	29.095164	-83.071505
129	0.21	7.95	91.84	1.59	3.86	30.66	60.89	3.01	None	None	29.094271	-83.067443
130	0.21	8.47	91.32	0.00	3.46	29.79	63.03	3.72	None	None	29.094271	-83.067443
131	0.18	7.58	92.24	0.09	3.86	34.82	58.76	2.47	None	None	29.094271	-83.067443
132	0.24	10.84	88.92	1.98	5.35	34.59	53.58	4.50	None	None	29.098882	-83.060695
133	0.18	3.43	96.38	0.15	8.59	44.20	45.90	1.16	None	None	29.098882	-83.060695
134	0.16	4.35	95.48	0.25	9.30	39.04	49.52	1.89	None	None	29.098882	-83.060695
135	0.19	5.26	94.55	1.09	6.64	31.14	57.11	4.02	None	None	29.098882	-83.060695
136	0.17	4.24	95.59	0.12	3.68	42.35	53.10	0.75	None	None	29.098981	-83.060775
137	0.16	1.55	98.29	0.00	12.01	44.68	42.93	0.38	None	None	29.098981	-83.060775
138	0.16	1.67	98.17	0.61	14.06	46.45	38.75	0.13	None	None	29.098981	-83.060775
139	0.22	2.22	97.56	0.00	1.27	31.04	66.83	0.86	None	None	29.098981	-83.060775
140	None	None	None	None	None	None	None	None	None	None	29.101780	-83.066119
141	0.20	9.82	89.98	0.20	2.89	32.94	58.19	5.78	None	None	29.101780	-83.066119
142	0.20	11.09	88.71	0.30	2.71	30.44	57.85	8.70	None	None	29.101780	-83.066119

Table A-2 continued.

Sample	Cover Class	% Cover	Sample Interval (in)	pH	EC	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	%OM
143	TS	75	0-6	8.00	12.20	8.04	478.00	7316.00	1008.40	10.35	5.85	4116.00	6.96
144	TS	75	6-12	8.16	9.90	17.99	394.00	6468.00	884.00	18.44	38.08	8.21	3.17
145	TS	75	12-18	8.19	8.60	14.30	422.80	7176.00	893.60	15.50	27.12	3216.00	2.59
146	TS	75	0-6	8.13	11.81	7.18	443.20	7388.00	941.60	7.65	5.64	4392.00	4.41
147	TS	75	6-12	8.14	9.28	23.40	398.40	6156.00	910.80	26.04	68.76	4292.00	5.44
148	TS	75	12-18	8.14	9.85	14.37	364.80	6196.00	662.40	17.33	45.08	4160.00	6.05
149	TS	10	0-6	8.11	9.67	12.67	374.40	6372.00	845.60	14.74	27.84	35.20	3.90
150	TS	10	6-12	8.15	9.51	5.06	405.20	6456.00	846.80	3.41	0.00	103.12	5.33
151	TS	10	12-18	8.21	9.26	10.00	410.80	6592.00	888.80	12.15	12.74	13.27	3.31
152	T	100	0-6	8.19	9.79	4.43	416.80	7436.00	877.20	5.13	0.00	4048.00	3.43
153	T	100	6-12	8.21	7.56	18.12	390.80	7332.00	854.80	21.20	45.04	3516.00	3.46
154	T	100	12-18	8.19	8.30	17.30	351.60	6340.00	743.20	18.62	41.32	3720.00	4.31
155	TS	100	0-6	8.11	8.50	4.33	374.00	6620.00	750.40	1.93	0.00	4128.00	5.24
156	TS	100	6-12	8.14	9.00	17.74	351.60	6340.00	744.40	18.04	42.00	4024.00	3.78
157	TS	100	12-18	8.14	9.49	8.17	409.60	6444.00	916.00	8.09	3.05	6.01	4.06
158	T	50	0-6	8.09	8.48	32.32	426.80	4484.00	886.80	49.64	98.28	4368.00	2.63
159	T	50	6-12	8.17	7.68	35.00	318.40	4212.00	788.40	48.76	94.52	3520.00	2.65
160	T	50	12-18	8.15	7.72	35.40	316.80	3228.00	810.40	56.16	94.04	3524.00	2.78
161	H	50	0-3	None	None	38.24	447.20	3892.00	1125.20	74.28	88.40	4224.00	3.02
162	H	50	3-9	8.22	6.52	25.80	201.20	2484.00	510.40	42.96	49.16	2748.00	1.29
163	H	50	9-18	8.30	6.90	37.04	289.60	3736.00	738.40	46.68	83.00	3320.00	2.71

Table A-2 continued.

Sample	% Clay	% Silt	% Sand	Sand Fraction					$d^{15}N$	$d^{13}C$	Longitude	Latitude
				% VC	% C	% M	% F	% VF				
143	0.25	13.55	86.20	0.23	3.16	35.64	53.08	7.89	None	None	29.104034	-83.066480
144	0.18	10.82	89.00	0.00	1.62	37.30	53.84	7.24	None	None	29.104034	-83.066480
145	0.24	9.48	90.28	0.00	4.03	39.92	50.55	5.49	None	None	29.104034	-83.066480
146	None	None	None	None	None	None	None	None	None	None	29.107089	-83.065803
147	0.22	11.76	88.02	0.16	2.27	35.67	56.62	5.27	None	None	29.107089	-83.065803
148	0.24	12.71	87.05	0.29	3.45	41.13	50.82	4.32	None	None	29.107089	-83.065803
149	None	None	None	None	None	None	None	None	None	None	29.105314	-83.067779
150	0.22	13.07	86.71	0.29	3.20	38.57	52.31	5.63	None	None	29.105314	-83.067779
151	0.21	11.14	88.66	0.47	6.32	43.45	45.75	4.02	None	None	29.105314	-83.067779
152	None	None	None	None	None	None	None	None	None	None	29.104263	-83.069195
153	0.21	11.53	88.26	0.20	3.08	37.16	54.07	5.48	None	None	29.104263	-83.069195
154	0.21	10.23	89.56	0.40	5.09	45.38	45.20	3.93	None	None	29.104263	-83.069195
155	0.22	12.48	87.29	0.15	2.84	31.76	57.00	8.25	None	None	29.103316	-83.073501
156	0.22	11.22	88.56	1.13	4.29	36.00	53.84	4.74	None	None	29.103316	-83.073501
157	0.22	13.58	86.21	0.19	3.29	34.10	55.68	6.73	None	None	29.103316	-83.073501
158	None	None	None	None	None	None	None	None	None	None	29.101801	-83.074983
159	None	None	None	None	None	None	None	None	None	None	29.101801	-83.074983
160	0.16	8.90	90.94	0.09	4.44	41.92	49.83	3.72	None	None	29.101801	-83.074983
161	None	None	None	None	None	None	None	None	None	None	29.101122	-83.074855
162	0.18	3.95	95.87	0.12	2.13	37.88	58.04	1.84	None	None	29.101122	-83.074855
163	0.20	8.50	91.30	0.15	2.85	37.98	55.29	3.72	None	None	29.101122	-83.074855

Table A-2 continued.

Sample	Cover Class	% Cover	Sample Interval (in)	pH	EC	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	%OM
164	NONE	0	0-3	None	None	44.60	162.08	1021.20	396.00	28.28	17.53	2664.00	0.69
165	NONE	0	3-9	8.35	7.02	31.24	248.40	2940.00	631.20	41.24	67.12	3356.00	3.00
166	NONE	0	9-18	8.30	7.19	26.88	293.60	3348.00	692.00	39.04	76.88	3728.00	None
167	TS	100	0-2	None	None	3.12	591.60	7072.00	1462.40	0.54	0.00	8320.00	6.73
168	TS	100	2-7	8.16	9.88	5.02	445.60	7336.00	1107.20	5.03	0.28	4508.00	5.29
169	TS	100	7-18	8.11	9.90	27.92	444.00	6748.00	1154.00	31.00	80.24	4160.00	5.97
170	TS	100	0-3	None	None	11.69	600.40	7400.00	1054.40	15.63	25.00	4596.00	5.91
171	TS	100	3-14	8.09	8.62	28.08	396.00	6316.00	880.00	38.24	101.76	4176.00	4.01
172	TS	100	14-20	8.09	8.65	24.76	394.40	5616.00	915.60	34.68	84.92	99.44	3.74
173	TS	50	0-2.5	None	None	4.00	536.80	7312.00	1232.40	5.31	0.31	7648.00	4.10
174	TS	50	2.5-10.5	8.10	10.12	4.82	449.60	7120.00	1069.20	2.68	0.00	4720.00	4.66
175	TS	50	10.5-20	8.19	9.23	7.46	430.40	7340.00	894.00	6.98	2.86	4164.00	6.54
176	TS	100	0-3	None	None	6.38	529.60	7284.00	1006.00	9.24	3.75	4012.00	5.02
177	TS	100	3-10	8.07	9.01	14.94	403.20	6684.00	890.80	17.86	36.04	4352.00	3.95
178	TS	100	10-20	8.13	8.47	23.36	415.60	6328.00	915.20	26.92	68.40	4564.00	2.84
179	NONE	0	0-3	8.16	7.26	18.52	224.40	914.80	441.20	47.72	28.36	2828.00	1.07
180	NONE	0	3-9	8.53	6.42	35.52	215.20	1693.60	469.20	39.52	24.48	3652.00	0.63
181	NONE	0	9-20	8.55	5.97	27.56	186.64	2588.00	502.40	41.52	44.28	2616.00	1.12
182	OS	100	3-18	8.28	8.63	5.53	351.60	7460.00	732.00	0.64	0.00	3320.00	3.63
183	OS	100	18-24	8.01	6.65	31.64	313.20	3188.00	810.00	47.80	90.12	3452.00	2.23
184	OS	100	24-28	7.87	6.17	16.23	227.20	983.20	605.60	31.76	54.76	3088.00	1.70

Table A-2 continued.

Sample	% Clay	% Silt	% Sand	Sand Fraction					$d^{15}N$	$d^{13}C$	Longitude	Latitude
				% VC	% C	% M	% F	% VF				
164	0.12	1.80	98.08	0.04	2.49	41.92	55.06	0.49	None	None	29.101060	-83.074872
165	0.15	6.93	92.92	0.11	2.63	36.12	57.12	4.03	None	None	29.101060	-83.074872
166	0.21	9.96	89.83	0.12	2.72	36.20	57.00	3.96	None	None	29.101060	-83.074872
167	None	None	None	None	None	None	None	None	None	None	29.109731	-83.075046
168	0.21	19.66	80.13	1.01	4.49	39.79	49.52	5.19	None	None	29.109731	-83.075046
169	0.20	12.76	87.04	1.01	5.70	39.48	50.05	3.77	None	None	29.109731	-83.075046
170	None	None	None	None	None	None	None	None	None	None	29.107409	-83.075297
171	0.22	13.17	86.61	0.10	4.34	36.62	55.10	3.83	None	None	29.107409	-83.075297
172	0.13	10.39	89.48	0.00	10.30	34.09	45.93	9.68	None	None	29.107409	-83.075297
173	0.00	13.68	86.32	0.93	4.63	35.91	53.24	5.28	None	None	29.105822	-83.075681
174	None	None	None	None	None	None	None	None	None	None	29.105822	-83.075681
175	0.22	12.59	87.20	0.87	5.50	34.50	54.96	4.17	None	None	29.105822	-83.075681
176	None	None	None	None	None	None	None	None	None	None	29.106835	-83.072200
177	0.15	12.14	87.70	1.26	3.83	35.35	54.36	5.20	None	None	29.106835	-83.072200
178	0.21	10.39	89.40	0.63	4.56	39.24	52.21	3.36	None	None	29.106835	-83.072200
179	None	None	None	None	None	None	None	None	None	None	29.106121	-83.070567
180	0.13	13.46	86.42	0.81	2.41	35.78	51.61	9.40	None	None	29.106121	-83.070567
181	0.16	3.86	95.98	0.33	8.34	58.05	32.97	0.31	None	None	29.106121	-83.070567
182	0.22	12.74	87.04	2.02	4.23	32.86	54.87	6.02	None	None	29.099979	-83.068563
183	0.19	7.53	92.28	0.13	5.03	40.01	51.24	3.60	None	None	29.099979	-83.068563
184	0.12	5.30	94.58	0.00	8.37	47.20	42.97	1.46	1.353	-18.469	29.099979	-83.068563

Table A-2 continued.

Sample	Cover Class	% Cover	Sample Interval (in)	pH	EC	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	%OM
185	OS	100	28-40	7.42	5.97	14.73	258.80	1242.80	845.60	23.40	87.24	3300.00	1.86
186	TS	80	0-4	7.99	12.17	1.80	9.54	72.48	54.60	0.29	4.29	206.40	4.56
187	TS	80	4-8	8.03	9.61	8.84	494.00	7312.00	1142.80	10.36	3.83	4616.00	3.94
188	TS	80	8-24	8.17	8.17	8.27	400.80	6816.00	791.20	5.68	0.81	3860.00	2.46
189	TS	80	24-36	8.09	8.58	32.44	466.00	6172.00	1069.60	36.16	51.36	97.16	3.17
190	TS	80	36-72	None	None	7.12	468.80	7428.00	936.40	2.62	0.00	4348.00	2.46
191	OS	25	3-10	8.18	6.88	7.71	353.60	7204.00	638.80	0.01	0.00	3080.00	4.20
192	OS	25	10-16	8.21	9.20	3.74	437.20	7860.00	875.60	0.00	0.00	3920.00	3.35
193	OS	25	16-36	8.35	5.97	28.84	242.80	6888.00	610.80	27.88	48.84	2516.00	1.62

Table A-2 continued.

Sample	% Clay	% Silt	% Sand	Sand Fraction					$d^{15}N$	$d^{13}C$	Longitude	Latitude
				% VC	% C	% M	% F	% VF				
185	0.17	1.75	98.08	2.65	7.67	43.96	45.23	0.49	1.212	-19.245	29.099979	-83.068563
186	None	None	None	None	None	None	None	None	None	None	29.103097	-83.068938
187	0.21	11.55	88.24	2.45	3.35	39.48	48.14	6.57	1.399	-11.514	29.103097	-83.068938
188	0.21	11.10	88.69	0.33	3.38	41.36	51.32	3.61	0.954	-10.617	29.103097	-83.068938
189	None	None	None	None	None	None	None	None	1.015	-10.935	29.103097	-83.068938
190	0.21	12.23	87.56	0.28	2.83	36.45	54.22	6.21	None	None	29.103097	-83.068938
191	0.20	10.80	89.00	8.04	7.78	28.94	49.84	5.39	None	None	29.102547	-83.069176
192	0.21	13.03	86.76	3.41	4.66	29.51	55.23	7.19	None	None	29.102547	-83.069176
193	0.16	6.84	93.00	0.99	4.30	43.78	48.56	2.37	0.795	-10.687	29.102547	-83.069176

APPENDIX B
SUBAQUEOUS SOIL SURVEY

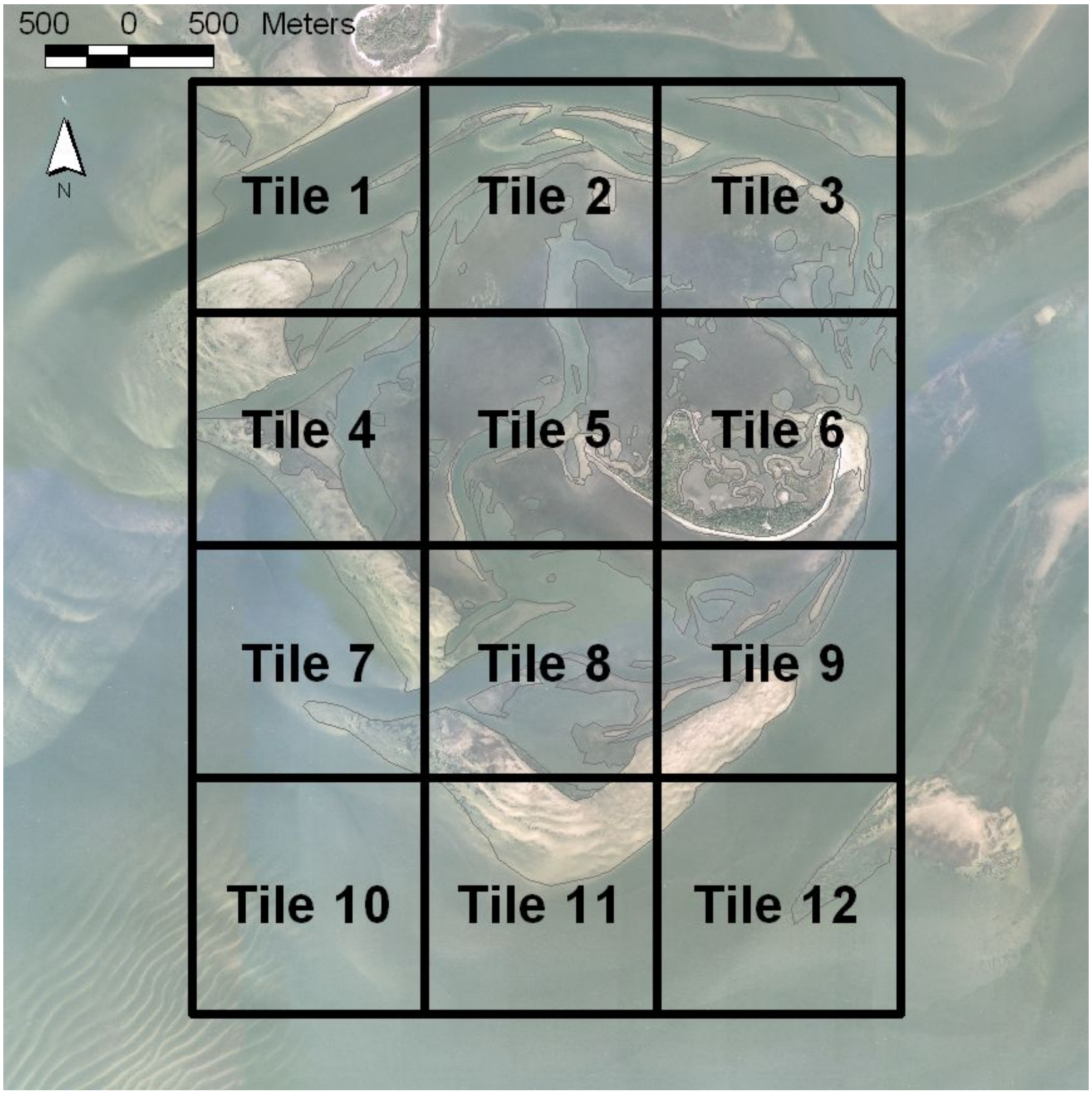


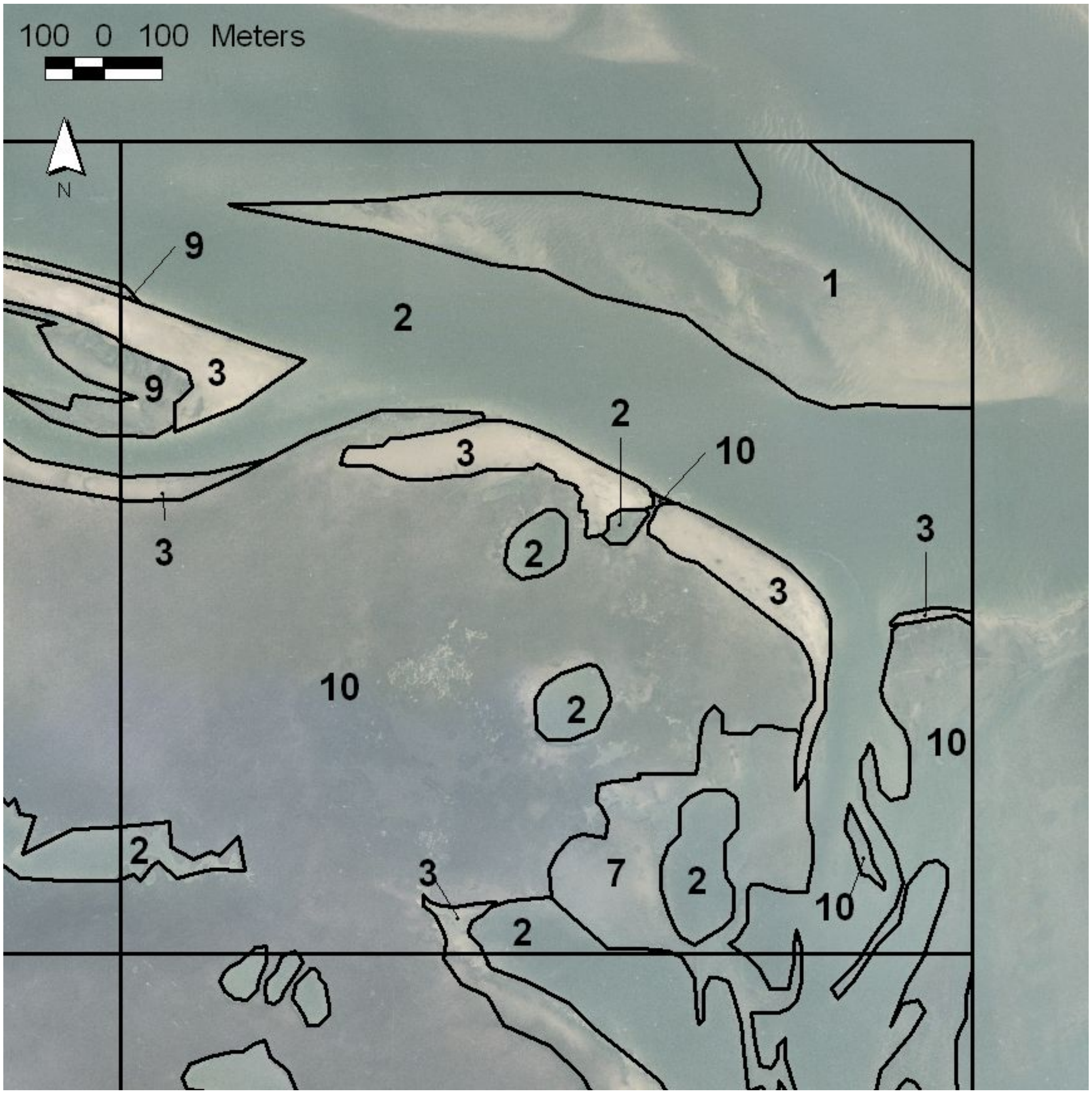
Figure B-1. Index map for the subaqueous soil survey.

MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-2. Tile 1 of 12 in the subaqueous soil survey.

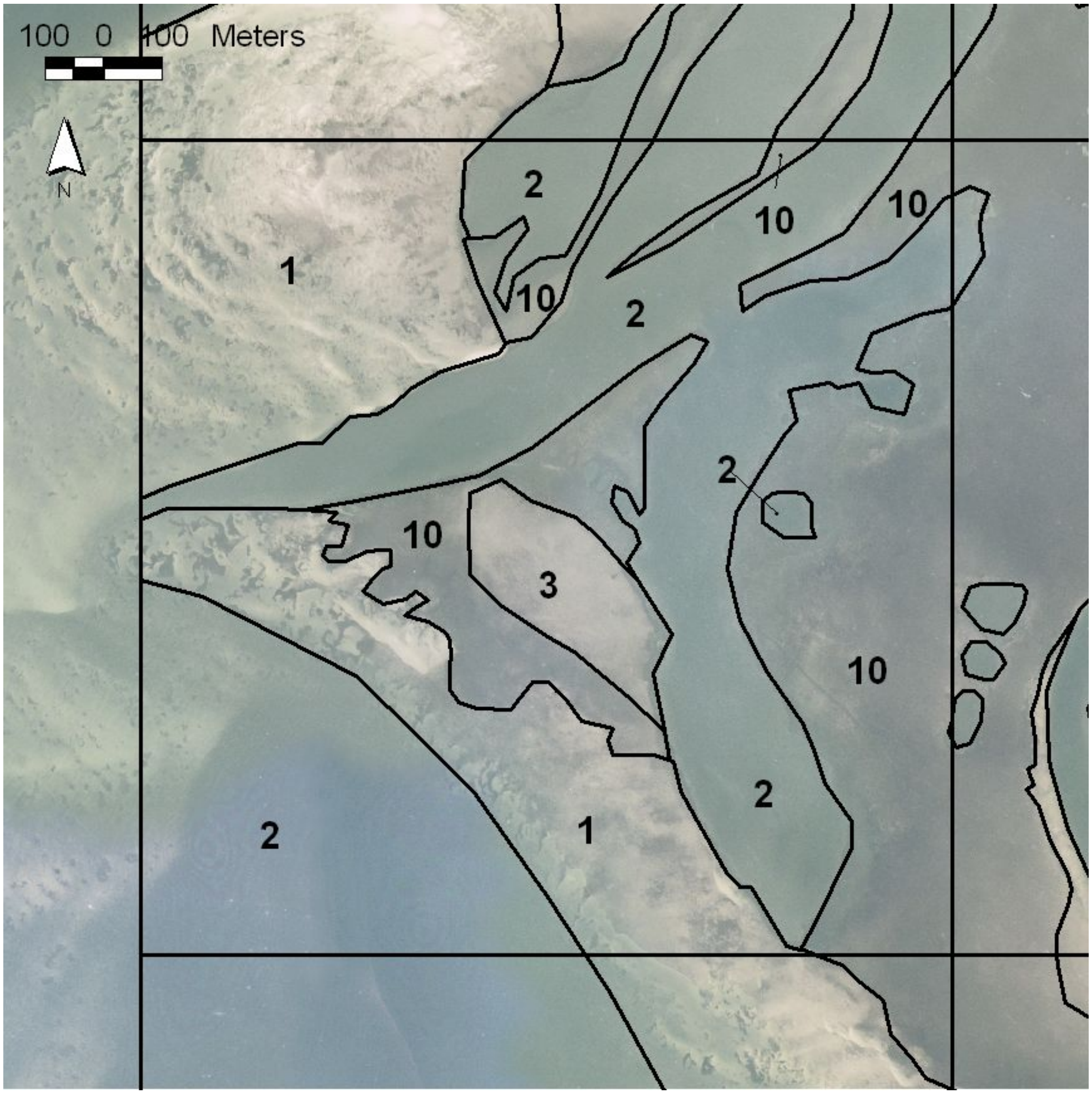
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-3. Tile 2 of 12 in the subaqueous soil survey.



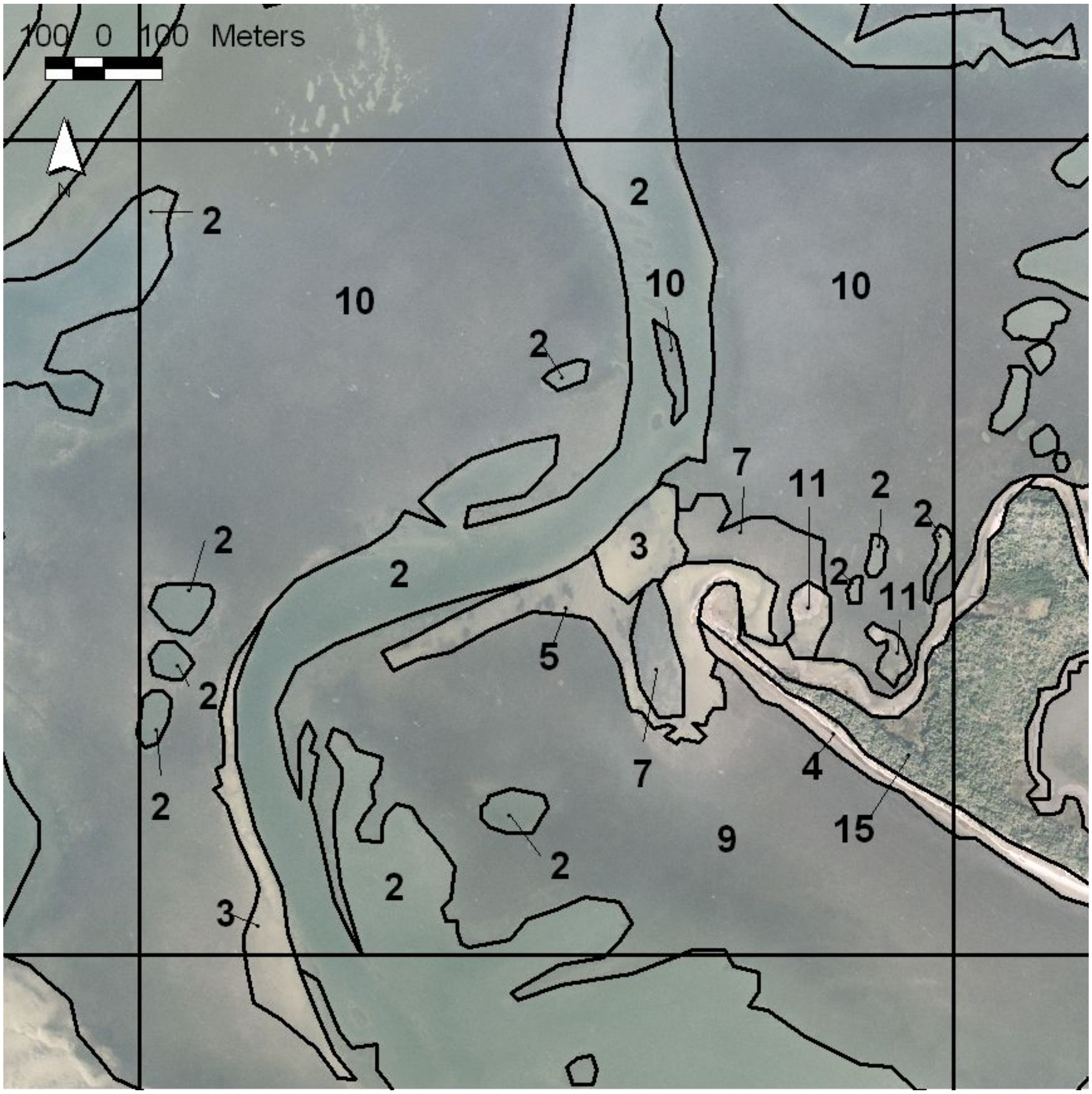
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-4. Tile 3 of 12 in the subaqueous soil survey.



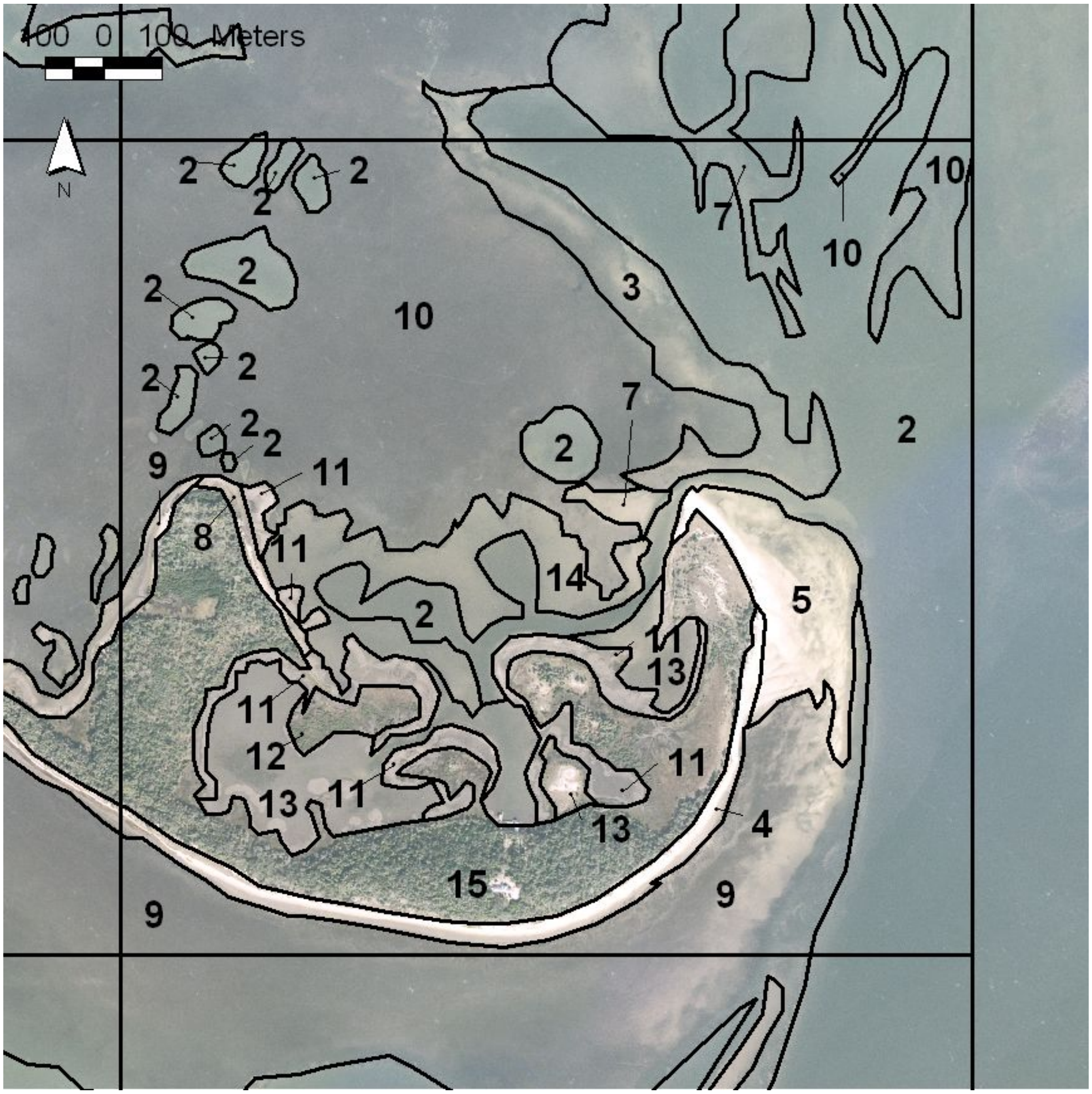
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-5. Tile 4 of 12 in the subaqueous soil survey.



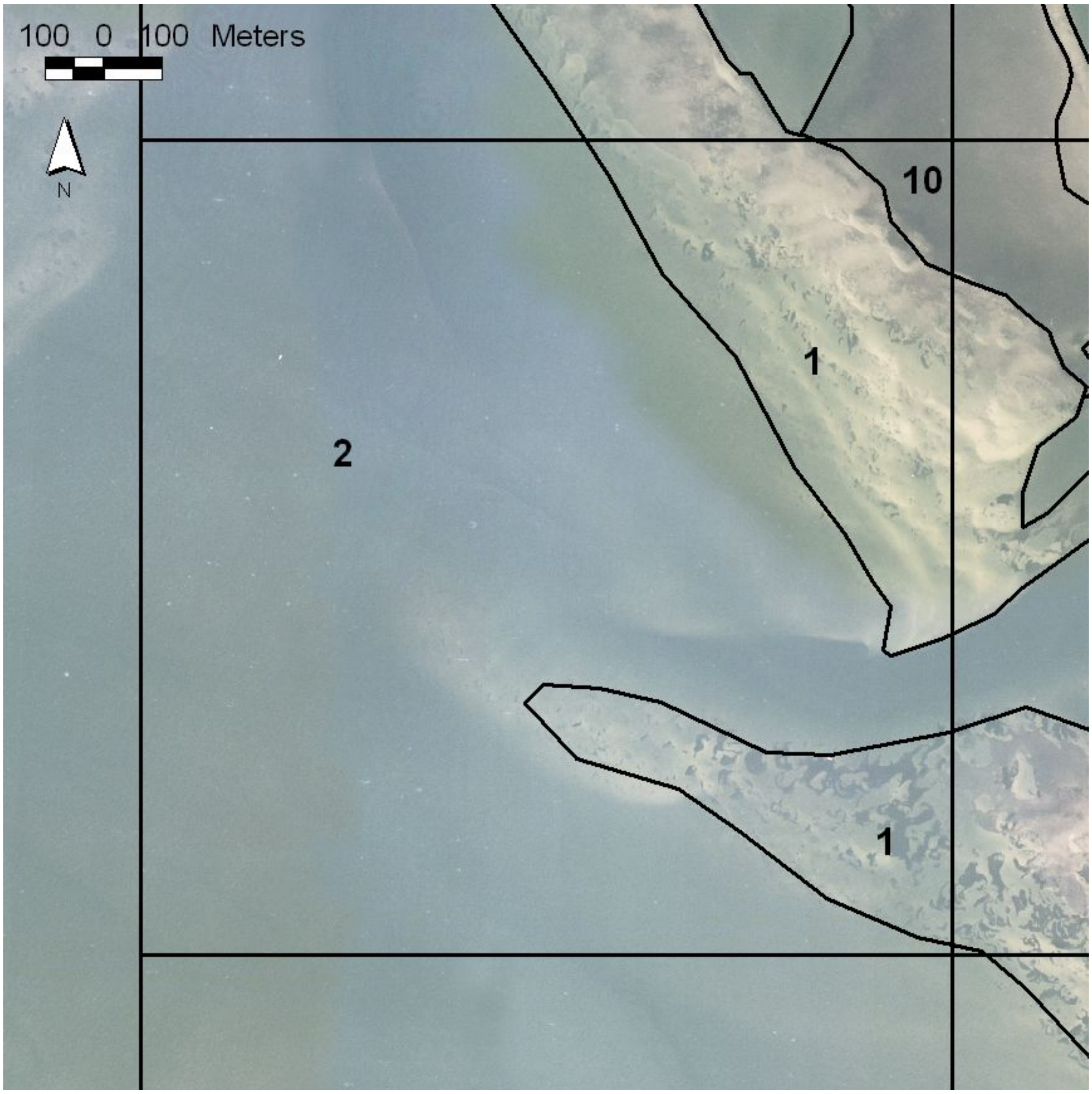
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-6. Tile 5 of 12 in the subaqueous soil survey.



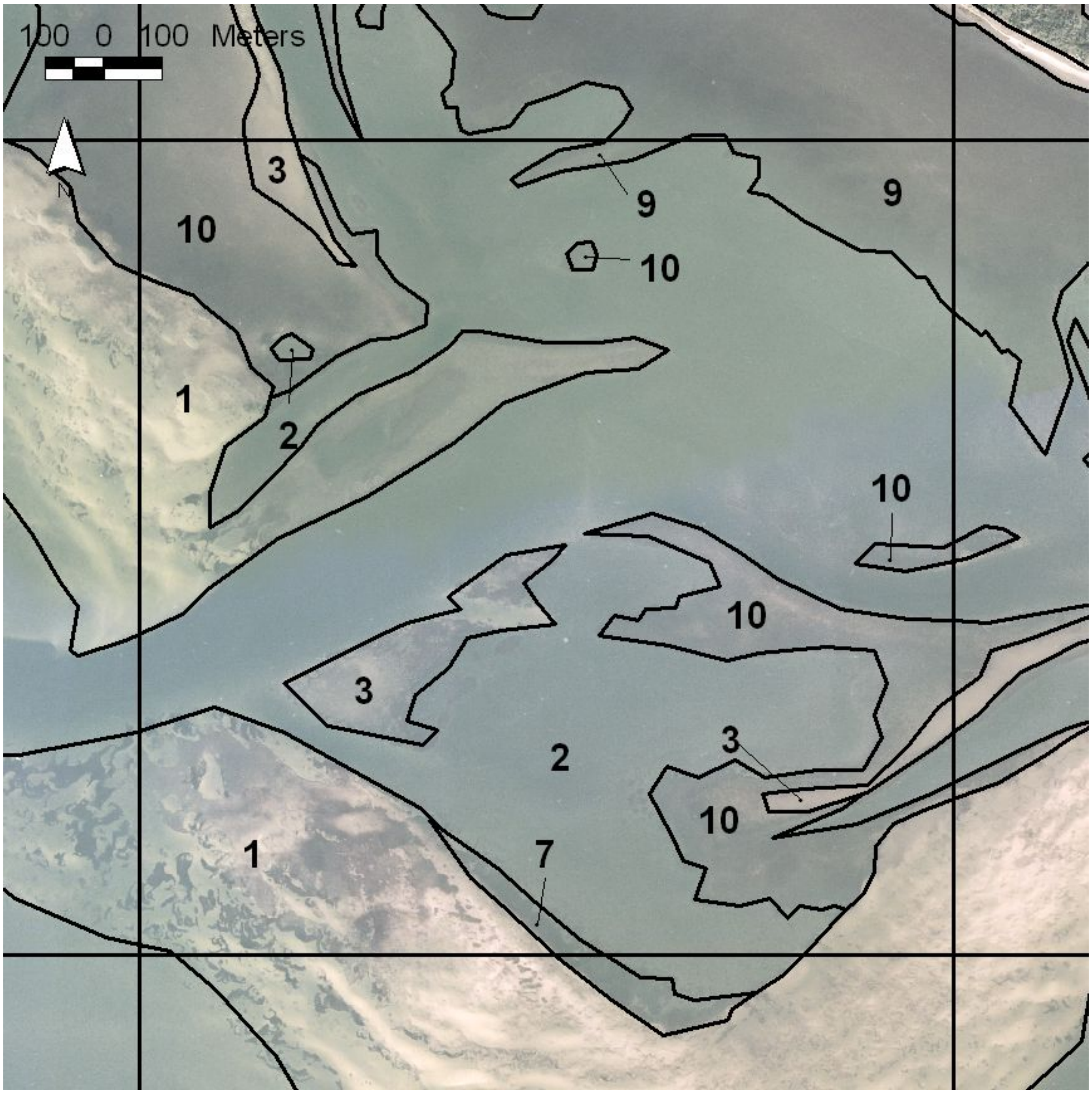
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-7. Tile 6 of 12 in the subaqueous soil survey.



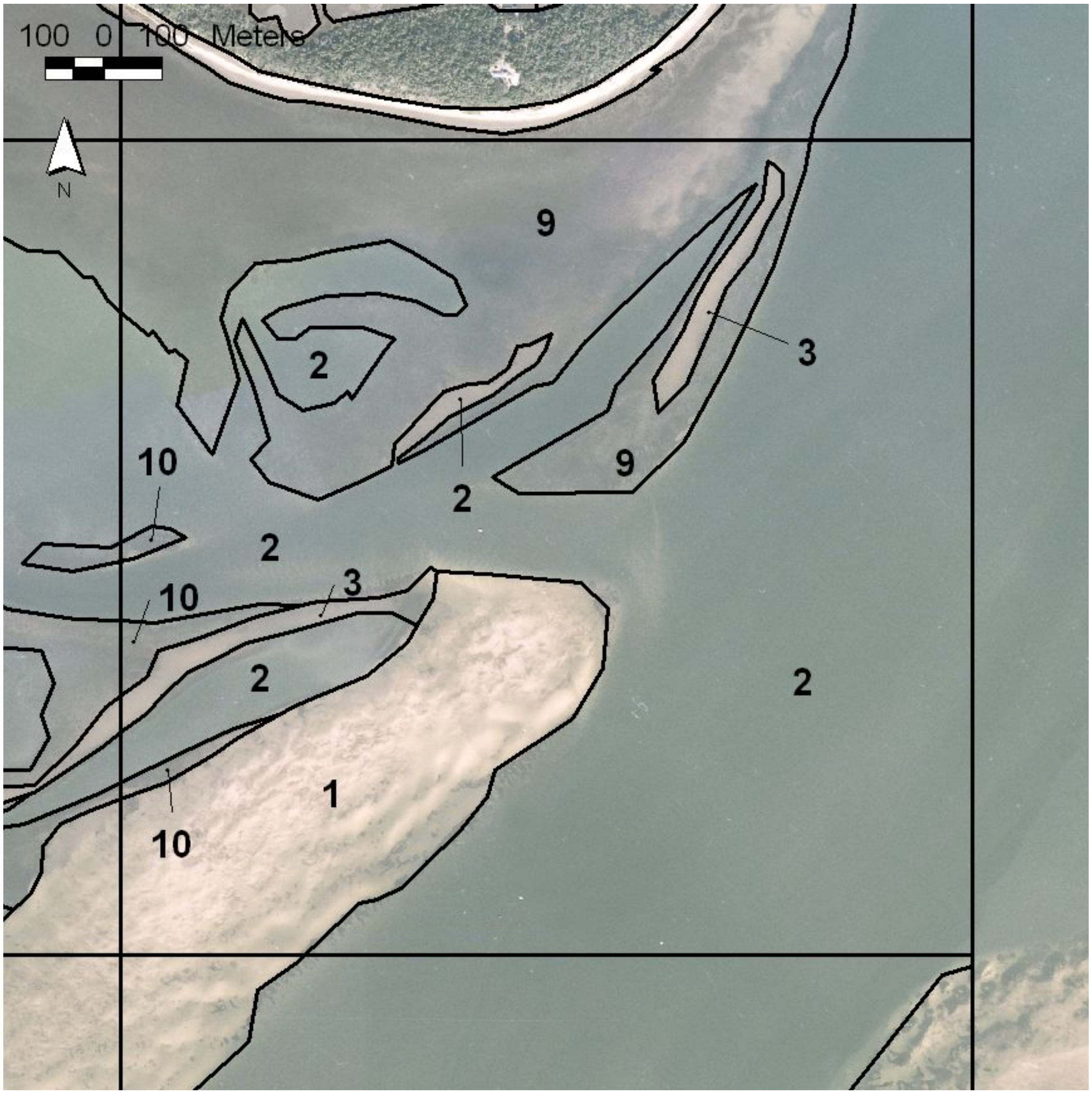
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-8. Tile 7 of 12 in the subaqueous soil survey.



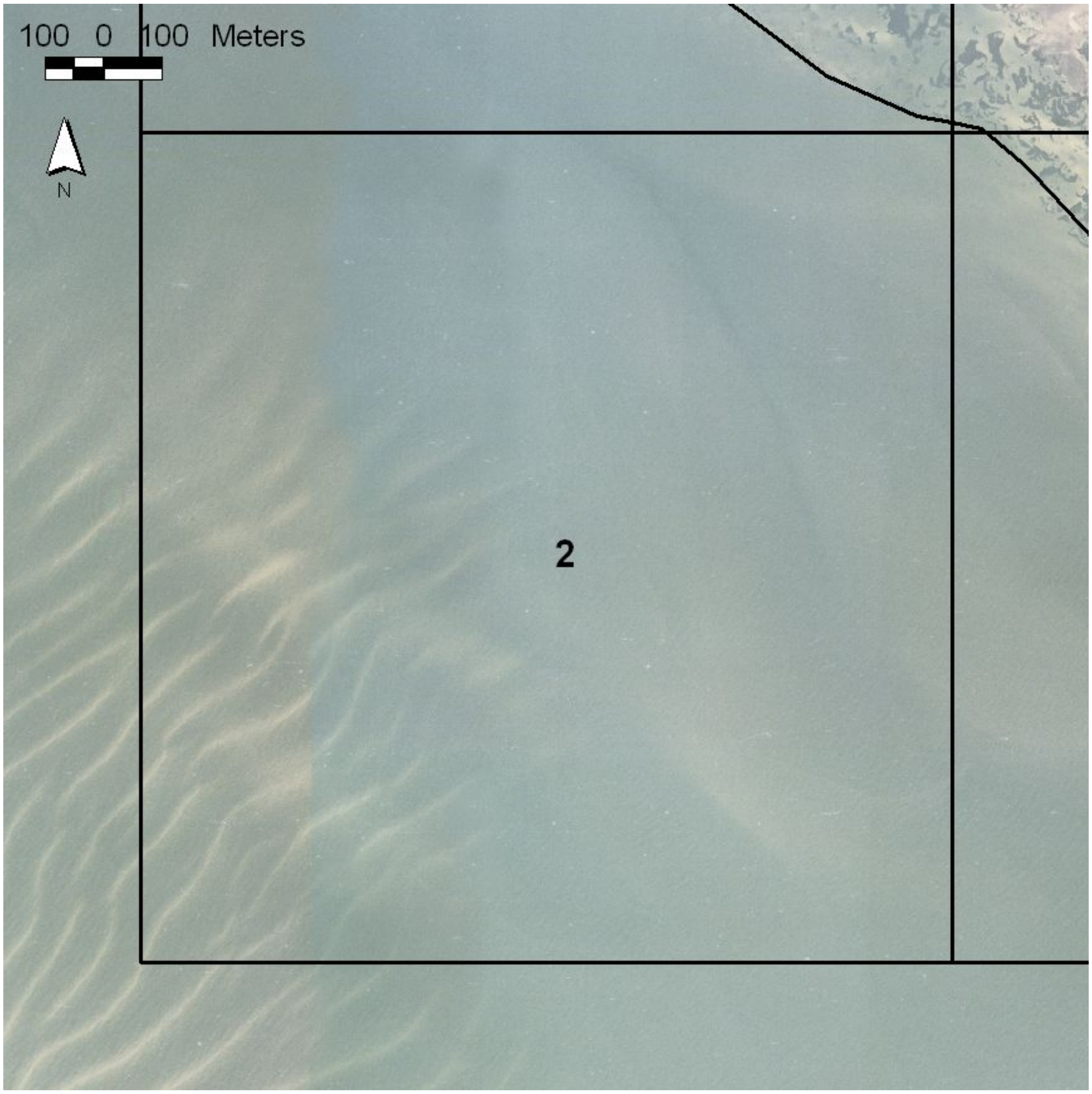
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-9. Tile 8 of 12 in the subaqueous soil survey.



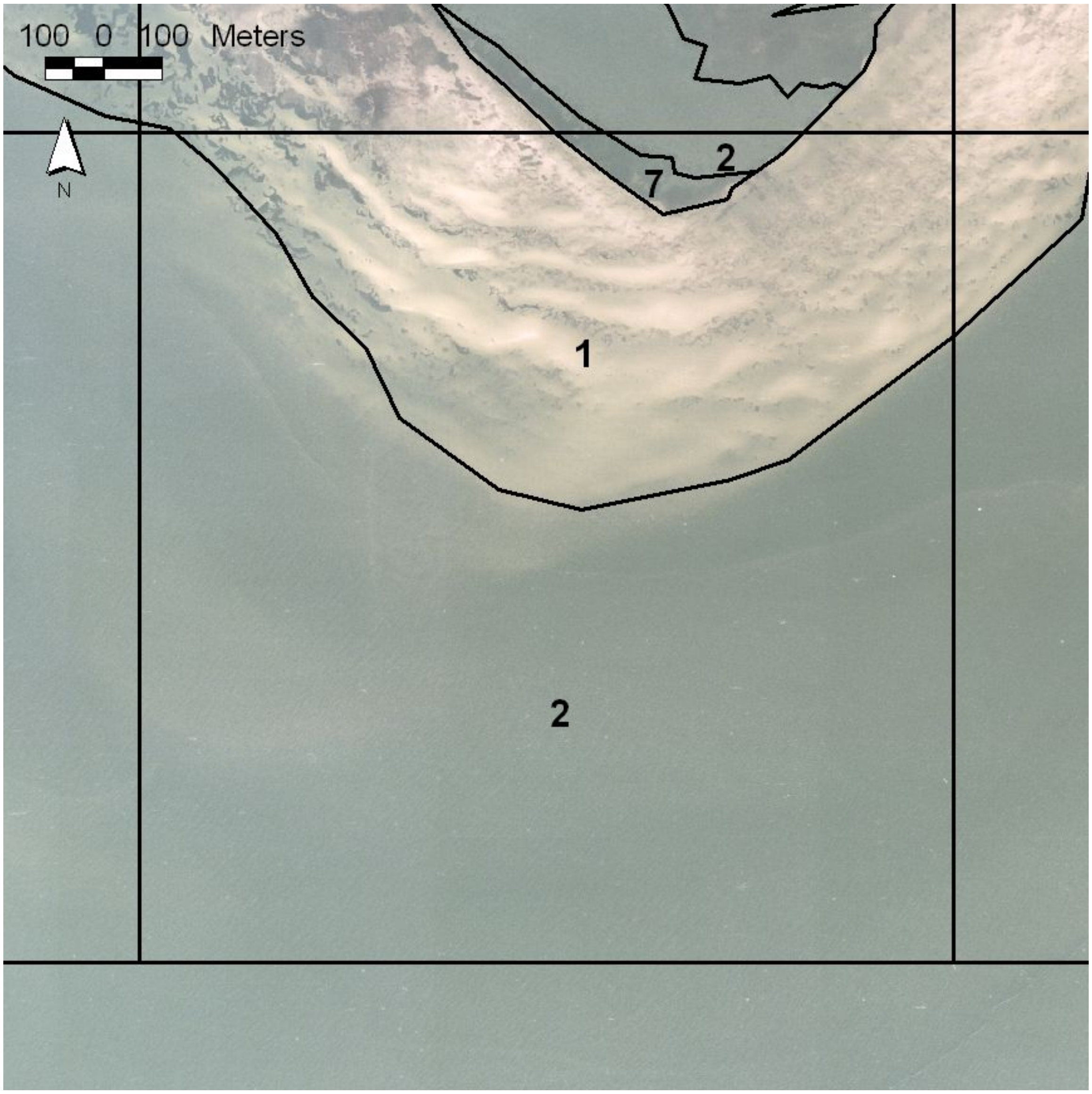
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-10. Tile 9 of 12 in the subaqueous soil survey.



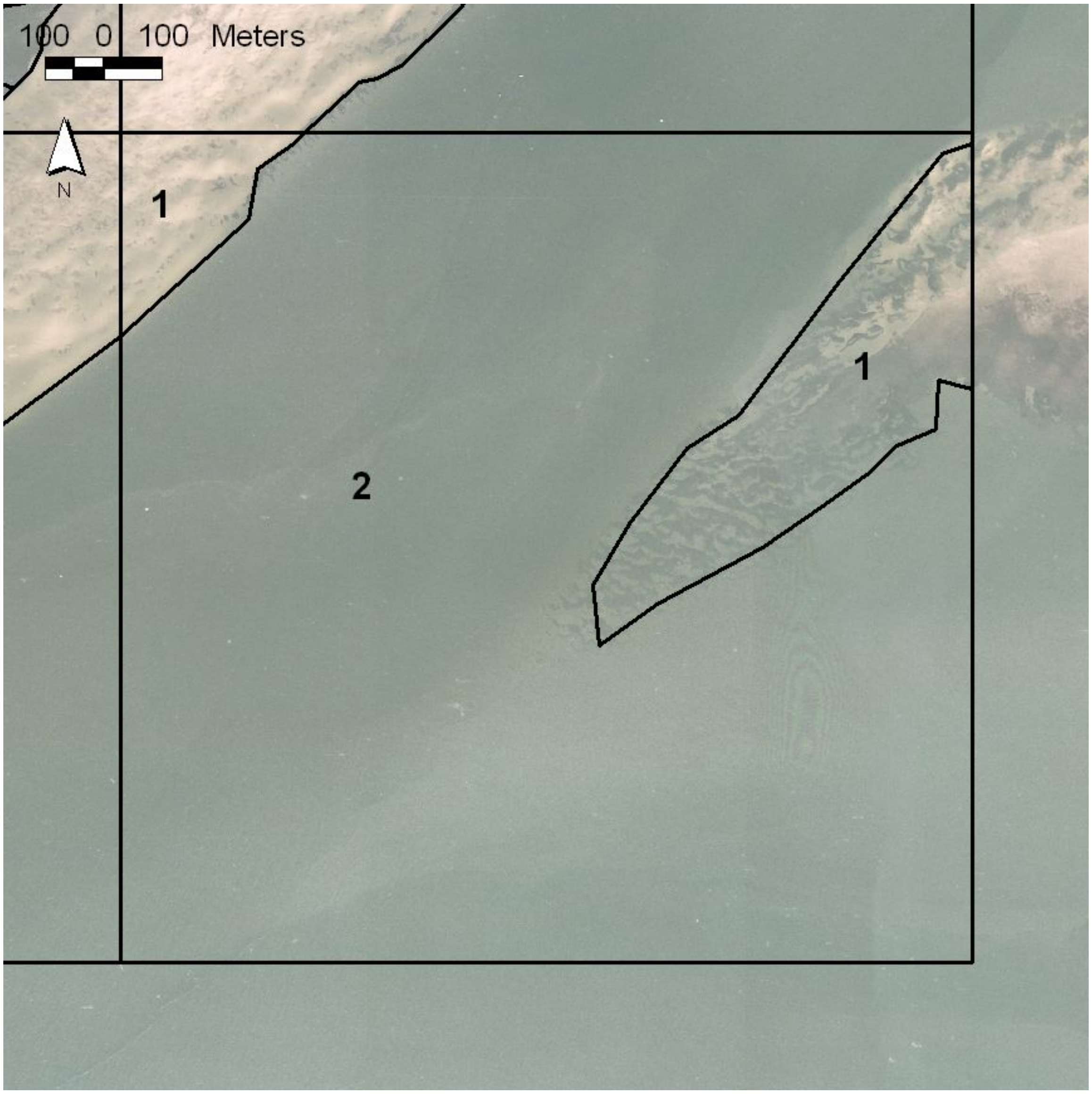
MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-11. Tile 10 of 12 in the subaqueous soil survey.



MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-12. Tile 11 of 12 in the subaqueous soil survey.



MUID	Landscape Unit	Series Name	New Series?	Current USDA Classification
1	Erosional Unvegetated Flat / Near Channel Bar Complex	Hornet / Nebar Complex	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
2	Deep Water	Deep Water	No	Non-soil
3	Edge of Channel Bar	North Key	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
4	Erosional Beach	Beaches	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
5	Erosional Unvegetated Flat	Hornet	Yes	Sandy, siliceous, hyperthermic Typic Fluvaquents
7	Near Bar Grassflat	Nebar	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
8	Drownded Flatwoods	Astenie Otie	Yes	Sandy, siliceous, hyperthermic Spodic Psammaquents
9	Near Shore Grassflat	Snake Key	Yes	Sandy, siliceous, hyperthermic Typic Psammaquents
10	Offshore Grassflat	Seahorse Key	Yes	Sandy, siliceous, hyperthermic Cumulic Endoaquolls
11	Oyster Bar	Reddrum	Yes	Sandy, siliceous, hyperthermic Typic Endoaquolls
12	Saltmarsh	Wulfert	No	Sandy or sandy-skeletal, siliceous, euic, hyperthermic Terric Sulfihemists
13	Saltmarsh Flat	Shell Mount	Yes	Loamy, siliceous, hyperthermic Sulfic Hydraquents
14	Unvegetated Flat	Lighthous Point	Yes	Siliceous, hyperthermic, Typic Psammaquents
15	Uplands	Uplands	No	Misc. Entisols and Spodosols

Figure B-13. Tile 12 of 12 in the subaqueous soil survey.

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BIOGRAPHICAL SKETCH

Larry Richard Ellis, “Rex,” was born and raised a Florida native. His roots run deep, as most of his immediate and extended family are within a few hours drive. He was fortunate to have attended excellent schools. His last school, the University of Florida, saw Rex bounce from one major to another, and from one interest to another, but ultimately zeroing in on a lifelong pursuit to understand soil.

Rex’s good fortune did not stop with his proximity to family and a wonderful state in which to grow up. He was able to combine an unbridled passion for the water with his newfound passion for soil: subaqueous soils. This dissertation topic brought him good fortune and good times, for both of which he is grateful beyond words. Rex eagerly awaits his postdoctoral life which he hopes will be filled with even more family, friends, and good fortune. Rex’s wife and son also eagerly await his imminent graduation as the three of them (and hopefully more in the near future) begin a wonderful journey together as a new family. Rex is very grateful for all he has, most importantly, his family.