ABSTRACT

GUNDERSEN, GILLIAN CLAIRE. Long-term accumulation of sediments, carbon, and nitrogen by coastal wetlands in the Albemarle Sound, North Carolina.(Under the direction of Marcelo Ardón-Sayao).

Wetlands of the Albemarle Sound provide important services including carbon sequestration, flood and storm protection, nutrient filtering, and productive nurseries that support the fishing and recreation industries of North Carolina. Sea level rise, climate change, and anthropogenic disturbances are affecting the wetlands ability to sustain these ecosystem services. The Albemarle wetlands are vulnerable to inundation and erosion due to their location on a low -lying peninsula in a drowned estuary with high shoreline erosion and low sediment deposition. In this study, I focused on the northern shoreline of the Albemarle-Pamlico peninsula, sampling two sites within a restored wetland and four transects along a salinity gradient that crossed natural forested wetlands (n=4), transitional wetlands (dying forest, emerging marsh, n=4)), marsh (n=4), and open water (n=4). I examined long-term (approx. 100 years) accumulation rates of sediment and associated carbon and nitrogen to answer the following questions.: 1) how and why are vertical accretion rates and carbon and nitrogen accumulation rates different across wetland types? and 2) how do soil, sedimentation, salinization, and anthropogenic disturbances affect wetland accretion and biogeochemistry? Wetland soil samples were analyzed for bulk density, pH, chloride, sulfate, nitrate, carbon (%C), nitrogen (%N), and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$). Excess ^{210}Pb and ^{137}Cs were measured in all 18 sites and 15 sites had usable results for calculating vertical accretion, mass accumulation, carbon and nitrogen accumulation rates for four forested, four transitional, two marshes, three open water, and the two restored wetland sites. There was no significant difference among wetland types in vertical accretion ($p>0.05$). Open water sites

had the lowest accretion rates, likely from erosion/deposition cycles along the shore. Vertical accretion rates across all wetland types averaged 0.16 cm/yr. Only two wetland sites had vertical accretion rates higher than global mean sea level rise (GMSLR) of 0.32 cm/year: a transitional wetland site with fine sediment sourced from a nearby channel (0.88 cm/yr) and a 12-year-old flooded restored wetland (0.35 cm/yr). Soil properties, bulk density, and %C suggest that wetland accretion in the study area is dominated by organic carbon deposition. Mass accumulation was lowest in marsh and open water sites (average 388.05 g m^{-2} yr^{-1}), compared with other sites (average 1096.1 g m^{-2} y^{-1}). Carbon accumulation rates were highest in transitional wetlands (average 249 g C m^{-2} y^{-1}) compared to other sites (118.7 g C m^{-2} yr^{-1}). Nitrogen accumulation was highest in a transitional wetland and a restored wetland (24.3 and 15.2 g N m^{-2} y^{-1}) and lowest in open water sites (1.4 g N m^{-2} y^{-1}). The $\delta^{15}N$ and sulfate results indicate several wetlands may have anthropogenic sources of N and sulfate. The average %C and %N in forested and marsh wetlands decreased with average soil chloride reflecting possible indirect disruption of carbon and nitrogen sequestration by salinization. Three transitional wetlands had the highest carbon accumulation rates among the natural wetlands. Finally, in addition to the wetland analyses, a citizen science mobile device application (app) was developed and deployed, providing an interface for people to document cypress trees as indicators of forested wetland health and transition. The app collected promising results in the first year, illustrating distinct areas along the coast where bald-cypress trees are stressed by salinity and erosion. Overall, my results indicate several challenges to sustaining the ecosystem services of the Albemarle wetlands including accretion rates lower than GMSLR, low sediment input, carbon dominated accretion, high erosion of shorelines, anthropogenic disturbances, and the impact of saltwater on forested and marsh wetlands’ ability to sequester carbon and nitrogen.

Long-term accumulation of sediments, carbon, and nitrogen by coastal wetlands in the Albemarle Sound, North Carolina.

by
Gillian Claire Gundersen

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APPROVED BY:

Christopher Osburn

Theodore Shear

Marcelo Ardón
Committee Chair

BIOGRAPHY

I grew up in beautiful northern Virginia and graduated with a Bachelor's of Science from the University of Massachusetts Amherst in May 2015. During my undergraduate career, I developed a keen interest in understanding how ecological processes respond to critical stimuli, such as global climate change and land development. I started a Master's in Biology at East Carolina University under the direction of Dr. Marcelo Ardón in August 2015, and transferred to North Carolina State University Forestry Department in August 2016 to finish the degree under Dr. Ardón. I hope to continue working at the frontier of climate change research, encouraging public involvement in learning about and protecting our changing ecosystems.

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CHAPTER 1. Introduction and Research Objectives

1.1 Introduction to North Carolina Wetlands, Ecosystem Services, Nutrient Cycling

The coastal wetlands of North Carolina are diverse and include many types of unique vegetation communities including long leaf pine savannas, sand hill scrubs, pocosins, pond pine woodlands, coastal plain bottomland forests, freshwater and brackish marshes, cypress-gum swamps, and salt marshes. These coastal wetlands provide critical ecosystem services such as carbon sequestration, flood and storm protection, nutrient filtering, and productive nurseries for a variety of important flora and fauna (Barbier et al. 2011, Palmer et al. 2005, Poulter et al. 2009). Climate change and sea level rise however, are affecting North Carolina wetlands and the ecosystem services they provide (Moorhead and Brinson 1995, Riggs and Ames 2003). The goal of this projectwas to understand ongoing change in carbon sequestration and nutrient cycling in coastal wetlands near the shoreline along the Albemarle Sound.

Coastal wetlands in North Carolina vary by gradients in elevation, water availability, and saltwater concentration (Figure 1.1) (Janousek and Folger 2014). As elevation is lost and saltwater inundation increases through mechanisms such as subsidence and sea level rise, the forested wetlands die off, leaving behind open water ponds or snags (standing dead trees), remnant understory, and increasing growth of emergent marsh vegetation (grasses, rushes, and sedges) (Moorhead and Brinson 1995). This transition zone between forested wetlands and marsh, often referred to as ghost forests, is an important indicator of wetland change and can be a visual cue for where change is occurring (Nash and Spear 1991, Senter 2003, Ault

2014). Tree mortality in forested wetlands can occur as the result of a variety of conditions, including: disease, parasites,, drought, inundation, fire, limited nutrients, (Carle 2001, Conner et al. 1997). These disturbances can be human induced, climate induced or natural change with time. Moreover, snags can stand for decades, and the rate of degradation can vary from location to location (Bater et al. 2009, Kim et al. 2009, Conner et al. 2007). While there has been research examining ecosystem services provided by forested wetlands and marshes, we still lack a clear understanding of services provide by transitional ghost forests. Understanding the nature and function of ghost forests, how they are formed along the coast and how they respond to changes in the ecosystem, is therefore critical to the future management of North Carolina wetlands.

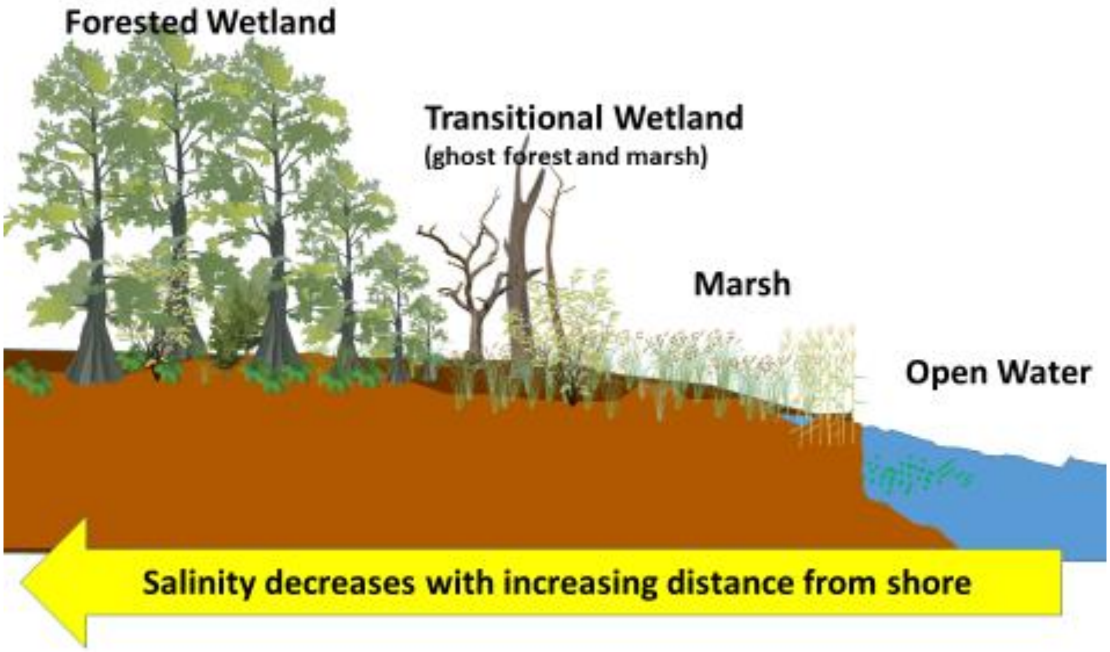

Figure 1.1 Schematic cross section through North Carolina wetlands in the Albemarle Sound showing the progression from forested wetland, transitional wetland, marsh, and open water along the salinity and elevation gradient.

One of the important ecosystem services wetlands provide is the sequestration of carbon (C) and nitrogen (N) (Barbier et al. 2011, Mitsch and Gosselink 2007). Carbon and nitrogen sequestration is dependent on inundation, sediment supply, vegetation community, organic deposition, microbial activity, and the chemistry of the wetland environment (Reddy and DeLaune 2008). By measuring vertical accretion and mass accumulation rates, along with C and N elemental composition, we can calculate carbon and nitrogen accumulation rates for wetlands (Mitsch and Gosselink 2007). Vertical accretion is dependent on organic deposition and sediment deposition. Organic deposition is a function of vegetation and the ability of the wetland to fix carbon through photosynthesis. For example, in forested wetlands, most deposition comes from above ground biomass, whereas in marshes most biomass deposition is belowground from roots (Reddy and DeLaune 2008). Sediment deposition in wetlands depends on the physiographic setting, and may be sourced from suspended sediment in rivers, flooding events, erosion and run-off from land, or daily deposition of sediment from tides(Kirwan et al 2013). Wetland accretion rates vary across wetland types due to varying contributions of organic material and sediment import and export (Webb et al. 2013).

In the Albemarle-Pamlico peninsula, black water rivers like the Alligator River and the many small blackwater streams of the coastal plain are sediment poor. Sediment supply into the Albemarle Sound is primarily through suspended fine sediment from the Roanoke and Chowan River systems (Harned and Davenport 1990, Riggs et al. 1995). These sediments get deposited in the estuary or at the mouth of the rivers and may be distributed to wetlands and shorelines by wind tides, flooding, and storm events (Moorhead and Brinson 1995, Riggs and Ames 2003). Coarser sediment and eroded organic material is derived by wind and storm erosion along the Outer Banks to the east and from marshes to the west (Corbett et al. 2007). The Albemarle Sound is protected from daily astronomical tides by the barrier islands of the Outer Banks, so daily tides are not substantial enough to provide a regular supply of sediment to wetlands. Drainage ditches and other hydrologic controls further complicate sedimentation. Marsh accretion in the northern Albemarle-Pamlico Peninsula is typically low in clastic sediment, probably due to the absence of diurnal tides and is primarily controlled by organic growth (Moorhead and Brinson 1995).

Marsh organic deposition is predominantly from the slow decay of vegetation and roots. Marsh vegetation also effectively traps sediment including sediment washed in from wave action and storm events (Gleason et al. 1979, Feagan 2009, Ensign et al. 2014). Wave action can also erode marshes and affect accretion (Riggs and Ames 2003). Where marshes occur at the outlets for rivers or streams they may have high accretion rates (Baumann et al. 1984, Reed and Cahoon 1992). Generally carbon accumulation is highest in brackish marshes (Craft 2012).

In forested wetlands, the main sources of accretion are sedimentation from streams, freshwater flooding events, and organic deposition from foliage and the slow decay of woody materials (Craft et al. 2007, Noe et al. 2016). In the forested wetlands of the Albemarle Sound there is input from black water streams (Moorhead and Brinson 1995), characterized by high tannin, low sediment load, and low flow. Carbon accumulation is generally lower in freshwater forested wetlands compared to marshes (Loomis and Craft 2010).

Ghost forests contain elements of both marshes and forests. When forested wetlands transition to ghost forests, there is a decrease in freshwater vegetation and increase in marsh grasses, changing the structure of the system. However, ghost forests do not have the same hydrology, soils, microbial community, or vegetation as a marsh. So, although they may have some aspects of marshes, ghost forest accumulation rates may or may not increase. In transitioning systems, where nutrient availability increases due to the combination of organic material deposited from dying vegetation and new emergent vegetation, microbial metabolism could increase decomposition through microbial priming (Herbert et al. 2015, Guenet et al. 2010). Microbial priming is the idea that microbes will increase decomposition activity of more recalcitrant organic material when they have an increase in labile carbon resources, like emergent marsh roots and stems (Neubauer et al. 2005). Conversely, ghost forests gain emergent marsh vegetation which contribute greater biomass and may positively increase carbon storage if carbon decomposition does not increase.

1.2. Vulnerability and Restoration in NC Wetlands

Understanding and anticipating landscape-scale change of coastal wetlands is a major focus for resource managers and ecologists. Mapping wetland change has been an important form of resource management since the development of the National Wetland Inventory (NWI) in 1954, for the conservation of waterfowl habitat (Cowardin et al. 1979). The advent of aerial photography and satellite imaging has advanced this classification significantly due to increasing data resolution and data types (Lane et al. 2014, Lunetta et al. 2002, Ozemi and Bauer 2002, Usman et al. 2015). Decades of data show a decline in wetlands, especially forested wetlands, as a result of human development (Dahl and Stedman 2013). In North Carolina, wetlands were disrupted as early as the 1600s by early colonial settlements that made room for farming; and had the largest losses during the 1970s from the logging and agriculture industries (Dahl and Allord 1997, Dahl 2013). The rate of wetland decline has decreased since then, but wetland area is still diminishing and fragmenting from encroaching human development, change to local hydrology, and from agricultural runoff.

Sea level rise imperils coastal wetlands through inundation, submergence, erosion, and salinization (Riggs and Ames 2003, Fitzgerald et al. 2008, Loomis and Craft 2010, Kirwan et al. 2013). Global wetland assessments estimate losses of 20-45% of marshland by 2100 as the result of sea level rise (Loomis and Craft 2010). Measurements of the global mean sea level rise (GMSLR) indicate that rates of sea level rise have increased from less than 0.17 cm/yr in the period between 1901-1993 to an average of 0.32 cm/yr over the period between 1993-2010 (Church et al. 2013). The rate of local to regional sea level rise, such as in North Carolina, is influenced by a variety of other factors including glacial isostatic adjustment, differential sediment compaction, tectonic adjustments, and variations in sea surface response to ice melting and ocean warming due to ocean currents, and interaction with Earth's axial rotation (Church et al. 2013, Kopp et al. 2015). In the area north of Cape Hatteras on the North Carolina coast, sea level rise is greater than the GMSLR (Sallenger et al. 2012, Kemp 2009, Kopp et al. 2015). In the Outer Banks, just east of the study area, the local rate of sea level rise has risen from about 0.33 cm/year over the period 1940-1980 (Kopp et al. 2015) to a current rate of 0.45 cm/yr (NOAA tidal gage https://tidesandcurrents.noaa.gov/sltrends/sltrends.html).

Because coastal wetlands occur at the interface of the land and sea, they are particularly vulnerable to inundation and erosion (Riggs and Ames 2003, Fitzgerald et al. 2008, Loomis and Craft 2010, Kirwan et al. 2013). Analysis of marsh response to sea level rise over the past millennia (Redfield 1972, Reed 1995, Fagherazzi et al. 2004) and modeling of marsh accretion (Kirwan and Megonigal 2013, Cahoon 2015, Kirwan et al. 2016) indicate that many coastal wetlands have either continued to build up at pace with sea level rise or have shifted landward (Kana et al. 1988); and could continue to do so even at much higher rates of sea level rise. The ability of coastal wetlands to accrete at rates that keep pace with sea level rise is a function of the rate of organic accumulation, availability of suspended sediment, and tidal range (Kirwan et al. 2013, 2016). A study by Morris et al. (2016)

calculated that U.S. tidal peatlands, dominated by organic accumulation, may be limited to steady state accretion rates of less than 0.5 cm/yr, given an absence of increased inorganic sediment loads. Along the northern edge of the Albemarle-Pamlico Peninsula, the conditions for wetland accretion are not ideal for keeping up with sea level rise, due to low sediment source and the lack of astronomical tides (Moorhead and Brinson 1995). Additional threats to wetlands from climate change include increased drought which raises salinity and stresses plant communities and extreme storms and inundation (Mulholland et al. 1997, Osland et al. 2016), which may add sediment to wetlands but also cause vegetation damage and erosion. Shoreline erosion, even in a relatively protected embayment, reduces the size of wetlands in response to advancing sea levels (Moorhead and Brinson 1995).

Salinization, the inundation of wetlands by seawater, can alter wetland biogeochemical cycles, increasing sulfur, decreasing carbon and nitrogen storage, damaging the health of freshwater species, and altering or transforming vegetation (Herbert et al. 2015). Seawater contains cations like Mg^{2+}, Ca^{2+}, Na^{+}, and K^{+} and anions like Cl^{-} and Br^{-}. Seawater cations can replace cations on soil cation exchange sites, such as ammonium and hydrogen, through ionic displacement (Ardón et al. 2013). Ammonium is available for uptake by plants, processed through anaerobic ammonium oxidation/aerobic nitrification, or leached from the soil to be consumed downstream possibly causing eutrophication (Herbert et al. 2015). Seawater also contains SO_4^{2-} which is a more energetically favorable electron acceptor in highly reduced wetlands compared with methane or carbon (Scheopfer et al. 2014). SO_4^{2-} is reduced to hydrogen sulfide, which is toxic to some plants and microbes and can inhibit vegetation growth (Lamers et al. 2013), nitrification, and denitrification (Rysgaard et al. 1999, Joye and Hollibaugh 1995).

Salinization can cause a cascade of biogeochemical processes which are complicated and not well understood under the diverse conditions of coastal wetlands (Herbert et al. 2015). However, hypothetically, increased nutrients from salinization further increase carbon mineralization through respiration of CO_2 from higher energy pathways like sulfate reduction (Herbert et al. 2015, Weston et al. 2011) which decreases carbon and nitrogen accumulation rates. Forested wetlands and marshes, without other impacts, would thus have decreased carbon and nitrogen accumulation with increased salinity. In freshwater peat marshes where methanogenesis is replaced by the more efficient sulfate reduction processes from saltwater intrusion, increased decomposition leads to a collapse in the peat structure (Henman et al. 2008). Salinity therefore, could also decrease the soil structure causing subsidence and lowering the accretion rate of wetlands further. Finally, the transition zone could have lower rates of carbon accumulation similar to marsh and forested sites or lower if microbial priming increases decomposition.

Restored wetlands are an important component in the effort to maintain ecosystem services as human development expands (Zedler et al. 2005). Although most restored wetlands follow a strict standard for construction and success when associated with mitigation, this is not always associated with the ability of a wetland to carry out the functions needed to protect it from sea level rise and saltwater incursion (Bosch and Matthews 2017, Johnson, Shear and James 2013, West, Clough and Ambrose 2000). A measure of this vulnerability is necessary when thinking about the usefulness of employing restored wetlands as a hard-measure protection from sea level rise (Edenhofer, Ottmar, et al 2011).

A restored wetland's vulnerability to saltwater intrusion compared to natural wetlands can be measured by sediment and carbon accretion. Some studies suggest that restored wetlands constructed for the purpose of protection from sea level rise or saltwater intrusion may function better than the reference, (Howe et al. 2009, Sheng et al. 2015) but this is not always the case (Kearney et al. 2011, Hunter et al. 2016). The original landscape and subsequent uses could have as much of an effect on the success of the restoration as the construction project itself (Zedler et al. 1999).

1.2 Research Questions

In this study I examined long-term (approximately 100 years) accumulation rates of sediment and associated carbon (C) and nitrogen (N) in wetlands along the Albemarle Sound. The following questions were addressed:

1. What is the difference in carbon and nitrogen accumulation rates in different wetland types?
2. How do the rates of carbon and nitrogen accumulation differ between restored and natural wetlands?
3. Can citizen science be used to monitor the health of forested wetlands?

I tested the following hypotheses:

1. Salinity will cause a decrease in vertical accretion rate, as well as carbon and nitrogen accumulation rates across a salinity gradient, regardless of wetland type.

2. Marshes will have the highest concentrations of C and N, and rates of soil C and N accumulation compared to forested wetlands.
3. Transitional wetlands will have lower rates of C and N accumulation compared to marsh and forested wetlands.
4. The rate of nitrogen and carbon accumulation will be less in a restored wetland relative to natural wetlands.

CHAPTER 2. Study Area, Soil Sampling, and Analyses Methods

2.1 The Albemarle Sound Study Area

The study area is located in the North Carolina coastal plain on the Albemarle-Pamlico peninsula which is bounded to the north by the Albemarle Sound, to the east by the Croatan Sound and to the south by the Pamlico Sound. Five transects, focused along the northern and eastern coast of the peninsula (Figure 2.1) were chosen based upon the ability to core all three major wetland types (forested, marsh, and open water) and had transition zones. The study area also lies within three adjacent counties - Washington, Tyrell, and Dare. Detailed maps and pictures of transects are provided in Appendix A.

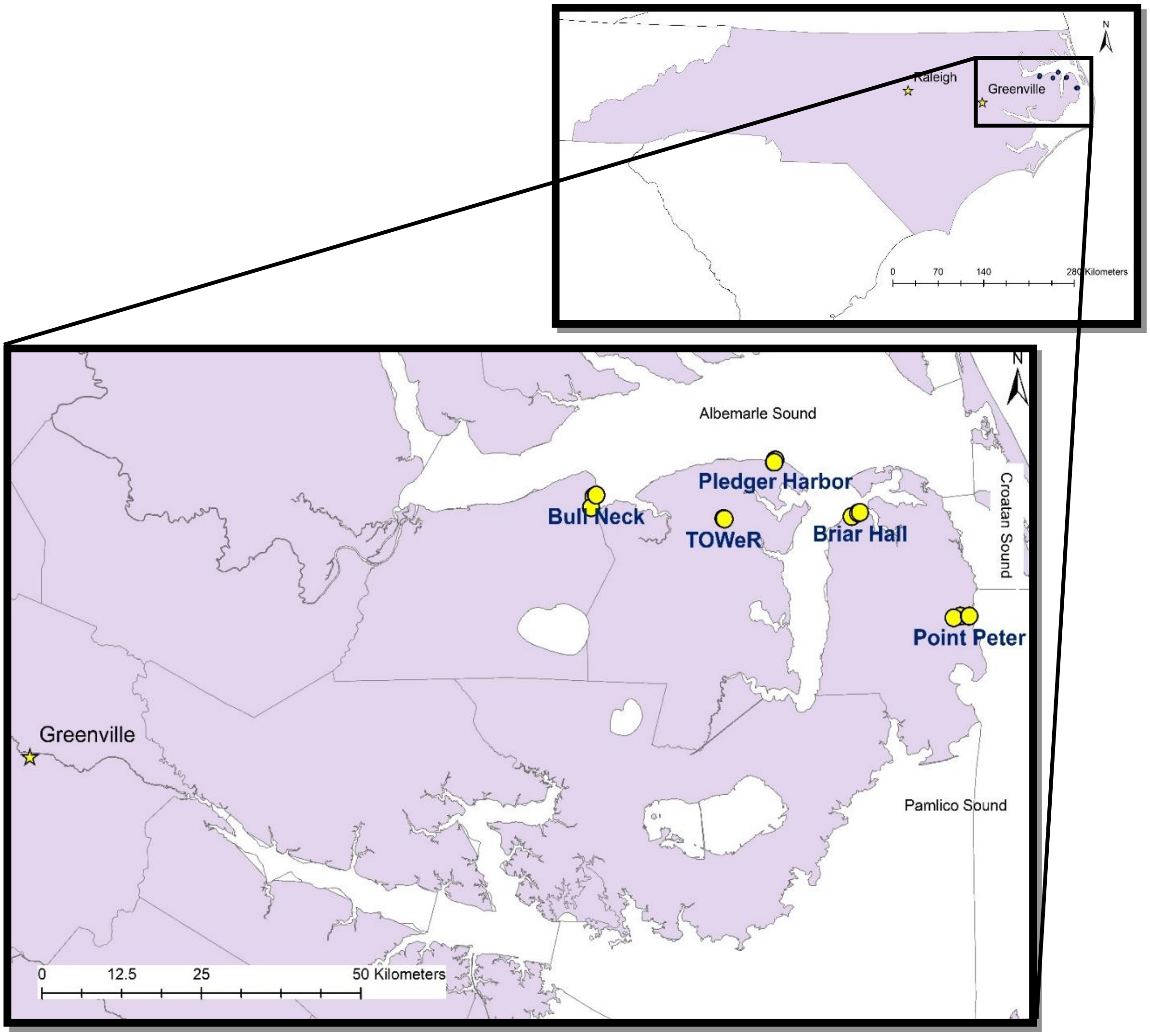

Figure 2.1 Map showing study area and wetland sites sampled on the Albemarle-Pamlico Peninsula in North Carolina.

Together, the Albemarle and Pamlico Sounds form the second largest estuary in the United States and include over 9,000 miles of freshwater rivers and streams and 1.5 million acres of brackish, estuarine waters (Riggs and Ames 2003). Much of the estuary is protected from astronomical tides of the Atlantic Ocean by the barrier islands of the Outer Banks. In the Albemarle Sound, hydrology and circulation are primarily driven by freshwater rivers and streams and wind-driven tides. Water in the estuary from the Albemarle Sound into the Upper Croatan Sound (the water surrounding the field area of this study) ranges from freshwater in the west to oligohaline in the east (Figure 2.2, Riggs and Ames, 2003). Salinity can vary from 0 to 8 parts per thousand (ppt) (Giese et al. 1985, Garrett 1993) and salinities as high as 12 ppt (Ardón et al. 2013) and 23.8 ppt (Garret 1993) related to low flow and drought have been reported. Salinity is generally lowest in March when runoff from rivers and streams is greatest and climbs steadily to a maximum in December when rivers and streams are at their lowest flow (Giese et al. 1985). The peninsula is underlain by Pliocene sediments (5.3 to 1.8 million years in age) and Quaternary surficial sediments (less than 1.8 million years in age) that are slightly consolidated to unconsolidated sediments including: mud, muddy sand, sand, and peat, creating a gentle topography (Riggs and Ames 2003).

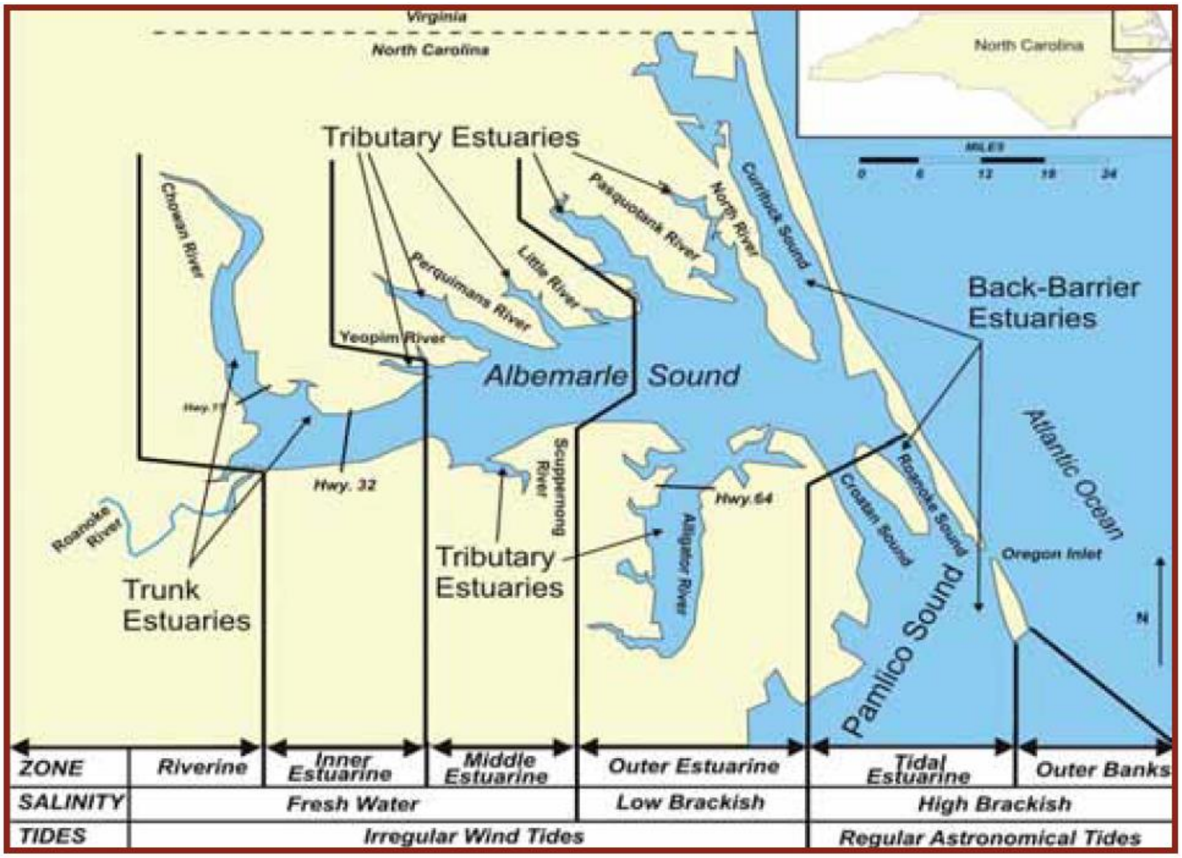

Figure 2.2 Map of the Albemarle estuarine system from (Riggs and Ames 2003) showing the general zones defined by salinity gradients and dominant tidal processes. Note that although Point Peter falls within the tidal estuarine category spatially, Riggs and Ames (2003) mentions in text that the area is dominated by wind tides.

The shoreline of the peninsula is dominated by wetlands as is much of the interior. The paper by Moorehead and Brinson (1995) noted some unique features of the peninsula that affect the sustainability of the wetlands: 1) low elevation with over half the area <1.5m in elevation, 2) extensive wetlands covering 53% of the area; 3) dominantly hydric soils, 4) absence of astronomical tides; 5) low slope of the land; and 6) low sediment sources. They concluded that these attributes inhibit vertical accretion and landward migration of marshes that have been modeled for other areas (Kana et al. 1988). Although the Roanoke and Chowan Rivers provide sediment to the estuary, it stays predominantly within the estuary or at the mouth of the rivers (Harned and Davenport 1990, Riggs and Ames 2003). Storm and wind induced flooding are the major ways sediment is delivered to the Albemarle Sound shoreline, often in high energy, erosional events, resulting in depositional/erosional cycles with a net shoreline loss because of the low elevation, mostly organic nature of shorelines (Riggs and Ames 2003). Several estimates of shoreline erosion have been made at or near some of the wetland sites measured in this study by Riggs and Ames (2003). They measured shoreline erosion rates of -0.5 to –1 m/yr at Woodards Marina on the shoreline halfway between the Bull Neck and Pledger Harbor sampling sites described below, and erosion rates of -2 to -2.5 m/yr at Point Peter Road near the Point Peter sampling site described below.

Site Descriptions - Natural Wetlands

The Bull Neck transect is located in the Bull Neck Swamp Forest in Skinnersville, NC, a private waterfront forest owned by the North Carolina State University Department of Forestry and Environmental Resources (Figure 2.2). The area has been under preservation since 1996. The forested site [35.9477005,-76.3877029] is a swamp dominated by tupelo, cypress, and maple trees. The transitional wetland [35.9328995,-76.3924026] is located along the Deep Creek channel and dominated by young or stunted blackgum and maple as well as emergent shrub and grass species. The marsh [35.9496994,-76.3835983] is a common reed monoculture, and the open water site [35.9496994,-76.3828964] was bare of any growth, but dotted with old bald cypress stumps in the substrate. The soil is Dorovan muck at the forested and transitional wetland and includes peat at the marsh and open water sites. The elevation at the sites ranges between 0 and 1 meter above sea level. The Dorovan Series (dysic, thermic Typic Haplosaprists) consists of very deep organic soils (50-100 inches thick), dark brown to gray and black, very poorly drained, moderately permeable, strongly acidic soils on forested flood plains and hardwood swamps (USDA SSURGO Database 2013; Tant 1981). In the area sampled, the Doravan muck is comprised of brown fibric organic muck that becomes more clayey and silty with depth.

The Pledger Harbor transect is located along Pledger Harbor road in the Palmetto-Peartree Preserve located in Columbia, NC (Figure 2.2). The area has been protected since 1999 through the North Carolina Conservation Fund. The forested site [35.9902,-76.0709991] is a swamp, dominated by pond pine and blackgum. The transitional wetland [35.9903984,-76.0700989] is also dominated by pond pine, but with younger or stunted vegetation and several emergent herbaceous and shrub species. The marsh [35.9874001,-76.0726013] is predominantly a monoculture of cord grasses with occasional wax myrtle. The open water site [35.9872017,-76.0718994] is dotted by tall standing pine and cypress snags. The forest and transitional wetlands soils are the Tomotely fine sandy loam and the marsh and open water soils are the Dorovan muck. Elevation was minimal; most sites are at or below sea level. The Tomotely Series (fine-loamy, mixed, semiactive, thermic Typic Endoaquults) are level, poorly drained, brown to gray, strongly acidic, fine sandy loams and fine sandy clayey loams with moderate to moderately slow permeability (USDA SSURGO Database 2008; Tant, 1981). In the field area sampled, the Tomotely of the forested wetlands was brown silty sand that becomes grayer and clayey with carbonaceous roots at depth. The Dorovan Series (dysic, thermic Typic Haplosaprists) consists of deep organic soils (51-80 inches thick), reddish brown to black, very poorly drained, moderately permeable, extremely acidic soils underlain by fluvial soils, and occurs on forested flood plains and hardwood swamps (USDA SSURGO Database 2013; Tant 1981).

The Briar Hall transect is located along Briar Hall Road in the Alligator River Wildlife Refuge in Manns Harbor, NC. The area has been preserved since 1984. The forested site [35.9101982,-75.9403992] is a pocosin and bottom-land swamp dominated by loblolly pine and blackgum with an understory of rush and fern. The transitional wetland [35.9146004,-75.9290009] is dominated by wax myrtle and sawgrass with some standing loblolly, mostly snags. The marsh [35.9149017,-75.9281998] is a mixture of sedges and grasses, dominated by saw grass. At the open water site [35.915699,-75.9256973], there are no standing snags but cores did contain wrack matching the nearby common reed. The soil series were variable across sites: the forested wetland soils are Hyde loam, the transitional wetland and marsh soils are the Roper muck, and the open water soils are the Hobonny muck. The elevation ranges between 0 and 1 meter above sea level. The Hyde Series (fine-silty, mixed, active, thermic Typic Umbraquults) consists of dark gray to brownish gray, strongly acidic, poorly drained loam soils, 40-70 inches thick, formed on loamy marine sediments (USDA SSURGO Database 2008, Tant 1992).. The Roper Series (fine-silty, mixed, semiactive, acid, thermic Histic Humaquepts) consists of black to gray and brown, strongly acidic, poorly drained muck and mucky loam, 30-60 inches thick overlying sandy marine sediments (USDA SSURGO Database 2000, Tant 1992).. The Hobonny Series (euic, thermic Typic Haplosaprists) is a dark grayish brown, organic, moderately permeable, acidic, poorly drained muck, 50-90 inches thick (USDA SSURGO Database 1999; Tant 1992).

Point Peter transect is located along Point Peter Road in the Alligator River Wildlife Refuge, in Manns Harbor, NC. The area has also been preserved since 1984 and has had regulated water control structures since 2011 (Perkins 2013). These structures ensure that the forested wetlands retain their freshwater nature. There have been efforts to replant cypress and blackgum in areas near the study sites, and evidence of a recent fire was seen in the field close to the transitional wetland site. The forested wetland [35.7681999,-75.7686005] is dominated by loblolly pine and is the closest to a pine flat or pocosin wetland of all the study sites. The transitional wetland [35.7703018,-75.7570038] is predominantly snags with one or two standing loblolly pines, and the understory is dominated by rushes and small shrubs, such as inkberry and wax myrtle. The marsh [35.7696991,-75.7419968] is a cord grass monoculture and the open water site [35.7697983,-75.7414017] is marked by short cypress snags and stumps. The soil is the Belhaven muck in the forested and transitional wetland and the Currituck mucky peat in the marsh and open water sites. The elevation ranges from 0 to 1 meter above sea level. The Bellhaven Series (loamy, mixed, dysic, thermic Terric Haplosaprists (USDA SSURGO Database 2008; Tant 1992) is a dark reddish brown to black or gray, poorly drained, organic, strongly acidic muck that becomes loamy at depth, organic material ranges from 16-51 inches. The Currituck Series (sandy or sandy-skeletal, mixed, euic, thermic Terric Haplosaprists) is a dark brown to black, very poorly drained, moderately permeable, strongly acidic, organic muck that becomes sandy at depth (USDA SSURGO Database 1999; Tant 1992). The open water site has exposed benches of Holocene peat (Riggs and Ames 2003).

Site Description - Restored Wetland

The TOWeR transect is located at the Timberlake Observatory for Wetland Restoration in Columbia, NC. The area was a pocosin wetland that was drained in the 1970s for soy and corn farming. In 2004-07, as part of the restoration, ditches were filled, pumps removed, and flow returned to the lowest elevation area (Ardón et al. 2010). In addition, 750,000 saplings were planted including three mixes of species: riverine, non-riverine, and Atlantic white cedar. Two sites were sampled, a dry site (T1) and a flooded site (T2). Both sites are considered successful by the mitigation service that restored them. The dry restored site [35.9123001,-76.1612015] was sampled in the non-riverine area where *Liquidambar styraciflua, Quercus michauxii, Q. phellos, Q. nigra, and Q. falcata* were planted (Reigel et al. 2013). The site is labeled dry, but still maintains the hydrology to be defined as a wetland, with water above the twelve foot water table for large portions of the year. The flooded restored site [35.9129982,-76.163002] was sampled in the riverine area where *Salix nigra, Taxodium distichum, Baccharis halimifolia, Fraxinus pennsylvania, Nyssa aquatic, N sylvatica var. biflora, Persea borbonia, and Rhus copallinum* were planted (Riegel et al. 2013). This site is dominated by young bald cypress in permanently flooded soils, similar to a cypress-gum swamp. The area is hydrologically connected to the Little Alligator River that flows to the Alligator River, and through monitoring, several saltwater intrusion events have been recorded since restoration (Ardón et al, 2013, and 2017). The soil at both sites is the Hyde loam and elevation ranges from 0 to 2 meters above sea level. The Hyde Series (Fine-silty, mixed, active, thermic Typic Umbraquults) consists of poorly drained soils formed on loamy marine and fluvial sediments that is dark gray to brownish gray and loamy to a depth of 50 inches (USDA SSURGO Database 2008; Tant 1981).

2.2 Soil and Chemical Analysis Methods

Soil Sampling and Processing

Soil sampling sites in the Albemarle-Pamlico peninsula were selected based on the ability to sample along a transect crossing the major wetland types and any transitions zones present. Sampling occurred from June 2, 2016 to July 20, 2016. The weather during this period of time was drier than normal (NOAA http://www.ncdc.noaa.gov/cag/). Soil cores from eighteen sites along five transects were collected. Four transects were in natural wetlands and one transect was in a restored wetland. Each transect consisted of four sampling sites representing forested wetlands, transitional wetlands, marsh, and open water. The restored wetland transect consisted of one dry forested wetland site and one flooded forested wetland site. In each wetland type, a 5m x 5m site was defined and six half cores of 50 centimeters depth were collected using a Russian corer. Two half cores were taken from the center of each site to be sent out for ^{137}Cs and ^{210}Pb dating and four half cores were taken at the corners of each site for analysis of extractable nutrients, $\delta^{13}C$ and $\delta^{15}N$ isotopes, % carbon, % nitrogen, C:N ratio, conductivity, pH, and bulk density. At each site, core profiles were visually described, soil texture was identified using hand-texturing method, and the dominant vegetation was noted. Cores were transported in aluminum foil-lined PVC pipes and kept frozen until sent out or processed. For each site, four half cores were sectioned every 2cm, weighed, and sediment color identified and mapped using a Munsell color chart. Samples from each 2 cm section were homogenized, subsampled for extractable nutrients, and oven-dried. The dried soil was then weighed, ground, and sieved with 2mm sieve. All samples were stored in freezers until analyzed or sent out for analysis.

Bulk Density and Soil pH

The pH of each wet sample was measured from a 1:2 soil to DI water solution using a Acument AB15 pH probe following standard protocol (Carter 1993). Bulk density was calculated from the dry weight and core volume (for 2cm depth) of the homogenized dry samples.

Cesium and Lead

The excess activities of ^{137}Cs and ^{210}Pb can be used for estimating surface sediment accretion rates in wetlands because these radioisotopes are deposited atmospherically and bind with clay and organic particles in sediment as they accumulate (Appleby and Oldfield 1992). The two middle half cores that we collected were frozen and sent to the UNC Coastal Studies Institute to be processed in the Reide Corbett lab, totaling 18 full cores. Gamma spectroscopy measurements of the excess activities of ^{137}Cs activities and ^{210}Pb were made using the methods described in Corbett and Walsh (2015). Accretion rates can be calculated using the ^{137}Cs activities by establishing the highest values and correlating that depth to the 1963 peak fallout in the northern hemisphere, and assuming that accretion rates were constant for the overlying sediments to the modern surface. Accretion rates using ^{210}Pb excess activities are calculated by subtracting ^{210}Pb activities tied to measured ^{226}Ra from total ^{210}Pb activities. The down core decrease in this excess ^{210}Pb is attributed to ^{210}Pb decay with a half-life of 22.3 years. For this study, the accretion rate was calculated using the constant flux-constant sedimentation model (CFCS) that assumes that the natural flux of atmospheric lead adhering to soil after deposition is constant, the sedimentation rate is constant, and that the initial ^{210}Pb at the soil surface is constant. The sediment accretion rate is calculated using the equation $A_z=A_0e^{-\lambda(z/S)}$, where Az is ^{210}Pb excess activity at depth z, A0 is the excess ^{210}Pb activity at the surface, λ is the decay constant 0.03114, and S is the accretion rate. The slope of a least-square fit derived from the linear regression of the natural log of the excess ^{210}Pb activity versus depth produces a best fit line with a slope b, so that accretion rate in cm/yr is determined by $S=\lambda/b$. The model was then modified for mass accumulation rate ($gm^{-2}yr^{-1}$) using bulk density to convert the accretion rates from vertical accretion by depth to mass accumulation by cumulative mass (m). To run the model, z is replaced by m in the equation. Using the mass accumulation rate, we then calculated carbon and nitrogen accumulation rates using the average %N and %C data for the core to the depth of measured excess lead (Craft and Casey 2000).

$\delta^{13}C$ and $\delta^{15}N$

Nitrogen isotopic ($\delta^{15}N$) values can be used to understand nitrogen cycling in a wetland system (Szpak 2014). Carbon isotopic ($\delta^{13}C$) values and C/N ratios can be used to understand sources of organic material (Lamb 2006). I dried soil samples and weighed and prepared them for isotopic measurement following (Levin and Currin 2012). I sent the samples to the Yale isotope lab for isotopic composition, % carbon, % nitrogen, and C:N ratio on a Costech ECS 4010 Elemental Analyzer. Soils were tested previous to analyses for carbonates using hydrochloric acid and observing whether effervescence occurred. No reactions were observed.

Major Nutrient Analyses

Half of wet sub-samples were water extracted following modified Visconti et al. (2010) protocol at a 1:10 dilution using deionized water. Extracted solution was measured for electrical conductivity using an YSI 80. Nitrate, sulfate, chloride, and phosphate anion concentrations were measured using an ion chromatograph machine (Metrohm Model 930). Concentrations were calculated using several calibration curves to cover the range of chloride and sulfate concentrations. All concentration data was corrected by dilution factors to back calculate for concentration of soil extractable nutrients in mg/g soil.

Statistical Analysis

Linear regression models were run for relationships between salinity and the biogeochemical factors analyzed (SO_4^{2-}, NO_3^-, PO_4^{3-}, %C, %N, bulk density, pH, $\delta\ ^{13}C$, $\delta\ ^{15}N$), ANOVA were run for all soil parameters by wetland type and all accretion and accumulation data for forested wetlands, transitional wetlands, and open water data (marshes and restored wetlands were excluded from statistical analyses given that n=2 for each wetland type). Post-hoc Ryon-Einot-Gabriel-Welsch test (REGW) was conducted for ANOVAs with p-value<0.05, alpha=0.1.

CHAPTER 3. Results

3.1 General Trends in Wetland Soil Properties, Salinity, and Major Nutrient Analyses

Soil properties, pH, bulk density chloride, NO_3^-, and SO_4^{2-}

Soil physical and chemical parameters varied by wetland type (Table 3.1). For natural wetlands, the average pH, Cl^-, and SO_4^{2--} increased from forested wetland to marsh, then slightly decreased or stayed relatively the same for open water (Table 3.1). Average nitrate values were similar for all natural wetlands, and average bulk density was highest for forested wetlands and lowest for marshes. The restored wetlands, as compared to the natural wetlands, had relatively higher average nitrate and bulk density and lower sulfate and chloride. There was no significant differences between wetland types for any biogeochemical parameters except chloride concentration and pH (Table 3.2)

Table 3.1 Average chloride concentration (Cl^-), nitrate concentration (NO_3^-), sulfate concentration (SO_4^{2-}), pH, and bulk density (Bd) for each wetland type in the study area. Nutrient concentrations are expressed in milligrams per gram of soil. ANOVA significance indicated by * and REWG significance indicated by letters.

	Forested	**Transition**	**Marsh**	**Open Water**	**Restored (dry)**	**Restored (flooded)**
Cl^- (mg/g)*	0.16 ± 0.07	0.42 ± 0.2	1.2 ± 0.41	0.98 ± 0.45	0.02 ± 0.001	0.15 ± 0.01
NO_3^- (mg/g)	0.005±0.001	0.004±0.001	0.005±0.001	0.005±0.002	0.006±0.001	0.007±0.001
SO_4^{2-} (mg/g)	0.021±0.008	0.031±0.009	0.046±0.013	0.05 ± 0.023	0.011±0.000	0.018±0.002
pH*	4.62 ± 0.42^{b}	5.29 ± 0.5^{ab}	6.16 ± 0.34^{a}	6.15 ± 0.27^{a}	5.05 ± 0.09	4.04 ± 0.01
Bd (g/cm^2)	0.74 ± 0.06	0.55 ± 0.05	0.25 ± 0.02	0.53 ± 0.05	1.17 ± 0.13	0.73 ± 0.14

Table 3.2 ANOVA table relating soil properties to wetland type. Significant where $p<0.05$.

	Degrees of Freedom	P-value	F-value
Cl^- (mg/g)*	14	0.03	5.23
NO_3^- (mg/g)	14	0.74	0.11
pH*	14	0.01	0.61
Bd (g/cm^2)	14	0.44	0.11
$\delta^{15}N$	14	0.07	3.58
$\delta^{13}C$	14	0.74	0.11
% C	14	0.71	0.14
% N	14	0.45	0.59
C:N Ratio	14	0.99	0.0001

In addition to varying by wetland type, soil parameters varied by location and depth. Appendix B provides detailed soil profiles of all cores by transect and includes graphs of soil physical and chemical parameters with depth. The measured chloride values for all wetlands ranged from a low of 0.010 mg/g (forested) to a high of 2.976 mg/g (marsh) reflecting the oligahaline nature of the wetlands and generally low salinity of the Albemarle Sound. The two easternmost transects – Point Peter and Briar Hall had the highest values of chloride as expected, following the salinity gradient of the region. The three western sites – Bull Neck, Pledger Harbor, and TOWeR had the lowest chloride values. Measured water extractable sulfate ranged from a low of 0.002 mg/g to a high of 0.29 mg/g (Appendix B). In general, SO_4^{2-} increased from west to east in concert with increases in chloride and was generally lower than 0.13 mg/g at most wetland sites. Notable exceptions are the marsh site at Bull Neck (0.13 mg/g SO_4^{2-}) and the Point Peter open water site (0.29 mg/g SO_4^{2-}). Measured water extractable nitrate ranged from a low of 0.001 mg/g to a high of 0.023 mg/g with most measurements lower than 0.012 mg/g. NO_3^{--} showed no clear trends in variability across transects. The measured pH values ranged from a low of 3.26 to a high of 6.8. The Point

Peter forested wetland and the TOWeR restored wetlands had the lowest pH measurements. In all transects, pH increased from forested wetland to open water. Measured bulk density values (Figure 3.1) ranged from a low of 0.05 to a high of 2.31 g/cm^3. Point Peter and Bull Neck had lower bulk densities than Pledger Harbor and Briar Hall, consistent with their soil profiles. The TOWeR restored wetlands sites had the highest average bulk density (Table 3.1). In general, lower bulk densities were found in high organic mucks and higher bulk densities were found in siltier, sandier soils.

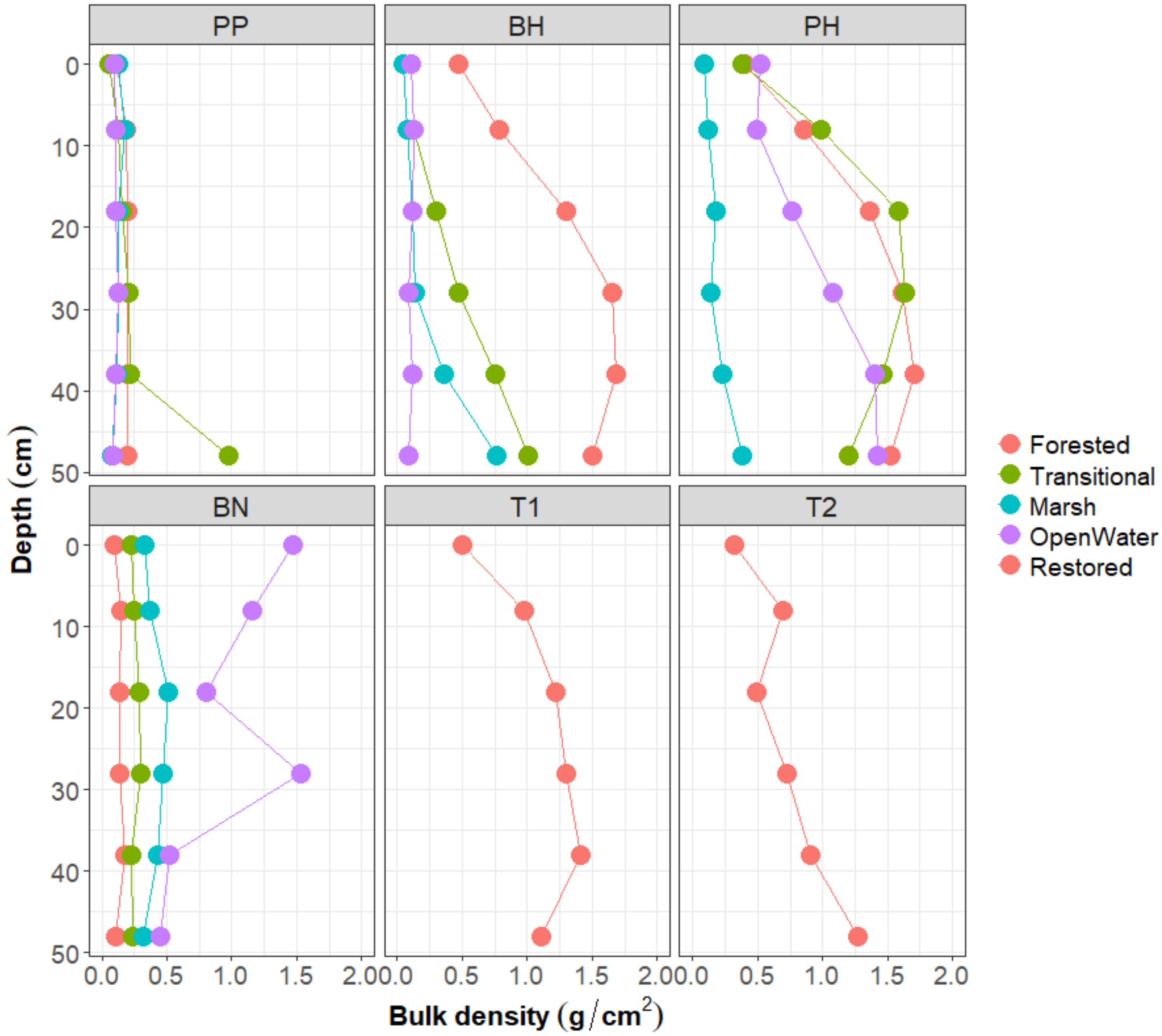

Figure 3.1 Variation in bulk density with depth for each wetland type at each transect from highest regional salinity to lowest (PP-T2). Locations are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), and Bull Neck (BN) and the TOWeR dry and flooded sites (T1 and T2).

Several trends in chemistry can be seen with depth (Appendix B). Chloride generally increased down core. Nitrate and sulfate generally decreased down core. In several cores both SO_4^{2-} and NO_3^- increased together though without a clear pattern across sites or transects. The pH showed few trends with depth, in many cores it was relatively constant with depth. The greatest variability of pH with depth was seen in the Bull Neck site (approximate range of 1.5 pH units). Bulk density generally increased with depth (Figure 3.1), and then decreased slightly at the bottom of the core. The sandier, siltier soil cores of Pledger Harbor, Briar Hall, and the restored wetlands showed the greatest increase in bulk density with depth, while the more organic Point Peter and Bull Neck soil cores had bulk densities that stayed relatively the same or had slight increases or decreases with depth. The open water site at Bull Neck was the only site where bulk density greatly decreased with depth.

Sulfate to chloride ratio

The ratio of SO_4^{2-} to Cl^- in seawater in mg/g solution is 0.14 (Pilson 1998). Comparison of this ratio with the ratios found in the study area can be used as a measure of possible marine or other influences on the wetlands. In the study area, the SO_4^{2-}/Cl^- ratios range from a low of 0.009 to a high of 1.59 (Figure 3.2). At most sites the ratio is lower than 0.14. A few ratios are near that of seawater (0.13-0.15) and occur at single depths at various sites with little consistency, likely due to the inconsistent processing of sea water with depth. The sites with ratios higher than seawater have low Cl^- content (<0.15 mg/g). In general, the forested and transitional wetlands have the highest SO_4^{2-}/ Cl^- ratios and the marshes have the lowest. The marsh at Bull Neck is the exception with SO_4^{2-}/ Cl^-ratios much higher than the other sites. Open water sites have decreasing SO_4^{2-}/ Cl^- ratios from the upper part of cores to the lower part.

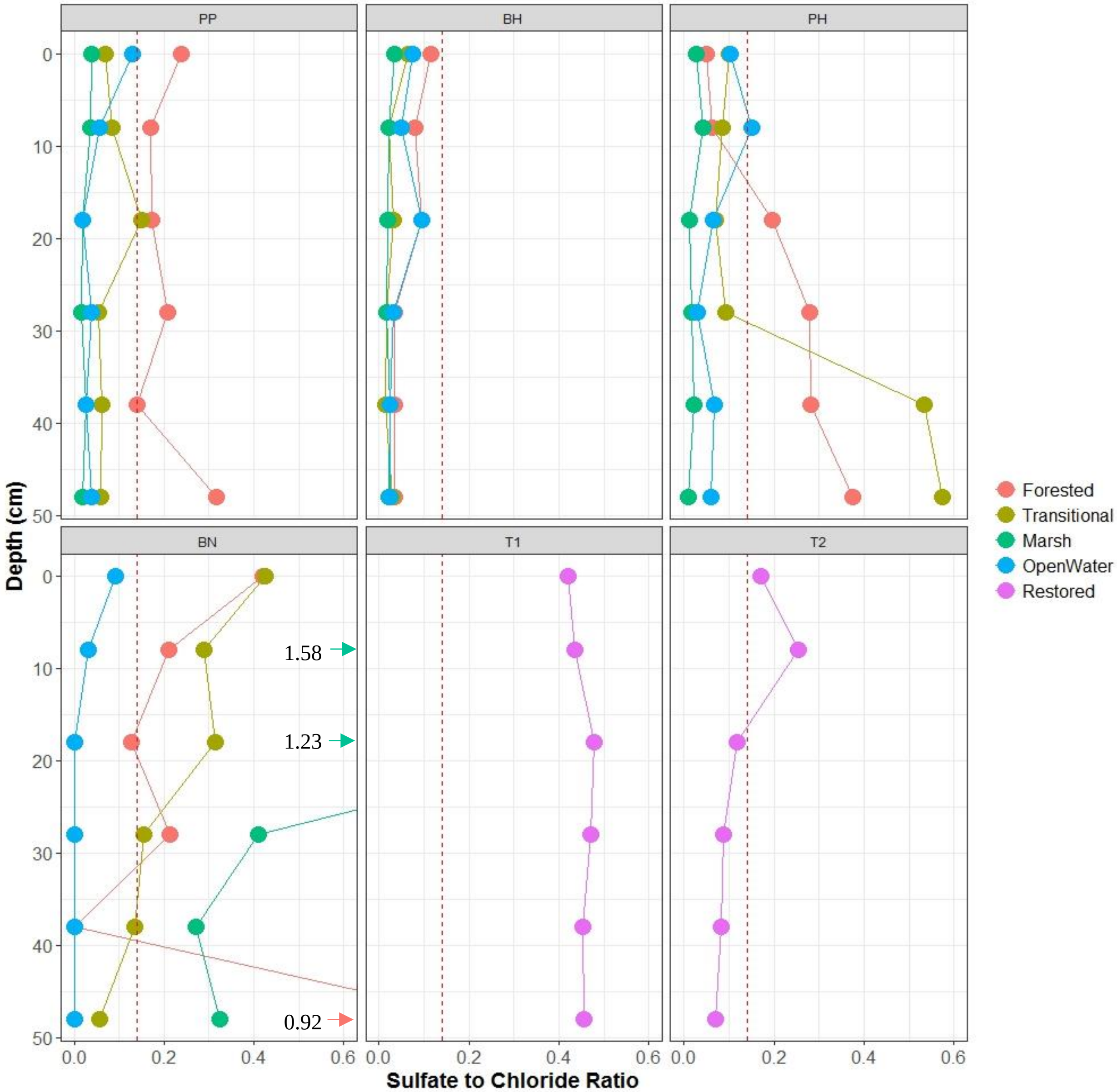

Figure 3.2 Plots showing the ratios of sulfate concentrations to chloride concentrations with depth for each wetland type at each location. The vertical dashed lines in each plot indicates that ratio for seawater in milligrams per gram (0.14). Locations are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), Bull Neck (BN), and the TOWeR dry and flooded sites (T1 and T2)

Carbon, nitrogen, and stable isotopes

Average values of $\delta^{13}C$, $\delta^{15}N$, %C, %N, and C/N ratio were examined by wetland type (Table 3.3) and by individual transect to look for broad trends (Table 3.4, Appendix B). The data were further grouped by averaging the upper 20 centimeters of the cores and comparing it with the lower 30 centimeters of the cores. This approximates the difference between younger and older sediments and the A horizon versus B horizon in the cores. Marshes had the highest average %C and %N in both the upper and lower parts of the cores (Table 3.3). The average % C and %N were higher in the upper part of the cores as compared to the lower part of the cores for all wetland types except for open water. For natural wetlands, open water wetlands had the lowest average %C in the upper part of the cores. Conversely, the average %C in the lower part of open water wetlands was greater than the lower parts of either the forested and transitional wetland. The restored wetlands had the lowest average %C in both the upper and lower parts of the cores. Average %N was lowest in the dry restored wetland. The average C:N ratio increased from the upper to lower parts of the core for all wetlands types except for forested, where it decreased (Table 3.3). The average C:N ratio was highest in the lower parts of both the transitional wetland and open water. The lowest average C:N ratios occur in the upper part of the dry restored wetland and lower part of the forested wetland. The average $\delta^{13}C$ does not vary significantly by wetland type and tends to be enriched in the lower part of the cores for the marsh, and restored dry site (Table 3.3). Average $\delta^{13}C$ is heaviest in the upper part of transitional wetland cores and most depleted in the upper dry restored wetland. Average $\delta^{15}N$ values increased from the upper to lower parts of the core for all wetland types except for marsh. Average $\delta^{15}N$ values were highest in both the upper and lower parts of the dry restored wetland and lowest in the upper part of the forested wetland (Table 3.3).

Table 3.3 Average isotopic ratios of carbon-13 ($\delta^{13}C$) and nitrogen-15 ($\delta^{15}N$) in parts per thousand, average percent carbon (% C) and nitrogen (% N), average ratio of carbon to nitrogen (C/N), and average bulk density (gm/cm3) of each wetland type in the upper 20cm of the core (U) and the lower 30 cm of the core (L)

		Forested	Transition	Marsh	Open Water	Restored (dry)	Restored (flooded)
%C	U	29.15±13.47	27.91±9.54	34.9±5.65	21.99 ± 7.3	3.23±0.23	20.87±2.71
	L	25.14 ±14.07	21.59±8.91	33.98 ± 5.46	28.17±12.46	2.14±0.29	12.45±4.65
%N	U	0.95 ± 0.39	1.09±0.28	1.44 ± 0.15	0.69 ± 0.21	0.17±0.01	0.87±0.11
	L	0.61 ± 0.35	0.54±0.19	1.15 ± 0.08	0.9 ± 0.42	0.09±0.01	0.51±0.18
C:N	U	26.68 ± 4.54	24.54±4.53	24.47 ± 3.35	30.8 ± 4.78	19.36±0.24	24.11±0.6
Ratio	L	19.88 ± 6.65	35.19±10.33	29.43 ± 3.04	31.35 ± 7.18	23.19±0.34	24.46±0.29
Bd	U	0.38 ± 0.11	0.28 ± 0.11	0.17 ± 0.04	0.51 ± 0.19	0.74±0.24	0.5±0.18
	L	0.86 ± 0.18	0.69 ± 0.14	0.28 ± 0.05	0.55 ± 014	1.26±0.06	0.85±0.17
$\delta^{13}C$	U	-28.68 ± 0.13	-28.81±0.24	-27.24±1.19	-28.56±0.39	-26.68±0.17	-28.06±0.04
	L	-27.98 ± 0.49	-28.4 ± 0.37	-28.63±0.26	-28.35±0.69	-28.40±0.09	-28.30±0.12
$\delta^{15}N$	U	0.92 ± 0.61	1.56 ± 0.51	1.25 ± 0.6	1.01 ± 0.08	4.88±0.01	2.63±0.2
	L	3.08 ± 1.26	2.39 ± 0.47	1.02 ± 0.48	1.24 ± 0.56	4.95±0.24	3.04±0.19

Concentrations of $\delta^{13}C$, $\delta^{15}N$, %C, %N, and C/N ratio can vary widely with location and depth. The % C was highly variable and ranged from a low of 0.23% to a high of 65.24% (Appendix B). The forested wetland sites at Briar Hall and Pledger Harbor had very low average carbon values (1.9% and 3.0%), whereas the forested wetland sites at Point Peter and Bull Neck had much higher average %C (50.5% and 50.4%) (Table 3.4). At the TOWeR restored wetlands transect, the average %C was low in the dry site (2.5%) and higher in the flooded site (15.25%). Concentrations of % N in all wetlands ranged from a low of 0.024% to a high of 1.84%. The lowest average %N (0.12-0.14%) was found in the Pledger Harbor forested and transitional wetlands, Briar Hall forested wetland, and, TOWeR dry restored wetlands. The highest average %N (1.36-1.61%) was found in the Briar Hall marsh and open water wetlands and the Bull Neck forested and marsh sites. The %C and %N co-varied at most sites and with depth except for a few samples in the Point Peter forested wetland, the Briar Hall transitional wetland, and the flooded restored wetland site at the TOWeR transect (Appendix B). The %C and %N decreased down core or remained relatively the same with depth at all sites except for the open water sites at Briar Hall, Bull Neck, and Point Peter, and the marsh at Point Peter where %C increased with depth (Appendix B)

Table 3.4 Average isotopic ratios of carbon-13 (δ13C) and nitrogen-15 (δ15N) in ppt, average percent nitrogen (% N) and carbon (% C), average ratio of carbon to nitrogen (C/N), average chloride concentration in milligrams per gram of soil (Cl^- mg/g) and average bulk density (Bd g/cm^3) of each wetland type for each transect.

		$\delta^{15}N$	$\delta^{13}C$	% N	% C	C:N Ratio	Cl- (mg/g)	Bd(g/cm^3)
Briar Hall	Forested	4.48 ± 0.83	-27.16 ± 0.42	0.12 ± 0.05	1.95 ± 0.93	13.41 ± 1.41	0.31 ± 0.09	1.23 ± 0.2
	Transitional	1.42 ± 0.52	-28.91 ± 0.16	0.8 ± 0.27	26.99 ± 9.76	36.02 ± 9.49	1.01 ± 0.1	0.46 ± 0.15
	Marsh	0.17 ± 0.23	-28.73 ± 0.13	1.37 ± 0.24	33.55 ± 5.36	24.89 ± 0.97	1 ± 0.09	0.25 ± 0.11
	Open Water	0.54 ± 0.12	-27.12 ± 0.26	1.43 ± 0.12	33.47 ± 2.36	23.48 ± 0.44	0.95 ± 0.15	0.11 ± 0.01
Bull Neck	Forested	0.16 ± 0.27	-28.58 ± 0.05	1.61 ± 0.08	50.4 ± 1.76	31.54 ± 1.03	0.08 ± 0.02	0.13 ± 0.01
	Transitional	1.78 ± 0.21	-28.48 ± 0.13	1.03 ± 0.06	19.08 ± 1.31	18.59 ± 0.92	0.12 ± 0.03	0.25 ± 0.01
	Marsh	2.14 ± 0.12	-27.92 ± 0.06	1.36 ± 0.03	46.5 ± 0.43	34.23 ± 0.72	0.13 ± 0.02	0.4 ± 0.03
	Open Water	1.04 ± 0.25	-28.97 ± 0.11	0.75 ± 0.19	30.66 ± 8.34	38.8 ± 2.29	0.34 ± 0.06	0.99 ± 0.19
Pledger Harbor	Forested	3.27 ± 1.11	-28.31 ± 0.21	0.14 ± 0.06	3.01 ± 1.4	17.61 ± 1.84	0.22 ± 0.01	1.24 ± 0.21
	Transitional	3.23 ± 0.39	-27.68 ± 0.17	0.13 ± 0.05	2.62 ± 1.16	18.67 ± 0.95	0.27 ± 0.04	1.21 ± 0.19
	Marsh	0.23 ± 0.07	-29.08 ± 0.11	1.14 ± 0.18	23.69 ± 2.98	21.47 ± 0.97	1.76 ± 0.16	0.19 ± 0.04
	Open Water	1.83 ± 0.35	-28.88 ± 0.08	0.2 ± 0.06	4.71 ± 1.39	23.92 ± 1.31	0.37 ± 0.06	0.95 ± 0.17
Point Peter	Forested	1.52 ± 0.1	-28.79 ± 0.12	1.03 ± 0.16	50.55 ± 9.37	63.13 ± 10.64	0.02 ± 0	0.18 ± 0.01
	Transitional	2.03 ± 0.21	-29.09 ± 0.07	0.94 ± 0.14	46.1 ± 1.4	53.29 ± 5.77	0.28 ± 0.11	0.29 ± 0.14
	Marsh	1.84 ± 0.16	-26.93 ± 1.02	1.11 ± 0.07	33.4 ± 3.58	30.5 ± 3.42	1.92 ± 0.31	0.12 ± 0.01
	Open Water	1.06 ± 0.1	-29.14 ± 0.07	0.97 ± 0.03	42.81 ± 1.06	44.14 ± 1.47	2.26 ± 0.11	0.1 ± 0.01
TOWeR (Dry)	Restored	4.93 ± 0.15	-27.83 ± 0.37	0.12 ± 0.02	2.5 ± 0.3	21.91 ± 0.84	0.02 ± 0.001	1.09 ± 0.13
TOWeR (flooded)	Restored	2.88 ± 0.15	-28.22 ± 0.09	0.63 ± 0.14	15.25 ± 3.5	24.34 ± 0.2	0.15 ± 0.01	0.73 ± 0.14

The relationship between %C and %N is further explored in Figure 3.3A-B with a side by side comparison showing all data. Point Peter and Bull Neck show a general decreasing trend in %C and %N from the forested wetland to open water while Briar Hall shows a generally increasing trend in %C and %N. None of these trends however are perfect. Pledger Harbor did not show an increasing or decreasing trend, rather %C and %N were low except for the marsh. The %C and %N increased in the restored wetland from the dry to the flooded site. Figure 3.4A plots average %C versus %N (R^2:0.68, p-value<0.001) for wetland type by transect. The correlation improves if Point Peter is not included (R^2:0.89, p-value<0.001). The average %C decreased with increasing average bulk density (R^2:0.61, value<0.001)(Figure 3.4B) and the average %N decreased with increasing average bulk density (R^2:0.78, p-value<0.001) (Figure 3.4C). The C:N ratio ranged from a low of 9.58 to a high of 90.61. In most sites, the C:N ratio increased with depth except for the forested and transitional wetlands of Pledger Harbor and Briar Hall where the C:N ratio decreased down core (Appendix B). The lowest C:N ratios are associated with the lowest %C values and the highest C:N ratios are associated with the highest %C (Table 3.4). Direct comparison of average values of C:N and %C show a positive correlation (R^2:0.55, p-value<0.001) (Figure 3.5).

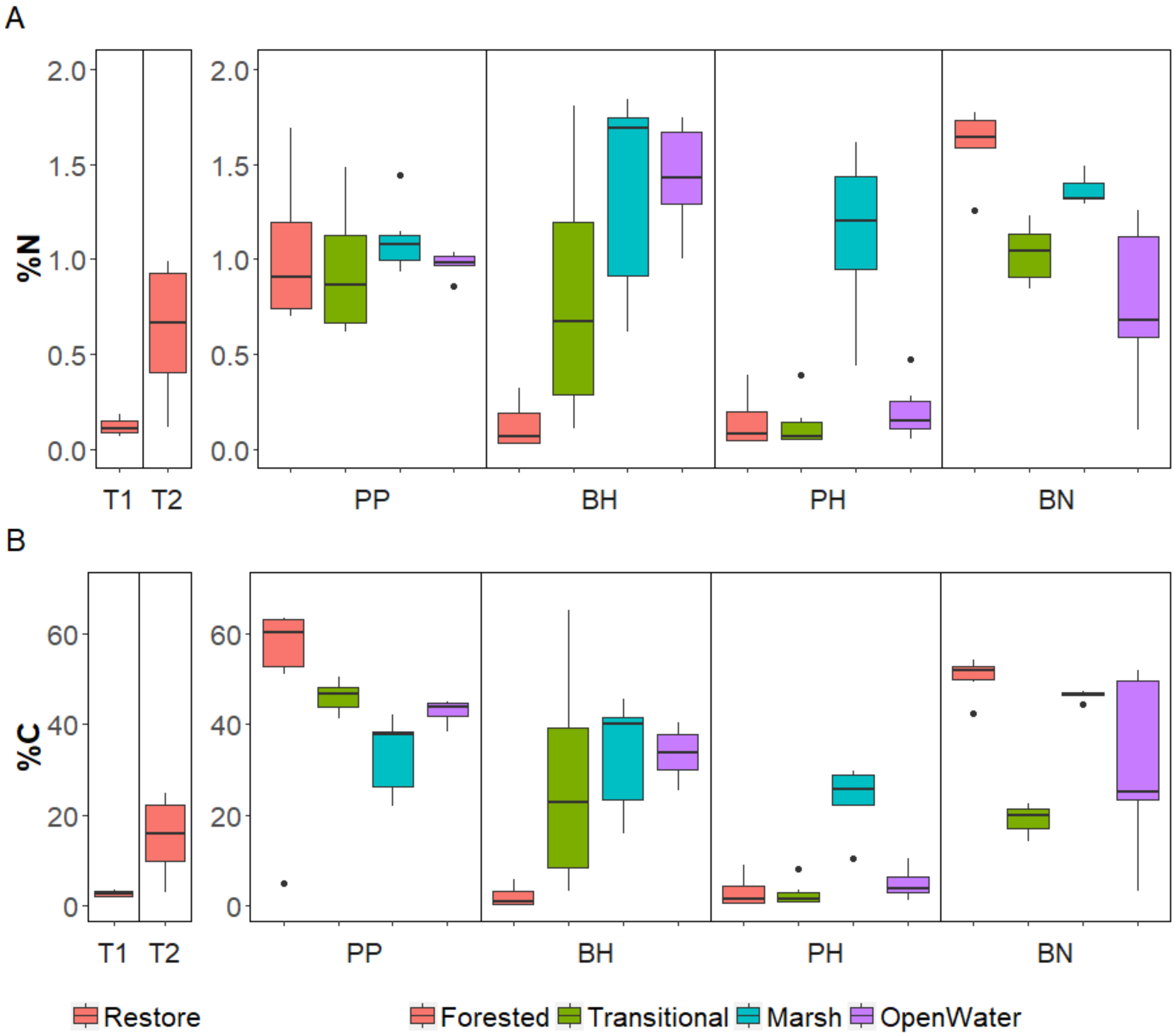

Figure 3.3 Distribution of percent carbon and percent nitrogen for each transect in this study. Horizontal lines indicate average values and boxes denote one standard deviation, lines denote two standard deviation and points denote outlying values. Location are Point Peter ((PP), Briar Hall (BH), Pledger Harbor (PH), Bull Neck (BN), and the TOWeR dry and flooded sites (T1 and T2 respectively).

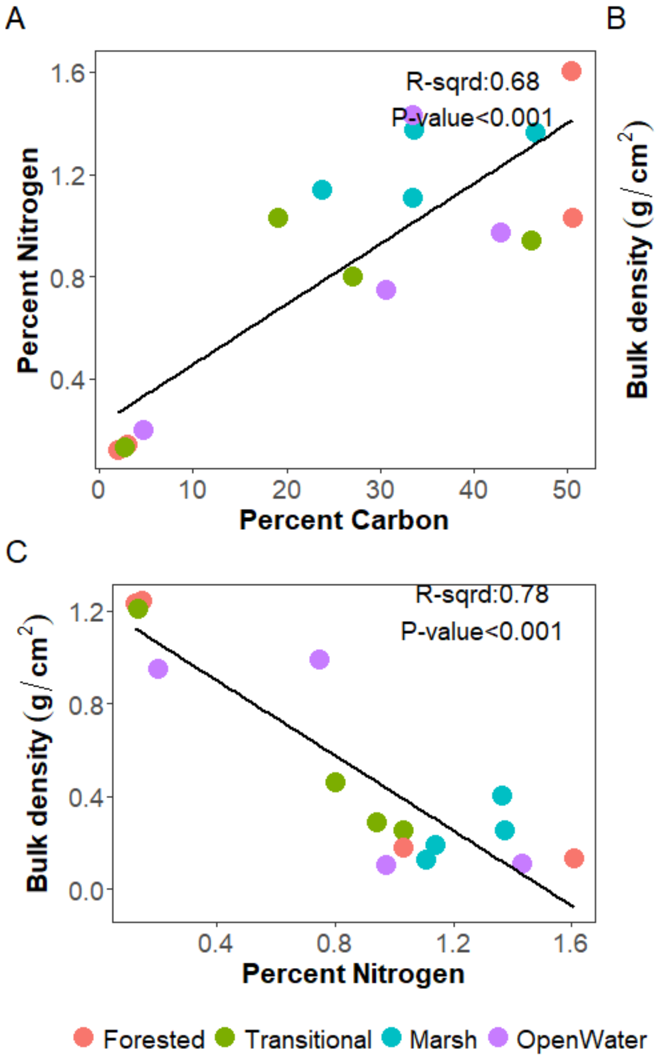

Figure 3.4 Average percent nitrogen to average percent carbon(A), average bulk density to average carbon(B), and average bulk density to average percent nitrogen(C) for each type of wetland (color) for all natural wetland sites in the study area. Locations (shape) are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), and Bull Neck (BN)

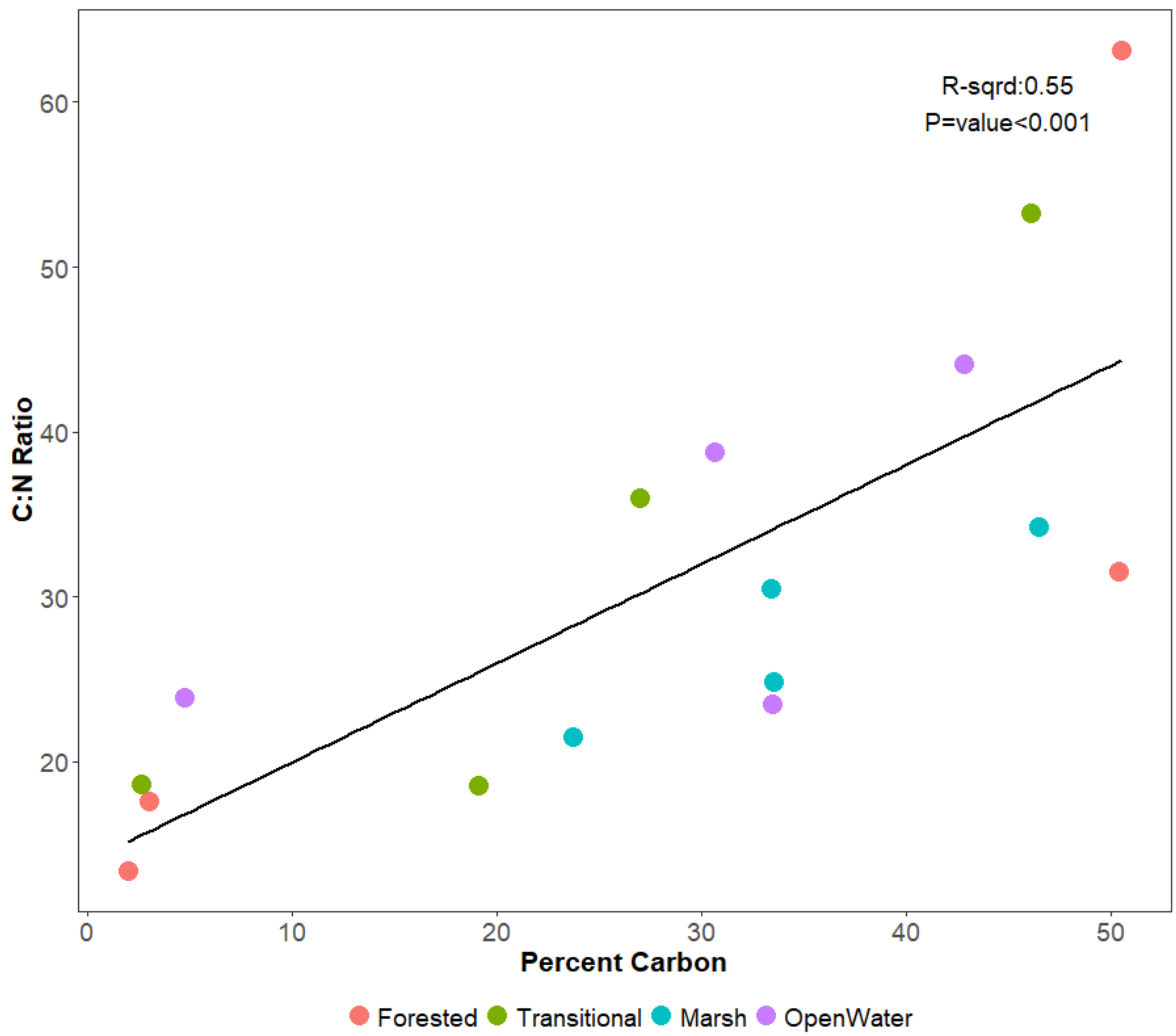

Figure 3.5 Plot showing comparison of average carbon to nitrogen ratio (C:N) to average percent carbon for each type of wetland (color) for all natural wetland sites in the study area. Locations (shape) are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), and Bull Neck (BN)

Nitrogen isotope ($\delta^{15}N$) values ranged from -2.1 to 6.3‰ (Appendix B) at all sites. The $\delta^{13}C$ values for all sites fell within the terrestrial range (-29 to -26‰), except for Point Peter, with an estuarine-marine value of -23‰. The heaviest value of $\delta^{13}C$ is in the upper part of the Point Peter marsh site (-23.5‰) however the average values for all sites are depleted than -26‰ (Table 3.4). All Pledger Harbor wetland sites trend toward enriched $\delta^{13}C$ and $\delta^{15}N$ with depth. Most marsh and open water sites at the other localities either show a trend toward depleted $\delta^{13}C$ and $\delta^{15}N$ with depth or no change with depth. The TOWeR restored site has an average $\delta^{13}C$ of -26.7‰ in the upper part of the dry site and is depleted (-28.4‰) in the lower part. The flooded TOWeR restored site has an average $\delta^{13}C$ of -28.1‰ and is depleted (-28.3‰) in the lower part. The heaviest average $\delta^{15}N$ values occur in the lower parts of the forested and transitional wetlands at Pledger Harbor and Briar Hall (between 4 and 5‰ and between 2.5 and 6.5‰) and both the upper and lower parts of both sites of the restored wetland (6.0‰ at the dry site and 4.5‰ at the flooded site) (Figure 3.6A-B).

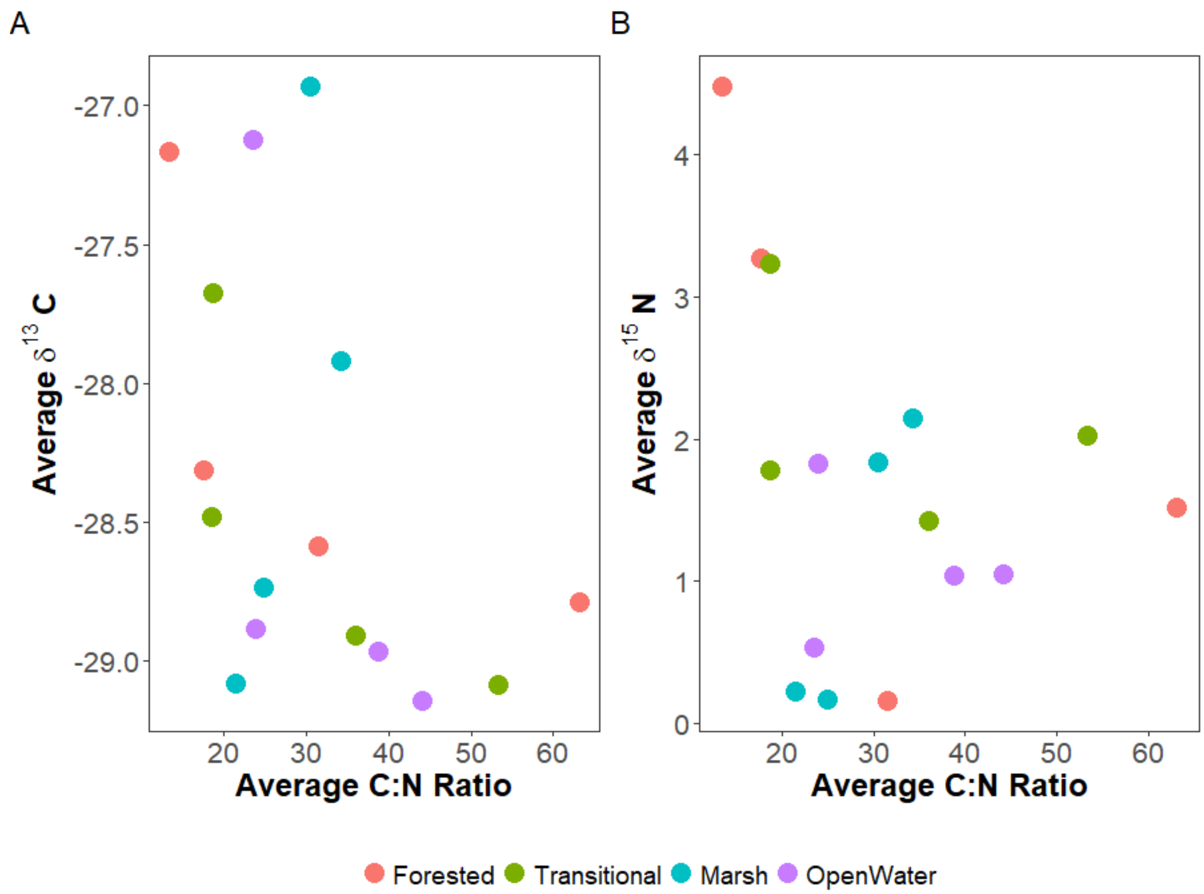

Figure 3.6 Average isotopic ratios of Nitrogen-15 (δ15N) (B) and Carbon-13 (δ13C) (A) in parts per thousand for all natural transects compared with average C: N.

There is a positive correlation between decreasing %C and increasing average Cl^- concentrations at forested (R^2:0.83, p-value:0.05) and marsh (R^2:0.57, p-value:0.15) sites (Figure 3.7), that is not seen in the plots for transitional and open water sites (R^2:0.02, p-value:0.85 and R^2:0.26, p-value:0.29 respectively). Average %N generally decreases with increasing average Cl^- (Figure 3.8) in the forested wetlands (R^2:0.53, p-value:0.17) and the marsh wetlands (R^2:0.68, p-value=0.11), and there is no correlation in the transitional (R^2:0.01, p-value=0.97) and open water (R^2:0.19, p-value=0.56) sites.

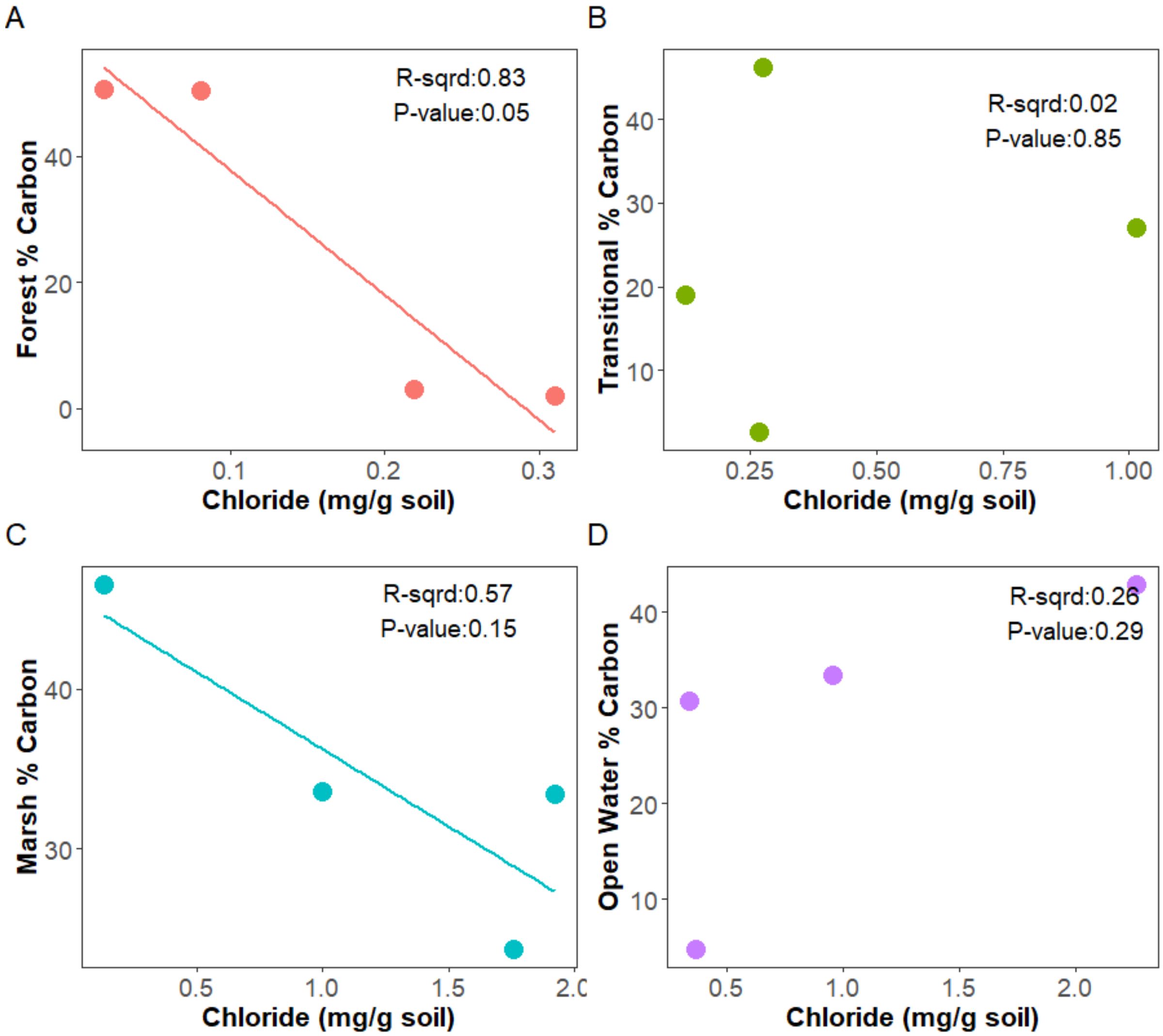

Figure 3.7 Plots showing comparison of average percent carbon to average chloride concentration in milligrams per gram of soil for each type of wetland (color) for all natural wetland sites in the study area.

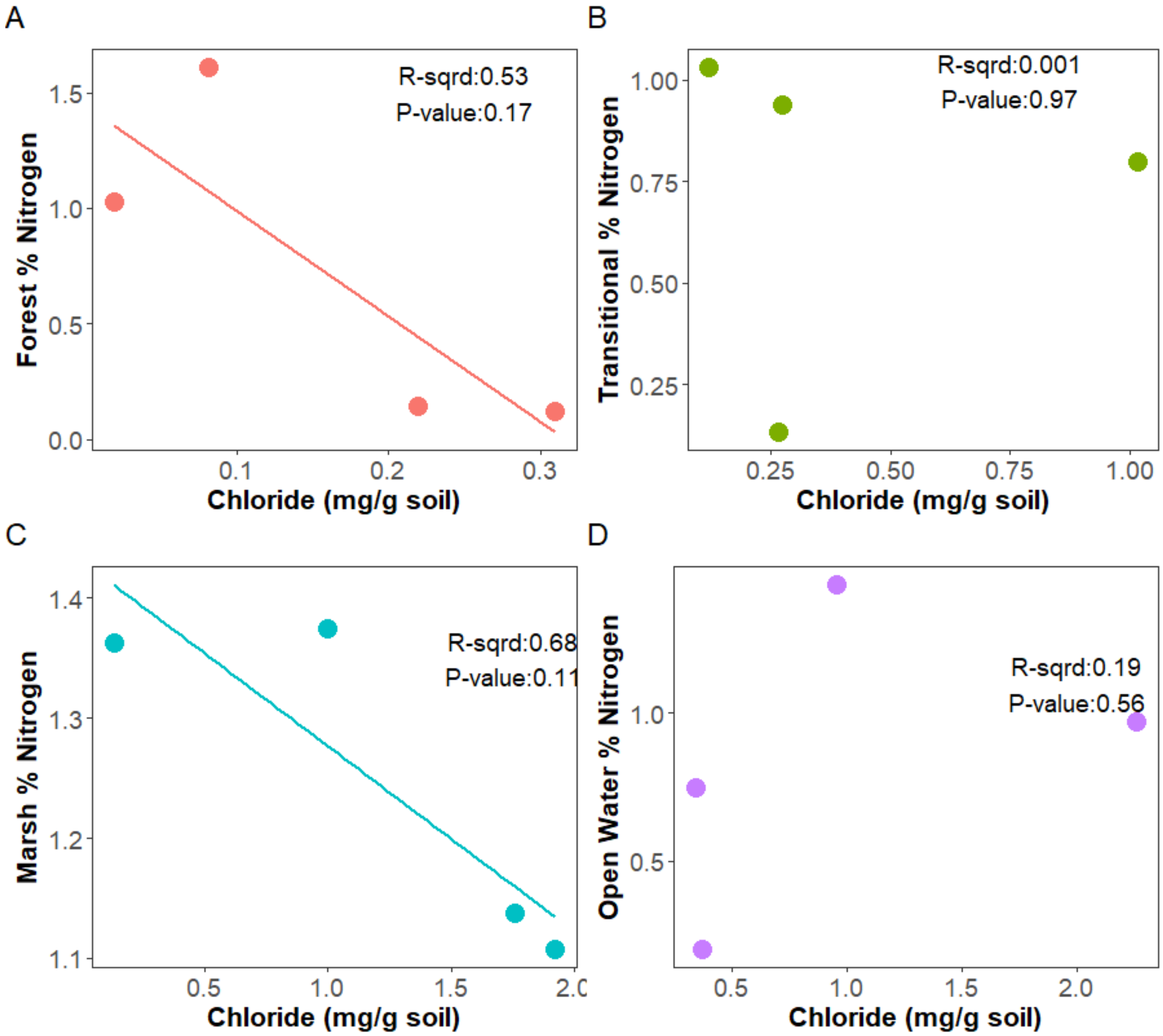

Figure 3.8 Plots showing comparison of average percent nitrogen to average chloride concentration in milligrams per gram of soil for each type of wetland (color) for all natural wetland sites in the study area.

3.2 Accretion and Accumulation Rates

Eighteen cores were analyzed for excess ^{210}Pb and ^{137}Cs to calculate vertical accretion rates of natural and restored wetlands. Fifteen of the natural and restored wetland cores had usable measures of ^{210}Pb. Four of those cores had usable measures of peak ^{137}Cs including the Bull Neck transitional wetland, Point Peter transitional wetland, Point Peter marsh and the TOWeR flooded restored site (Figure 3.9). The remaining cores had trace amounts of excess ^{137}Cs that did not show peaks or peaked at the surface of the core (indicating erosion). The three cores where accretion could not be calculated (Pledger Harbor marsh and open water, and Bull Neck marsh), had excess ^{210}Pb that did not fit the linear CFCS model. At Bull Neck and Point Peter open water sites, excess ^{210}Pb was very low close to the core surface, indicating erosion, resulting in possible underestimation of vertical accretion rate.

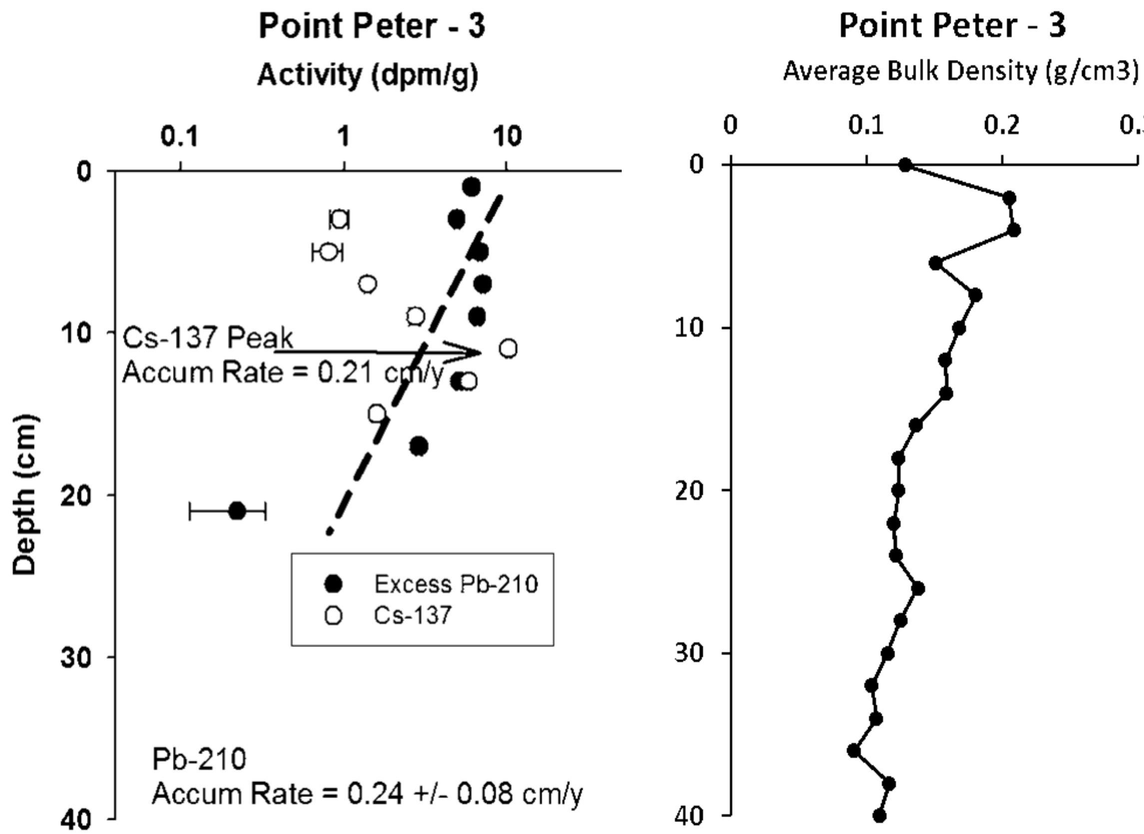

Figure 3.9 Example plots of excess Lead-210 (Pb-210) and total Cesium-137 (Cs-137) distribution with depth, and the distribution of average bulk density with depth at the Point Peter marsh wetland site. Accretion rates (Acc Rate) are based on log linear model of 210Pb distribution down core (dashed line) and the maximum 137Cs in the year 1963 (arrow).

Vertical accretion, mass accumulation, carbon accumulation, and nitrogen accumulation rates were calculated using ^{210}Pb at four forested, four transitional, two marsh, three open water, and two restored wetland sites (Figure 3.10). There was no significant difference between forested wetlands, transitional wetlands, and open water. ANOVA was not run for marsh or restored sites, since there were only two measurements each (Table 3.5).

Overall, open water sites along transects had the lowest accretion rates. Mass accumulation rates (Figure 3.10B) were highest in the forested wetlands and restored sites. Transitional, marsh, and open water sites had lower and generally similar mass accumulation rates with the exception of the Bull Neck open water site which was sandy at the surface. Carbon accumulation rates (Figure 3.10C) are highest in the transitional wetlands of Briar Hall, Point Peter and Bull Neck transects, and highest at the forested wetland site along the Pledger Harbor transect. Generally, the open water sites had the lowest carbon accumulation rate within transects. Nitrogen accumulation rates (Figure 3.10D) showed a decreasing trend from forested wetland to open water sites along the Briar Hall, Point Peter, and Bull Neck transects. Along the Pledger Harbor transect, nitrogen accumulation rate was highest in the transitional wetland, similar to the trend in the carbon accumulation rate.

Table 3.5 ANOVA table relating accretion and accumulation rates to wetland type (marsh, open water, and restored data excluded). Significant where p<0.05.

	Degrees of Freedom	**P-value**	**F-value**
Mass Accumulation ($g/m^2/y$)	9	0.47	0.56
Vertical Accretion (cm/y)	9	0.44	0.62
Nitrogen Accumulation ($g/m^2/y$)	9	0.71	0.14
Carbon Accumulation ($g/m^2/y$)	9	0.84	0.042

Table 3.6 Average salinity, vertical accretion, nitrogen accumulation, and carbon accumulation for all wetland sites with available 210Pb data.

Transect	Wetland Type	Salinity (Cl- mg/g)	Vertical Accretion (cm/y)	Nitrogen Accumulation ($g/m^2/y$)	Carbon Accumulation ($g/m^2/y$)
Briar Hall	Forested	0.31 ± 0.091	0.24 ± 0.12	5.42 ± 2.48	93.54 ± 42.85
	Transitioning	1.01 ± 0.099	0.22 ± 0.04	5.08 ± 0.53	179.15 ± 18.70
	Marsh	1.00 ± 0.087	0.12 ± 0.01	2.04 ± 0.10	48.98 ± 2.49
	Open Water	0.95 ± 0.145	0.09 ± 0.01	1.41 ± 0.27	33.84 ± 6.53
Point Peter	Forested	0.02 ± 0.002	0.14 ± 0.03	4.22 ± 0.95	127.57 ± 28.63
	Transitioning	0.28 ± 0.110	0.21 ± 0.02	3.14 ± 0.34	54.14 ± 5.84
	Marsh	1.92 ± 0.309	0.24 ± 0.08	1.53 ± 0.62	62.61 ± 25.46
	Open Water	2.26 ± 0.113	<0.06	0.68 ± 0.15	15.23 ± 3.29
Pledger Harbor	Forested	0.22 ± 0.009	0.1 ± 0.02	2.77 ± 0.28	57.72 ± 5.75
	Transitioning	0.27 ± 0.044	0.07 ± 0.02	6.70 ± 0.85	248.94 ± 31.64
Bull Neck	Forested	0.08 ± 0.022	0.22 ± 0.07	0.72 ± 0.09	15.03 ± 1.84
	Transitioning	0.12 ± 0.027	0.88 ± 0.2	27.83 ± 4.25	652.16 ± 99.57
	Open Water	0.34 ± 0.059	<0.03	9.42 ± 4.07	386.75 ± 167.10
TOWeR dry	Restored	0.02 ± 0.001	0.32 ± 0.03	4.41 ± 0.43	89.54 ± 8.79
TOWeR flooded	Restored	0.15 ± 0.013	0.35 ± 0.02	15.20 ± 0.66	369.77 ± 16.15

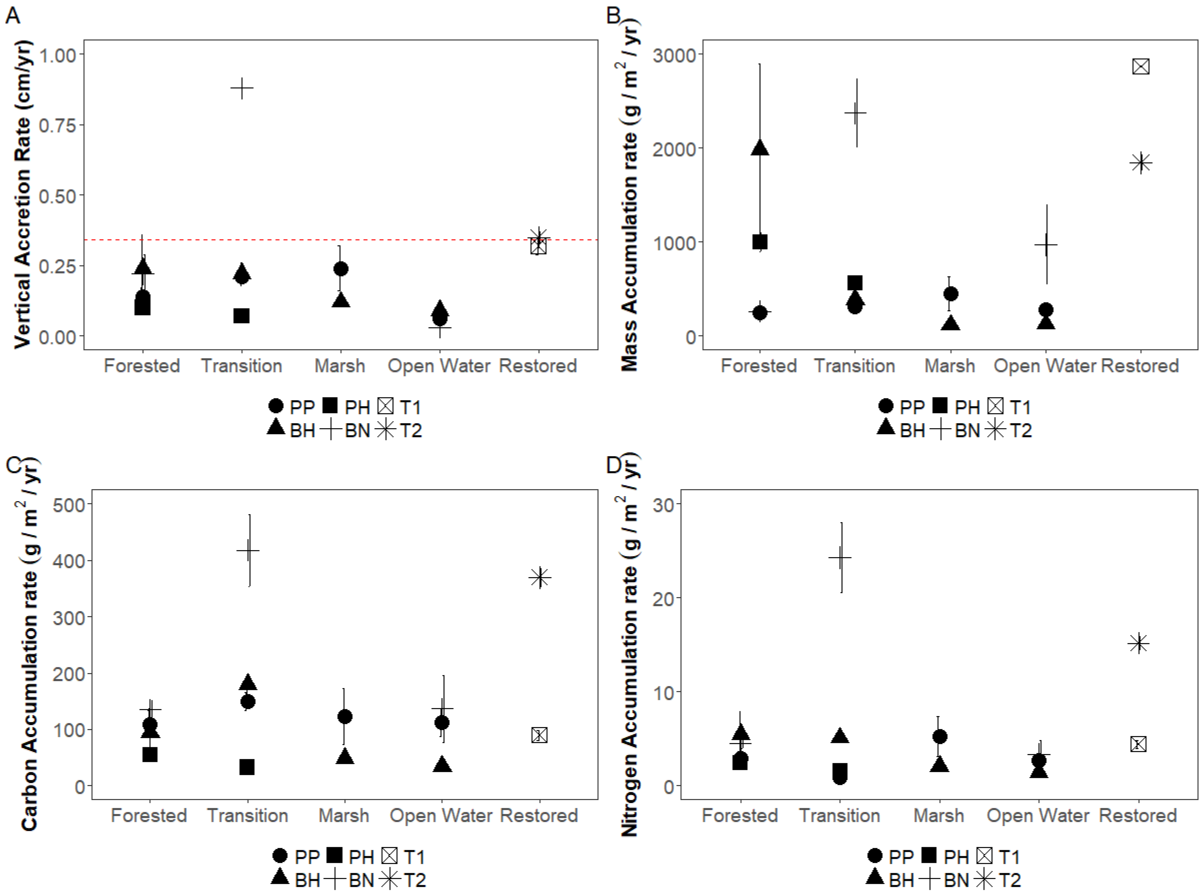

Figure 3.10 Plots showing (A) vertical accretion rates, (B) mass accumulation rates, (C) carbon accumulation rates, and (D) nitrogen accumulation rates at each wetland type for each of the study locations. Vertical bars indicate standard error in the measurement. The horizontal dashed in A represents the mean global sea level rise at the time of this study (0.32 cm/yr). Locations are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), and Bull Neck (BN) and the TOWeR dry and flooded sites (T1 and T2).

The Bull Neck transitional wetland site and TOWeR flooded restored wetland site were the only two sites that had vertical accretion rates above the current GMSLR of 0.32 cm/y. (Figure 10A) The rest of the vertical accretion rates across wetland types generally have similar values. The Bull Neck transitional wetland site has an anomalously high accretion rate. Within transects, Briar Hall accretion rates declined from forested to open water sites and Point Peter accretion rates increased from forested to marsh sites. Pledger Harbor accretion rates were within error of each other and Bull Neck sites were variable from forest to open water. Briar Hall shows mass accumulation rates decreasing from forested to open water sites. Generally, mass accumulation rates increase with the vertical accretion rates. (Figure 3.11A) In two of the forested sites (Pledger Harbor and Briar Hall) the accumulation rate was much higher than the other sites indicating that the mass accumulated over time is denser and probably reflects more sediment accretion in the forested wetlands. This can be seen in the sediment profiles in Appendix B showing more sediment and less fibric materials than the transitional or marsh sites. This is further supported by Figure 3.11B showing mass accumulation generally decreasing with increasing percent carbon.

Vertical accretion, carbon accumulation, and nitrogen accumulation do not have any clear relationship with chloride (Figure 3.12A, B, C). Mass accumulation however appears to decrease with increasing chloride. The highest mass accumulations were observed when chloride values were less than 0.5 mg/g (Figure 3.12D).

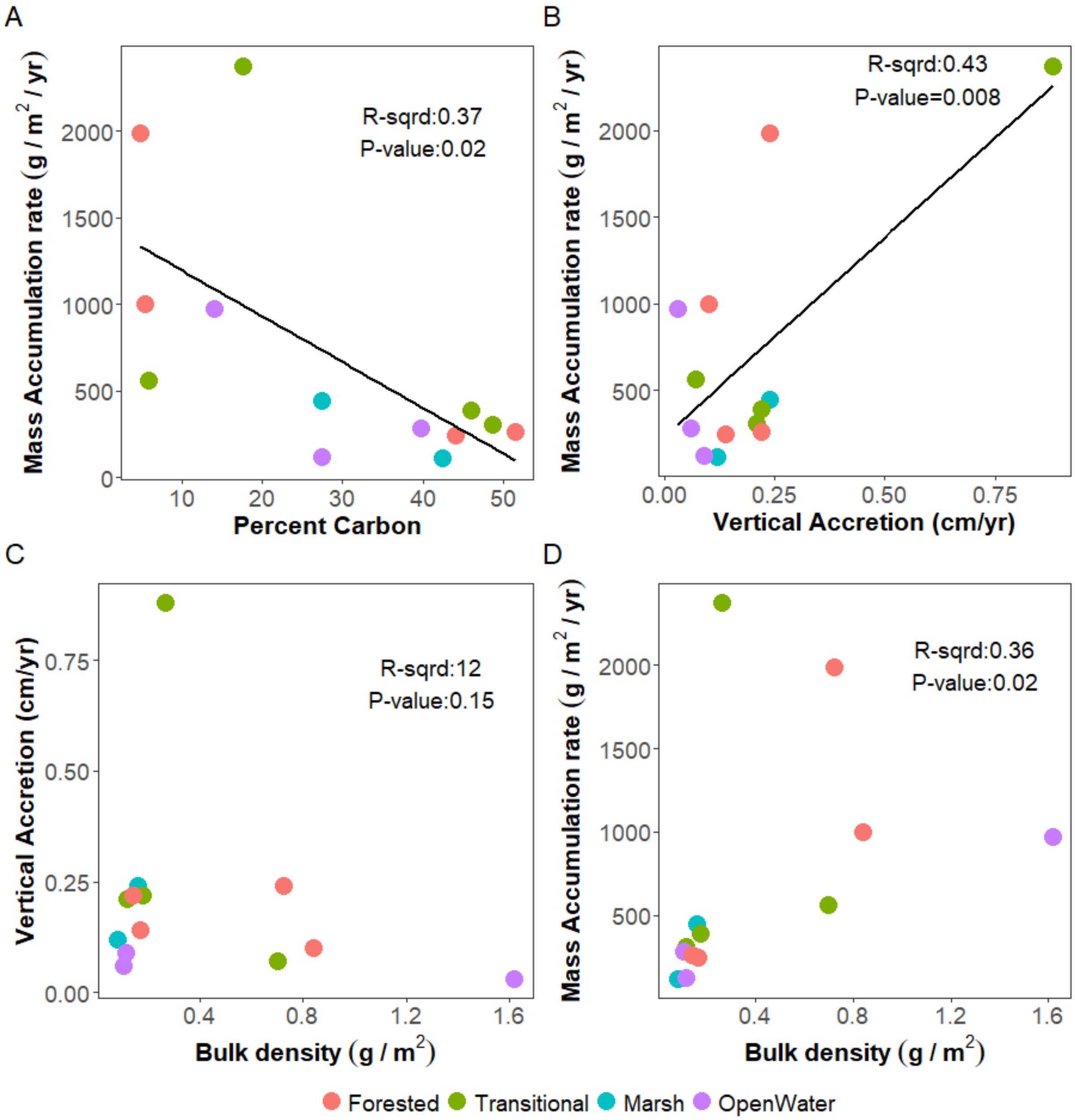

Figure 3.11 Comparison of (A) mass accumulation rate to vertical accumulation rate, (B) mass accumulation rate to average percent carbon, (C) vertical accumulation rate to average bulk density, and (D) mass accumulation rate to average bulk density for each type of wetland (color) at all natural wetland sites in the study area.

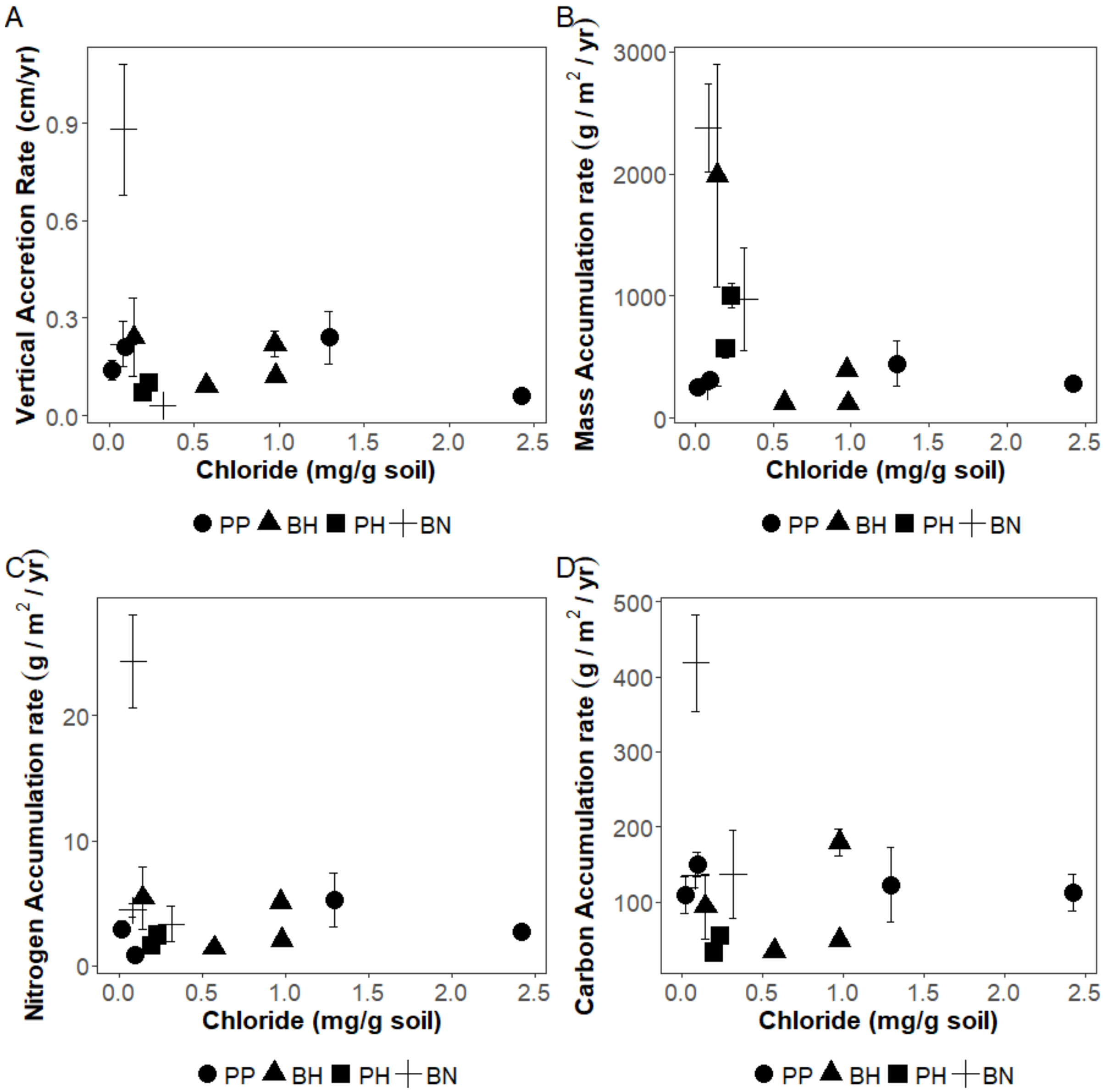

Figure 3.12 Vertical accretion rates(A), mass accumulation rates(B), carbon accumulation rates(C), and nitrogen accumulation rates(D) versus average chloride concentration in milligrams per gram of soil for each of the study locations. Vertical bar indicate standard error. Locations (shape) are Point Peter (PP), Briar Hall (BH), Pledger Harbor (PH), and Bull Neck (BN).

CHAPTER 4. Wetlands in the Albemarle-Pamlico Peninsula: Discussion and Conclusion

4.1 Discussion of Results

This study examined long-term (approximately 100 years) vertical accretion rates and mass accumulation rates of sediment and associated C and N in natural and restored wetlands along the Albemarle Sound. Below I restate each hypothesis and discuss if my results supported or failed to support each hypothesis:

1) Increasing salinity will cause a decrease in vertical accretion rate, carbon and nitrogen accumulation rates across a salinity gradient. I found partial support for this hypothesis. Vertical accretion rate was not correlated with salinity (Figure 3.12A). Except for the high vertical accretion observed in Bull Neck transition site (see below for more explanation about this site), there was little change in vertical accretion with increasing salinity. While there was not a significant negative correlation between salinity and mass accumulation rates across all transects, the average values of mass accumulation rates below a salinity of 0.5 mg/g were 4 times higher (average= 1243 g m^{-2} yr^{-1}, n=10) than values above that salinity (average = 271.4 g m^{-2} yr^{-1}, n=5, Figure 3.11b, $p<0.05$). Carbon and nitrogen accumulation rates were 1.5 to 2 times higher in low salinity sites on average (C accumulation = 158.7 g C m^{2} yr^{-1}, N accumulation =6.5 gNm^{2}/yr^{-1} compared to high salinity sites on average (C accumulation = 99.4 g C m^{-2} yr^{-1}, N accumulation = 3.3 g N m^{-2} yr^{-1}), but the differences were not statistically significant.

2) Marshes will have the highest concentrations of carbon and nitrogen and highest rates of vertical accretion, mass accumulation, carbon and nitrogen accumulation compared to forested wetlands. Marshes did have higher % C and % N than forested wetlands (Table 3.2 and Table 3.3). In terms of vertical accretion, mass accumulation, and carbon and nitrogen accumulation rates, I was unable to statistically test this hypothesis because we were only able to estimate vertical accretion, mass accumulation, carbon and nitrogen accumulation rates for two marsh sites. These two marsh sites had similar rates to forested wetlands (Figure 3.10).
3) Transitional wetlands will have lower rates of carbon and nitrogen accumulation compared to marsh and forested wetlands. I found the opposite, transition sites had higher carbon accumulation rates than marsh and forested wetlands within transects, though the differences were not significant (Figure 3.10C) across all transects. Nitrogen accumulation rate was very high in Bull Neck transition zone, but the other transition zones had rates similar to forest and marsh sites.
4) The rate of vertical accretion, mass accumulation, nitrogen and carbon accumulation will be less in a restored wetland relative to natural wetlands. Again, I found the opposite, vertical accretion, mass accumulation, carbon and nitrogen accumulation were higher in the restored wetland compared to the other sites (Figure 3.10).

Discussion of accretion and accumulation in wetlands of the Albemarle Sound

Of the 18 wetland sites I sampled, only two of the sites have vertical accretion rates higher than global mean sea level rise (GMSLR) of 0.32 cm/year: a transitional wetland site that appears to have fine sediment sourced from a nearby channel (0.88 cm/yr) and a restored wetland (0.35 cm/yr) that has undergone extensive restoration in the past 12 years. The remaining wetlands have similar vertical accretion rates below GMSLR ranging from 0.03 cm/yr to 0.32 cm/yr (Table 3.6). Vertical accretion was not significantly different across wetlands types similar to other recent studies (Craft 2007, Noe et al. 2016), though accretion rates are lowest in open water sites. Vertical accretion rates in this study are lower than freshwater forested wetlands and brackish marshes in the southeastern United States (0.66 ± 0.08 and 0.60 ± 0.07 cm/yr respectively) as reported by Craft (2007), and also lower when compared to my synthesis of 15 published studies of wetlands along the east and Gulf coasts (Table 4.1). Many studies used in both my and Craft's (2007) syntheses focused on areas with high sediment sources from either riverine or tidal estuarine sediment (Neubauer et al. 2005, Khan and Brush 1994, Orson et al. 1990). Sediment source is an important component of accretion in wetlands along the coast (Kirwan and Megonigal 2013, Kirwan et al 2016). The low accretion rates I observed agree with previous studies that have shown that the Albemarle-Pamlico wetlands are starved for sediment (Moorehead and Brinson 1995).

Table 4.1 Synthesis of average vertical accretion in natural wetlands for fifteen sources with standard error and sample size (n=84).

Wetland Type/Method	Citation	Location	Vertical Accretion
Freshwater			0.49±0.07 n=(34)
^{137}Cs			0.64±0.14 n=(11)
	Craft (2012)	Georgia	0.23±0.018 n=(4)
	Griener and Hershner (1998)	Virginia	0.47±0.095 n=(2)
	Hatton et al. (1983)	Louisiana	0.99±0.222 n=(4)
	Orson (1990)	New Jersey	1.2 n=(1)
^{210}Pb			0.42±0.079 n=(23)
	Breithaupt et al. (2014)	Florida	0.35±0.029 n=(7)
	Craft (2012)	Georgia	0.13±0.027 n=(4)
	Noe et al. (2016)	South Carolina	0.25±0.025 n=(8)
	Orson (1990)	New Jersey	1.2±0.078 n=(4)
Brackish Marsh			0.49±0.07 n=(50)
^{137}Cs			0.62±0.057 n=(29)
	Callaway et al. (2012)	California	0.34±0.021 n=(11)
	Craft et al. (1993)	North Carolina	0.3 n=(1)
	Delaune and Prezeshki (2003)	Louisiana	0.65±0.102 n=(3)
	Griener and Hershner (1998)	Virginia	0.37±0.065 n=(2)
	Hatton et al. (1983)	Louisiana	0.6 n=(1)
	Kearny and Stevenson (1991)	Maryland	0.78±0 n=(3)
	Nyman et al. (2006)	Louisiana	0.82 n=(1)
	Nyman et al. (1993)	Louisiana	0.96±0.097 n=(8)
^{210}Pb			0.33±0.03 n=(21)
	Callaway et al. (2012)	California	0.26±0.021 n=(11)
	Kearny and Stevenson (1991)	Maryland	0.48±0.039 n=(3)
	Merrill (1999)	Maryland	0.39±0.062 n=(7)

At our study sites in the Albemarle-Pamlico peninsula, bulk density data suggests that there were two large groups across out eighteen sites. Figure 3.11C shows two distinct groups of accretion rates when plotted against bulk density, the low bulk density sites are more organic carbon dominated sites, and the higher bulk density sites are associated with more mineral soils and sites with sediment input. Bull Neck, the freshest water wetlands and Point Peter, the most saline sites, are both underlain by deep organic soils. They have the highest % C and %N and the lowest bulk densities. The Pledger Harbor and Briar Hall wetlands are underlain by mineral soils and have lower %C and %N and higher bulk densities (Table 3.4). Soil bulk density has the strongest correlation with the % C and %N at all sites reflecting the low bulk density of organic matter and the higher bulk density of mineral sediments. Fine suspended sediments are delivered to the Albemarle Sound mainly from the freshwater Chowan and Roanoke rivers (Harned and Davenport 1990, Riggs et al., 1995), and are mostly deposited at the mouth or within the sound by the slow current in the estuary, reducing sediment input onto the shoreline and marshes (Riggs et al. 1995). Noe et al. (2016) argued that freshwater riverine sediments in his study area were the main source of sediment for his freshwater wetland systems. Their work was corroborated by modern accretion values measured by Ensign et al. (2014) in the same area. Without freshwater inputs of sediment from rivers, the main source of sediment in the Albemarle-Pamlico wetlands is from wind driven tides and storm over-wash (Riggs and Ames 2003). Sediment deposition is therefore sporadic and the net gain from storm and flooding events are diminished by the accompanying erosion of the shoreline. Pledger Harbor and Briar Hall exhibit these deposition/erosion cycles at the eroded shoreline and in the higher quantity of sandy sediment in the cores (Appendix B). Low sediment deposition and highly eroding shorelines in this area means these wetlands are vulnerable to accelerating sea level rise.

The exception to low sediment deposition in our study sites is the Bull Neck transition site. This transition site is located very close to the man-made channel connecting Deep Creek to Bull Bay and the Albemarle Sound (Appendix A). The site has lower %C than the other Bull Neck sites, but has the highest carbon and nitrogen accumulation rate (Table 3.4, Table 3.6). The site had the highest mass accumulation rate, likely from deposition from the channel. Bull Neck transition site does not group like the other sandy textured, high bulk density cores (Figure 3.11C). Based on hand texturing, the site is mostly fine sediments like clay and silt, which have lower bulk density than sandy materials, suggesting this site was more similar to the riparian sites described by Noe et al.

Given the low sediment delivery of most sites, deposition of organic material is the dominant source of accretion. The C accumulation rates I measured are on par with rates in the southeastern United States (Craft 2007) for freshwater forested wetlands (140±20 $gm^{-2}yr^{-1}$) and oligohaline marshes (240±30 $g\ m^{-2}\ yr^{-1}$, Table 3.6). However, values are not statistically different between wetland types. Interestingly, the transitional wetlands of this study had higher rates of carbon accumulation than the forested and marsh sites at Briar Hall, Point Peter, and Bull Neck. Briar Hall and Point Peter transitional wetlands do not appear to have additional sources of sedimentation (Figure 3.11C), nor do they have comparably high accretion rates. This pattern could be caused by two different mechanisms. First, in transitional wetlands, the changing vegetation causes an increase in the below-ground biomass from encroaching emergent marsh grasses and in the above-ground biomass deposition from dying or dead forested wetland vegetation. Some studies (Krauss and Whitbeck 2012) argue that salinity increases decomposition of roots by weakening recalcitrance of dying vegetation, and several studies have shown a decreases in carbon and nitrogen with increases in salinity (Baustian et al. 2017, Herbert et al. 2015, Weston et al. 2010, Morissey et al. 2014). This holds true for the decreases in %C and %N observed in my forested wetlands and marshes but not for transitional wetlands (Figure 3.7 and 3.8). It might be that the additional emergent vegetation masks the effects of the salinity temporarily in transitional wetlands. As far as I know, no studies have examined the possible biogeochemical functions in transitional wetlands, but one study has seen a similar increase of carbon accumulation in their transitional wetlands. Noe et al. (2016) documented a sedimentation spike associated with an estuarine turbidity maximum and an increase in organic deposition at a highly salt impacted forested wetland along the Savannah River and a moderately impacted site along the Waccamaw River. The Noe et al. (2016) study also documented salt impacted forested wetlands sites with no carbon deposition, arguing that the site was in a small tributary with low sediment trapping. Pledger Harbor transitional site also has no increase in accumulation compared with marsh and forested wetland. Unfortunately, sediment sources seem non-existent in our study area. More research on transitioning wetlands is needed to better elucidate the functions that these unstable wetlands provide, but it is clear that the relationship is more complicated than just sedimentation or vegetation.

Nitrogen accumulation rates are rarely recorded in accretion and accumulation studies. However, Craft (2007) provided %N values for the southeastern United States (1.11±0.14forested wetland and 1.13±0.12 %N brackish marsh) that are similar to %N values of this study's sites (Table 3.3). Moreover, the range of nitrogen accumulation rates across the entire United States (3-18 and 3-39 $gm^{-2}yr^{-1}$) is also similar to the nitrogen accumulation rates in this study at both freshwater forested wetlands and brackish marshes (Craft 2007b)(Table 3.6). Nitrogen accumulation in our study is highest in the Bull Neck transitional wetlands and flooded restored wetland (24.3 and 15.2 $gm^{-2}yr^{-1}$) and lowest in open water (1.4 $gm^{-2}yr^{-1}$). low nitrogen accumulation in the open water sites is probably a function of eroding substrate.

$\delta^{13}C$ and $\delta\ ^{15}N$ as indicators of carbon and nitrogen sources and processes

The organic matter measured in this study of wetlands in the Albemarle Sound is dominated by terrestrial values of $\delta^{13}C$ (-29‰ to -26 ‰) with more marine values only near the inlet to the Pamlico Sound at Point Peter (Corbett et al. 2007). This range of $\delta^{13}C$ also indicate C3 plants are the dominant source (Kemp et al. 2009) Several sites (mostly marsh and open water sites) had less depleted $\delta^{13}C$ at depth which may reflect changes to the organic composition by soil processes (Tiunov, 2007) where microbial decomposition may deplete the $\delta^{13}C$ isotope signature.

Corbett et al. (2007) reported that the upper parts of their cores had enriched $\delta\ ^{15}N$ in the western Albemarle Sound with depleted $\delta\ ^{15}N$ values to the east. They also reported that $\delta\ ^{15}N$ values were depleted with depth. They attribute the enriched values to anthropogenic influences such as fertilizer and waste coming in with the surface drainage to the west. Fertilizer and surface water wastes contain inorganic nitrogen, which have a higher composition of enriched nitrogen isotopes than is naturally found (Thornton and McManus 1994). They also found that the Alligator River has depleted values in the upper parts of their cores than the main Albemarle Sound. My study found a similar distribution of $\delta^{15}N$ in the upper parts of the cores with enriched values in the western open water and marsh sites and more depleted in the east. Moreover, I had depleted values at the Briar Hall site on the Alligator River (Table 3.4). Unlike Corbett et al. (2007) however, the $\delta^{15}N$ in the cores of this study trend slightly enriched with depth or show no change. This trend is most pronounced in the forested and transitional wetlands and is less developed in the marsh and open water sites.

The %N and NO_3^- concentrations all show a strong decrease with depth in the forested and transitional wetlands which suggest that microbial action may be removing them and preferentially enriching N isotopes concentrations (Szpak 2014). In the Pledger Harbor forested and transitional wetland and the Briar Hall forested wetland, increase in $\delta^{15}N$ enrichment correlated well with the depth of highly reduced sediment. In contrast the transitional forest and marsh at Bull Neck show very high values of $\delta^{15}N$ without additional visual indication of highly reduced sediment, which could suggest an anthropogenic influence on top of microbial processing. In the marsh and open water sites where $\delta^{15}N$ does not change with depth, it is likely that variation in %N and NO_3^- concentrations may be a result of continually recycled nitrogen in the system (Robinson 2001, Szpak 2014).

SO_4^{2-}/Cl^- ratios as indicators of sulfate sources and processes

There are several reasons why the SO_4^{2-}/Cl^- ratios might diverge from the seawater ratio of 0.14 including: 1. Sulfate reduction by microbial processes, yielding ratios lower that seawater; 2. freshwater flushing of chloride resulting in lower overall concentration of Cl^-

and ratios higher than seawater; and 3. SO_4^{2-} introduced from another source such as from fertilizer which would yield high SO_4^{2-} and ratios higher than seawater.

In this study, the wetland sites with ratios lower than 0.14 likely have sulfate reduction occurring. Most open water and marsh sites, where salinization occurs, have low sulfate to chloride ratios. Wetland sites with ratios higher than seawater are characterized by low total values of chloride that increase with depth or remain relatively the same and are probably affected by freshwater flushing. For example, the forested and transitional wetlands at Briar Hall and Bull Neck both show a decrease in the SO_4^{2-}/Cl^- ratio with depth and low chloride concentrations, which could reflect leaching of chloride from the system. The forested wetland at Point Peter shows a decrease in the SO_4^{2-}/Cl^- ratio with depth, but a sharp increase in the ratio at the bottom of the core where it is sandier. The Point Peter transitional wetland there shows a general decrease in the ratio with depth with sharp increase in the ratio coincident with a gray siltier, organic poor interval. These may be indicative of flushing of Cl^- with some variability in response to different sediment types.

The SO_4^{2-}/Cl^- ratios higher than seawater at the Pledger Harbor forested and transitional wetlands, at the restored wetland sites, and the marsh at Bull Neck are difficult to explain by the flushing mechanism. First of all, they have SO_4^{2-} values that are higher than those for sites with much higher Cl^- values (Appendix B). The Bull Neck marsh site is likely disturbed, possibly by anthropogenic additions. The vegetation is a monoculture of common reed, a species that grows well in disturbed soils. The ^{210}Pb profile (Appendix C) indicated soil that was deposited all at the same time. This peat soil is not similar to the surrounding forest. The Pledger Harbor forested and transitional sites have high SO_4^{2-}/Cl^- and are well removed from the inlet into Albemarle Sound, suggesting seawater is not the only source of sulfate. At Pledger Harbor and the dry restored wetland sites, the SO_4^{2-}/Cl^- ratio increases with depth. These elevated ratios may be reflecting an addition of sulfate to the system from anthropogenic influences, oxidation of sulfides, or the preferential concentration of sulfate in certain substrates. Sulfate is a common addition in agriculture in North Carolina (Crozier et al., 2014, NC State Extension Publications, https://content.ces.ncsu.edu/sulfur-fertilization-of-north-carolina-crops). An anthropogenic sulfate argument is strengthened by the observation of heavy $\delta^{15}N$ values in the Bull Neck marsh site and the restored wetland sites. Another way of adding sulfate to the sediment is through the oxidation of sulfide minerals (McLaughlin et al. 2011, Edwards 1998). There is evidence of oxidation in the lower portions of the Pledger Harbor forested and transitional wetland sites, but not in the Bull Neck marsh or TOWeR dry and flooded sites further supporting an anthropogenic source (Appendix B). The SO_4/Cl ratio indicate that sulfate reduction may be one process effecting carbon decomposition in wetlands. Moreover, it's possible that the source of sulfate is not just saltwater but also anthropogenic sources in Bull Neck and the forested sites of Pledger Harbor. This is not conclusive evidence and requires deeper study into the sulfur biogeochemical pathway in these wetlands.

4.2 Comparison of Natural and Constructed Wetlands

The two sites in the Timberlake Observatory for Wetland Restoration (TOWeR) are freshwater forested wetlands on Hyde loams, with thin A horizons composed of fibric muck and silty B horizons of reduced silty loam (Appendix B). This soil profile is similar to Pledger Harbor forested wetland and Briar Hall forested wetland, and has similar bulk densities as well (Table 3.4). Salinity can increase periodically by surface water input from downstream of Little Alligator River via the western side of the Alligator River, but hydrologically the area is not isolated, with water flowing from runoff, groundwater flow, and inputs both upstream and downstream depending on wind tides and current (Ardón et al. 2010). Similarly, Briar Hall is also connected to the Alligator River, via Broad Creek on the eastern side of the river and surrounded by local agricultural fields. During the sampling time of this study, chloride concentrations at TOWeR were very low (0.2 and 0.15 mg/g), which is comparable with the freshest natural wetland sites such as the forested wetlands at Point Peter and Bull Neck.

The soil chemistry at both TOWeR sites are influenced by past land use, with the highest NO_3^- concentration values of any site and low sulfate values. The dry TOWeR site had percent carbon and nitrogen similar to Briar Hall and Pledger Harbor forested wetlands. The flooded TOWeR site had higher values in comparison for both nitrogen and carbon, but still low relative to the organic rich sites like the Bull Neck and Point Peter forested wetlands. The C:N ratio increases down core at the dry TOWeR site, but not at the flooded TOWeR site, perhaps indicating higher rates of organic material processing in the dry TOWeR site. This would make sense, given that the wetland is saturated for less time seasonally than at the TOWeR flooded site. The $\delta^{15}N$ is heavy at both sites, similar to Briar Hall and Pledger Harbor forested wetlands at depth lower than 30cm). Carbon and nitrogen accumulation rates at the dry TOWeR site are comparable with Briar Hall forested wetland and higher than Pledger Harbor forested wetland. At the flooded TOWeR site, carbon and nitrogen accumulation rates are higher than all other sites besides the Bull Neck transitional wetland. The dry TOWeR site has the highest mass accumulation and the flooded TOWeR site has high mass accumulation. Vertical accretion at both sites is higher than all natural wetland sites except the transitional wetland in Bull Neck.

Overall, the TOWeR restored sites are similar to the mineral rich forested wetland sites at Pledger Harbor and Briar Hall, though with some limitations. The natural wetland sites are all closer to shore than the restored wetlands and have high-energy hydrology that only occurs along shorelines like wave action and storm over-wash. TOWeR can be affected by storm surges and wind tides, but the hydrology in the wetlands are comparably slow flowing. This may be part of the reason that the restored sites have a higher vertical accretion rate overall, since the disturbances to the system are mostly from chemical changes instead of physical reactions. Moreover, the higher rates of carbon and nitrogen accumulation in the flooded TOWeR site may be an indication of the success of the restoration, indicated by healthy cypress tree growth (Powell et al. 2016) and nutrient cycling that is returning to reference levels (Ardón et al. 2017). It is unclear if the artifacts of the previous farmland are inhibiting accumulation rates, like legacy nitrate in the dry TOWeR site, but without major incident, both sites are behaving better than the natural counter parts in terms of accretion.

Previous studies of wetland restoration that compare accretion and accumulation rates are mostly focused on marshes. In most of these studies, sediment is the main driver of accretion and is necessary for maintaining rates higher than sea level rise, or higher carbon accumulation rates compared with reference sites (Calvo-Cabero et al. 2010, Sheng et al. 2015, Howe et al. 2009). A study of natural wetlands in Florida calculated accretion and carbon accumulation rates for bald cypress swamps and pine flats which were lower than this study's rates (average accretion 0.24 and 0.04cm/yr, average carbon sequestration 98±5 and 22±5 $gm^{-2}yr^{-1}$)(Villa and Mitsche 2015). Craft and Casey (2000) also measured natural cypress-gum wetland accretion, with even lower averages (0.08±0.02 depressional forested wetlands, 0.19 ± 0.01 in flood plain, and 0.22±0.05 in depressional savanna wetlands). Reasons for these low rates in comparison with the restored wetland could include sediment sources. The sediment source is higher in the Craft and Casey (2000) savanna wetland than in their floodplain and depressional forested wetlands, which may be a major source of accretion in that system. The flooded restored site at TOWeR has free flowing water and additional sources of nutrients and DOC from agricultural and precipitation runoff (Ardón et al. 2013). The wetlands in Craft and Casey's study also had a decreasing accretion rate over time, with lower rates in the last 30 years compared to the last 100 years. In comparison, the cypress trees growing in the flooded TOWeR wetland are young, and organic accretion is faster than in older forests. Perhaps as time passes and the vegetation ages, accretion rates will decrease similar to a natural wetland.

The memorandum established for the creation of mitigation bank restoration sites like TOWeR states that the goal of the restoration is ''to establish self-sustaining, functioning aquatic systems to replace the functions and acreage of wetlands and other aquatic resources anticipated to be adversely affected'' (Army Corps of Engineers 1997). Although this is only measurable in the short term, considering the comparisons we've provided and the data concerning accretion and accumulation for both restored sites, the TOWeR restored wetlands are meeting this goal for services related to sea-level rise and carbon storage, though not at the scale needed to replace dwindling hardwood bottomland forests in the Albemarle-Pamlico peninsula.

4.3 Conclusion

Most of the Albemarle-Pamlico peninsula coastal wetlands examined in this study are dominated by organic matter dominated accretion; have accretion rates below GMSLR; and may have insufficient sediment sources to adapt to increasing seal level rise rates in the future. As said in previous studies (Moorehead and Brinson 1995, Riggs and Ames 2003), the erosion and hydrologic regimes of wetlands along the Albemarle Sound have a large impact on the source of sediments available to wetlands. Erosional cycles along the shoreline from wave mechanics or storm events make sediment deposition incredibly low. In open water sites, where deposition is the lowest, the effects of this erosional activity are clear. Few river channels provide proper freshwater sediment sources, like the channel at the Bull Neck transitional zone. Although the long term effects of salinization on accumulation rates are unclear, the modern percent of carbon and nitrogen measured in forested and marsh wetlands of this study decreased with salinity. Transitional wetlands, in contrast, seem to have higher rates of carbon accumulation possibly indicating that the change in vegetation from forest to marsh grasses may be a driver in protecting or increasing carbon and nitrogen storage in these environments despite increases in salinity. $\delta^{13}C$ signatures did not give insight into how vegetation may be affecting this and there are few studies to corroborate the phenomenon. Further research is necessary to understand the true function of transitioning wetlands. Isotopic signatures of $\delta^{15}N$, agree with this hypothesis. Fortunately, despite the degradation and threats to the natural wetlands of this study, the restored wetland site is meeting or exceeding the GMSLR rate, indicating the positive impact of restoration on the protection and resilience of forested wetlands in the Albemarle-Pamlico peninsula.

CHAPTER 5. Monitoring Transitioning Wetlands in North Carolina Using Citizen Science

5.1 Advantages of Crowdsourcing in collecting spatial and temporal data

State-wide monitoring of wetland transitions from forested to marsh and open water as the effects of climate change progresses, will be difficult. The timeframe for a transition will be dependent on the source of saltwater, be it a storm flooding event, a drought, or the gradual rise in sea level. The spatial scale of a transition will also vary, requiring finer resolution than currently available temporal spatial data and remote sensing data provides. Given the time resolution needed and the spatial scale of this land cover class, the man power needed to map the changing extent of this class is substantial. Crowdsourcing from invested locals and visiting tourists throughout the state may offer a solution to providing visual temporal monitoring data and additional ground truth to current mapping efforts. To test this idea, we have developed an accessible, mobile citizen science application (app) that allows volunteers to provide pictures, descriptions, locality, and date/time of specified cypress tree species as indication of the health of forested wetlands.

Citizen science is a form of public science outreach that provides educational and research opportunities to interested participants (Cooper 2016). There are several methods of practice for citizen science projects, but crowdsourcing has become a dominant method for collecting large batches of preliminary and monitoring data used for providing spatial context and evaluation of sites before more in-depth study (Laso et al. 2016, Elmore et al. 2016). This form of outreach also allows a wide audience to learn about the research in their region and actively apply that knowledge towards a reachable, visually accessible goal (Roy et al. 2012). Some of the more successful citizen applications such as the National Phenology Network (https://www.usanpn.org/) are providing critical climate change science and information.

My mobile application is aimed at helping inform research projects examining saltwater intrusion and wetland vulnerability, as well as assessing the changing spatial extent of forested wetlands in North Carolina. I developed a citizen science mobile app that asks a series of site related survey questions and provides for download of GPS and photo observations. (https://scistarter.com/project/15731-Sentinels-of-the-Sounds) The app was developed under two platforms to evaluate the accessibility and interest of citizen science apps. The app focuses on cypress trees, which are dominant hardwood bottomland forested wetland species that are sensitive to increases in salinity but tolerant to flooding. These species are well known to casual naturalists and are often a subject of photography, considered interesting and beautiful to both residents and tourists alike. By narrowing the subject of observation, the app is easier to use by possible citizen scientists, photographers, school children and other participants (Roy et al. 2014).

5.2 Creating the Sentinels of the Sound App

The citizen science apps were created using EpiCollect (http://www.epicollect.net/) and iNaturalist (https://www.inaturalist.org/) platforms (Figure 5.1). Both applications included a website based database with a map interface and access to survey data answers.

Each app contains seven questions for citizen scientists to fill out (Table 5.1). Each database was then manually uploaded to a single server space, added to google maps, and is available as a single dataset on our website (http://sentinelsnc.weebly.com/). Protocols for downloading and using the apps were also provided on our website.

Table 5.1 Sentinels of the Sound survey questions

Question	**Answer Options**
Date	month-day-year
GPS	WGS 84 Coordinate System
Photo	Available for viewing
Are you taking a picture of one tree or many	One
	Many
Is the cypress on land or in water	On Land
	In Water
How healthy do the cypress look?	very healthy
	Healthy
	Stressed
	very stressed
	Unsure
Distance to observation	1 meter (approximately 1 yard)
	5 meter (approximately a 12 seater passenger van)
	10 meter (approximately a yellow school bus)
	15 meter (approximately length of a basketball court)
	greater than 15 meters
Additional Comments	optional text

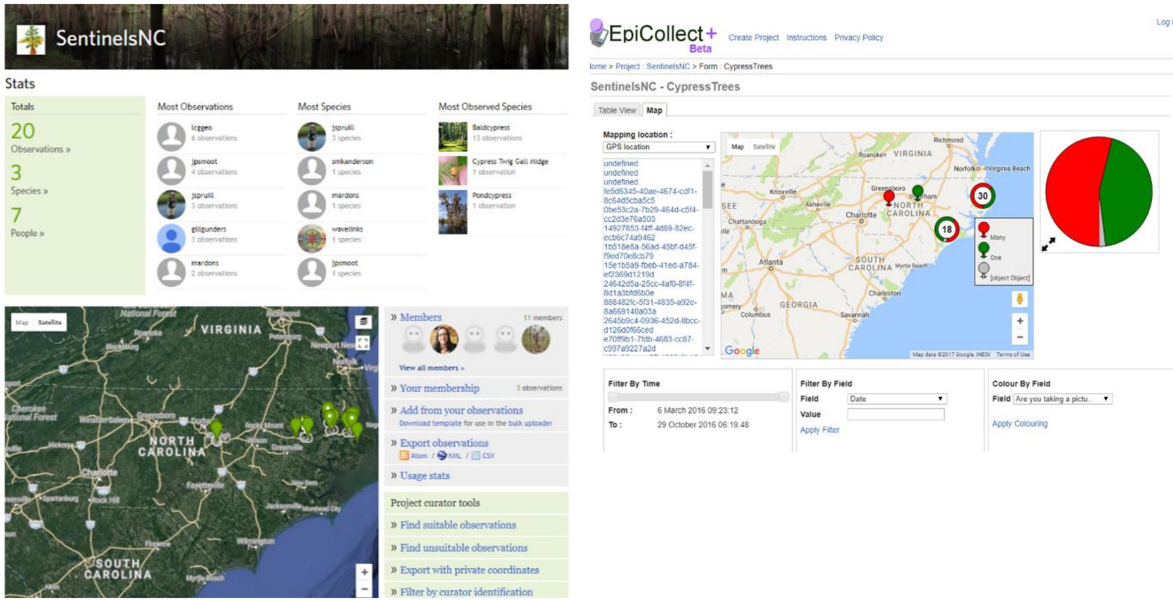

Figure 5.1 View of both INaturalist (left) and Epicollect Plus (right) database pages currently available online (July 24 2017).

After the first year of data collection, I went through a systematic evaluation of each photo independently and categorized them based on similar categories used by the citizen science observers (very healthy, healthy, stressed, very stressed, unsure, and lost – for photos that were no longer in database). This evaluation (referred to as the independent categorization below) was based almost exclusively on level of defoliation observable for each photo (Figure 5.2).

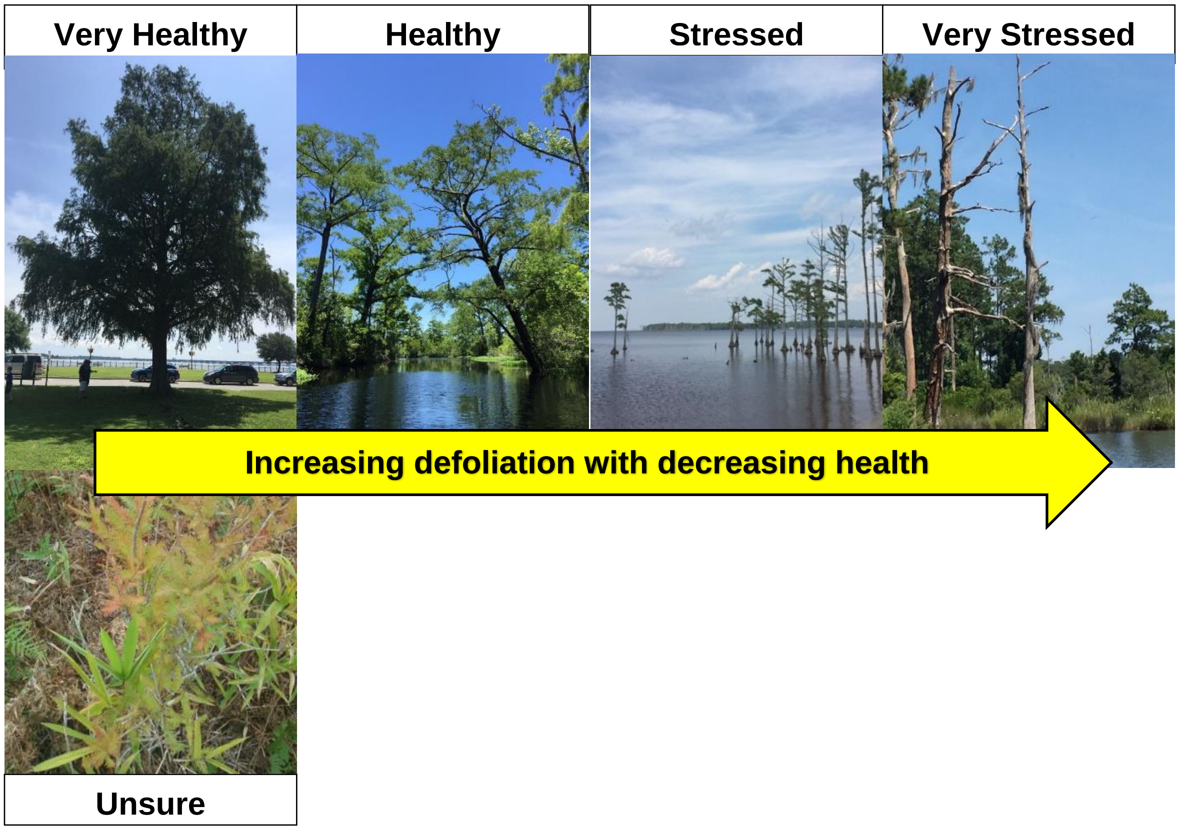

Figure 5.2 Example observations from the Sentinels of the Sounds photo database showing independent categorization by defoliation and one example of unsure – a young cypress with changing leaves (taken in September) at a very close up angle.

5.3 First Year Results and Conclusions

Our citizen science applications have had 65 submissions over the course of June 2016 to June 2017. Nineteen observations are from the INaturalist application and 46 observations are from the Epicollect plus application. Fourteen of the INaturalist observations and three of the Epicollect plus observations had mobile location accuracy >10m. Accuracy of the citizen science observations were calculated using confusion matrices, comparing the citizen observations with my independent characterization (Laso et al. 2016). Preliminary review of observation photos showed lower accuracy between observer and independent categorization of healthy forests (29%) and very healthy (54%), all other accuracy was >80%. Fifty-eight percent of the observers reported “healthy” or “very healthy” cypress, 37% of the observers reported “stressed” and “very stressed” cypress trees. Using independent categorization when reviewing “on land” or “in water” cypress, only 25% of “on land” observations were reported as “stressed” or “very stressed” (9% observed photos lost, 25% unsure, 41% reported as healthy or very healthy), whereas “in water” observations were 56.2% “stressed” or “very stressed” (15.6% unsure, 28.2% “healthy” or “very healthy”)(Table 5.2).

Most “stressed” or “very stressed” observations were made along the shore of the Albemarle Sound, and most “healthy” or “very healthy” observations were made inland, following the regional salinity gradient of the area (Figure 5.3). Using only data with location accuracy <10m (n=49), I analyzed how observations fell within system categories of the national wetland inventory (FSW 2016). Observations were mostly taken in palustrine (40.8%) and estuarine wetlands (53.1%), with six taken in riverine (6.12%) wetlands. Health observations were evenly distributed across palustrine and estuarine wetland types (Table 5.3). Observations in riverine wetlands were exclusively reported as “healthy” by observers, but could not be validated by the independent categorization due to missing photos or “unsure” observations. Overall, with the current data available, there is a clear pattern of healthy inland forests and stressed shoreline forests

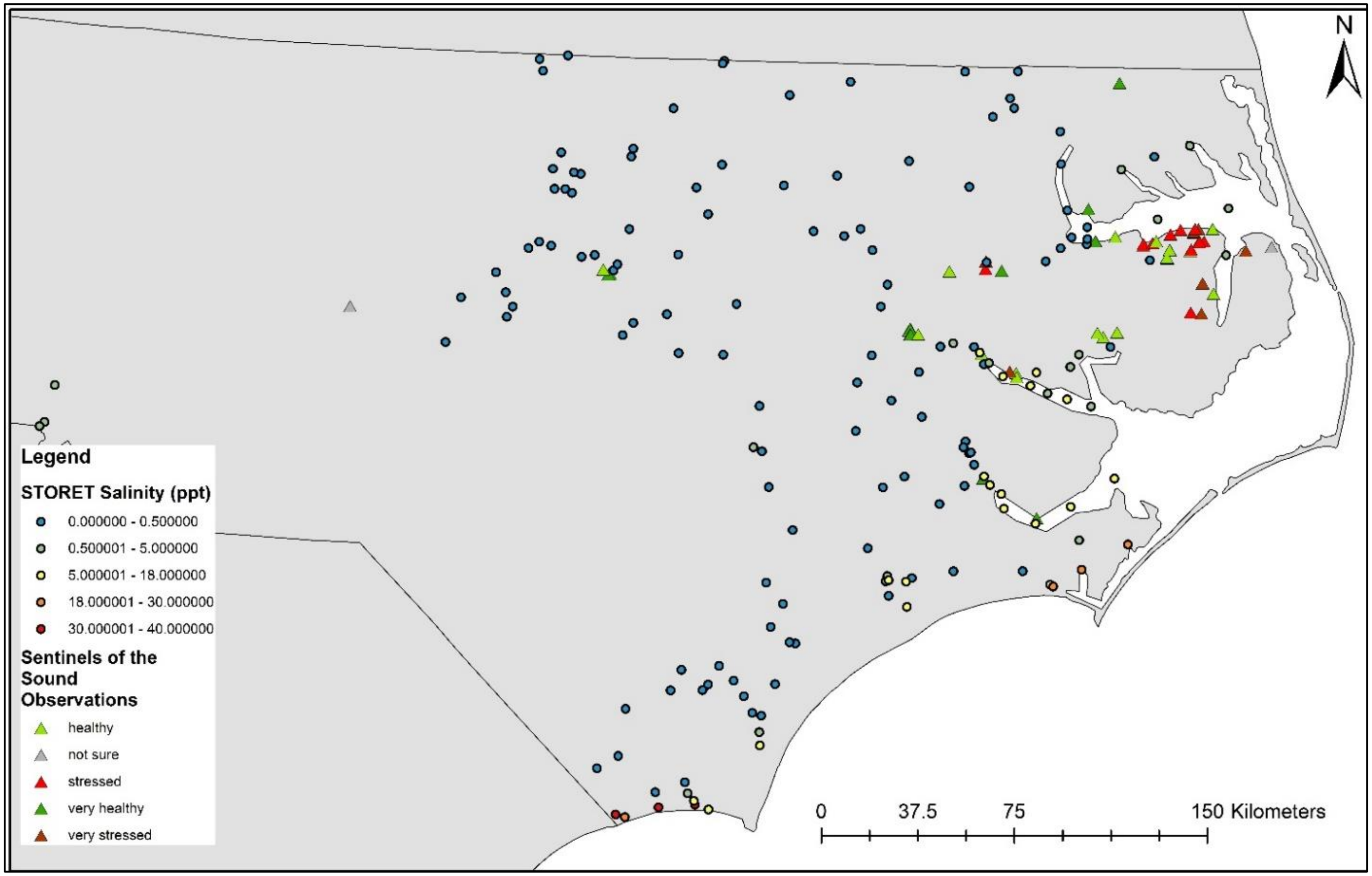

Figure 5.3 Map of North Carolina with observations from Sentinels of the Sounds and average summer salinity values for 2016 from STORET monthly monitoring data (NOAA 2017)

Table 5.2 Frequency of observations by independent categorization of observational health and location.

	% In Water	% On Land	% Total
Very Healthy/Healthy	28.13 (n=9)	40.63 (n=13)	34.38 (n=22)
Very Stressed/Stressed	56.25 (n=18)	25 (n=8)	40.63 (n=26)
Unsure	15.63 (n=5)	25 (n=8)	20.31 (n=13)
Lost	0 (n=0)	9.38 (n=3)	4.69 (n=3)
Total	50 (n=32)	50 (n=32)	100 (n=64)

Table 5.3 Frequency of observations by independent categorization of observational health and wetland classification from NWI (system level) for observations with location accuracy <10m.

	% Estuarine	% Palustrine	% Riverine	% Total
Very Healthy/Healthy	38.46 (n=10)	50 (n=10)	0 (n=0)	40.82 (n=20)
Very Stressed/Stressed	61.54 (n=16)	20 (n=4)	0 (n=0)	40.82 (n=20)
Unsure	0 (n=0)	30 (n=6)	0 (n=0)	12.24 (n=6)
Lost	0 (n=0)	0 (n=0)	100 (n=3)	6.12 (n=3)
Total	53.06 (n=26)	40.82 (n=20)	6.12 (n=3)	100 (n=49)

An important aspect of citizen science is accuracy of data. In some instances, accuracy is dependent on the machine. The GPS mobile location accuracy requires good satellite reception. Epicollect Plus observation accuracy was almost always within 10m of location and never more than 30m. However, INaturalist values were sometimes much higher >100m. There is some practice among INaturalist users to post informative journal entries associated with their project and a common recommendation they make is to ask users to pay close attention to location accuracy when taking observations (Pauly and Smart 2014, Birds of Broadmoor 2014). Some location bias associated with satellite reception is unavoidable because of the nature of the application. Previous studies have indicated that with proper training and education, citizen science data collection is on par with research quality observation (Dickinson et al. 2012, Roy et al. 2012, Fowler et al. 2013). Upon reviewing citizen observation photos, it was clear that tree age/height, time of season, and scope of picture all affected the ability to evaluate the observation. Moreover, what an observer considered healthy varied greatly when left to the imagination of the user.

In conclusion, analysis of the first year of data collected through the Sentinels of the Sounds citizen science app indicate that they can be useful for mapping where disturbed cypress and healthy cypress are located. The data show a clear pattern of healthy inland forests and stressed shoreline forests. Accuracy analysis of the citizen science observations, tested against my independent observations, indicate that more training is needed for citizen scientists to understand the finer distinctions between categories such as “healthy” and “very healthy.” Optional training in the form of a short video could be helpful in encouraging proper identification and informed answers to the survey. Starr and others (2014) found video training to be most effective in a comparison of several training methods for citizen science apps. Increasing the accuracy of the data collected by the app could make it useful in directing or indicating areas of interest for future field studies and wetland mapping. In addition, making the app more publicly known through local schools and environmental groups dedicated to conserving the health of North Carolina wetlands will provide the density needed to begin using the tool for mapping and anticipating change.

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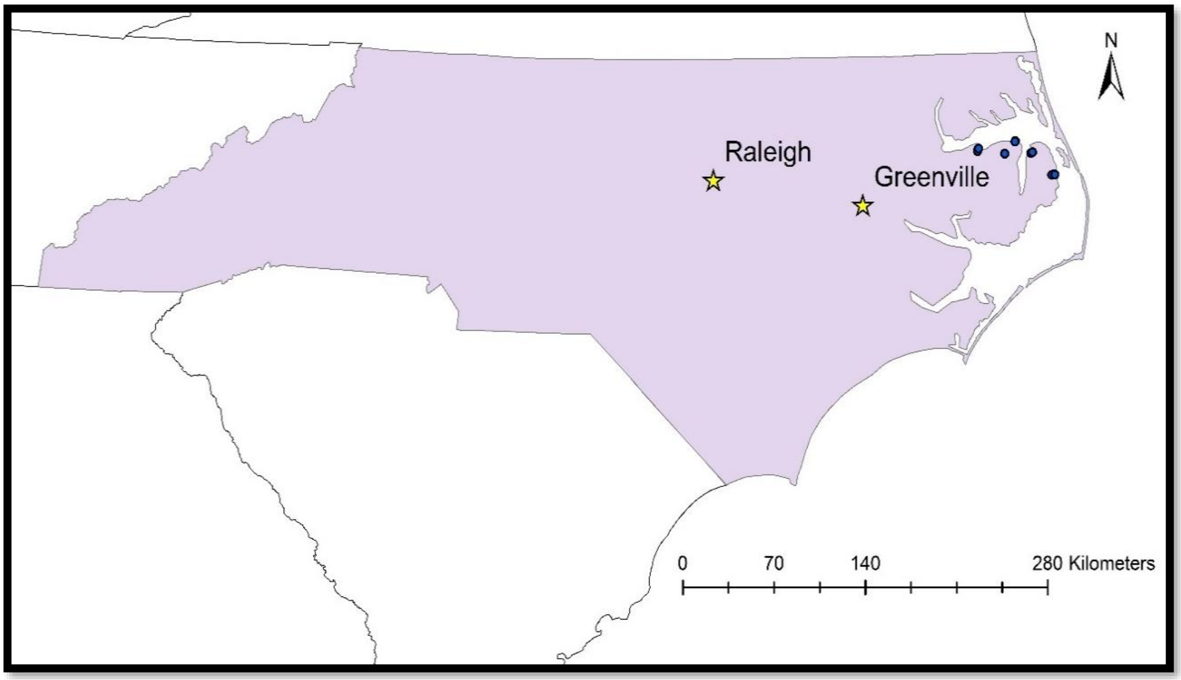
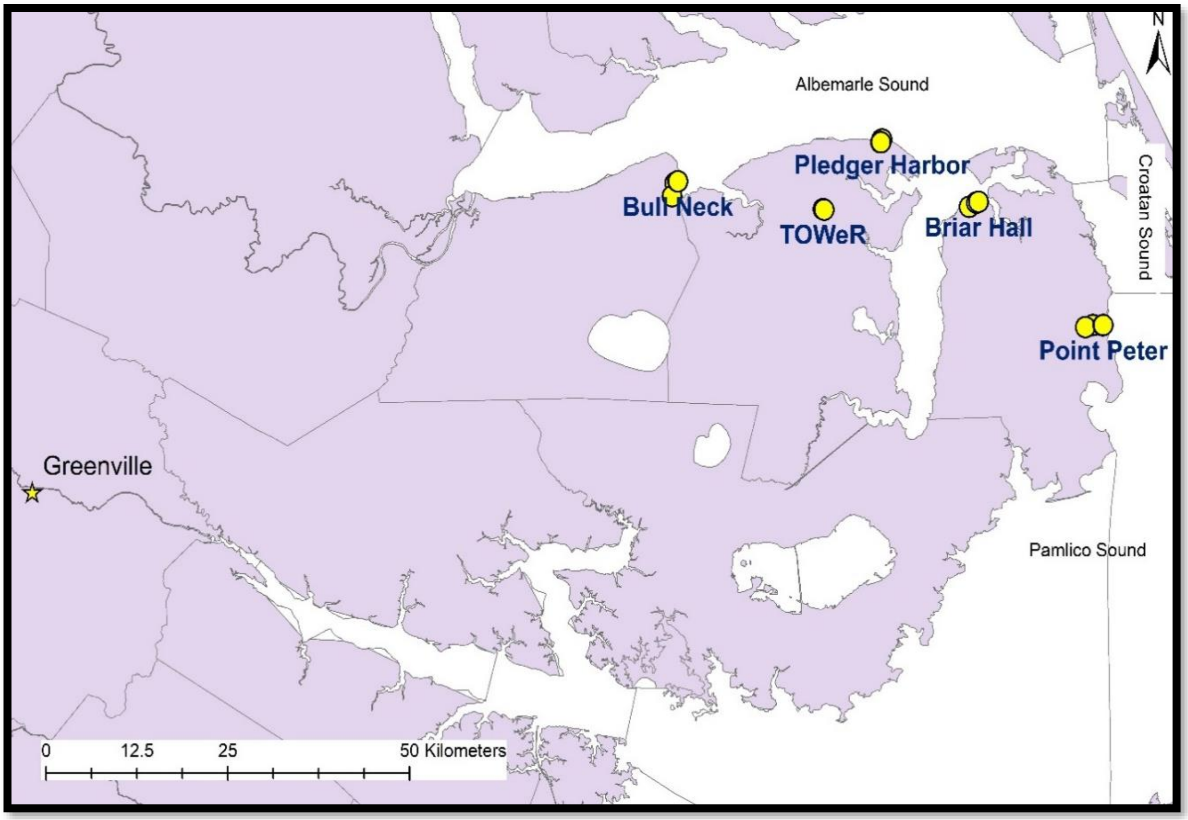
APPENDICES

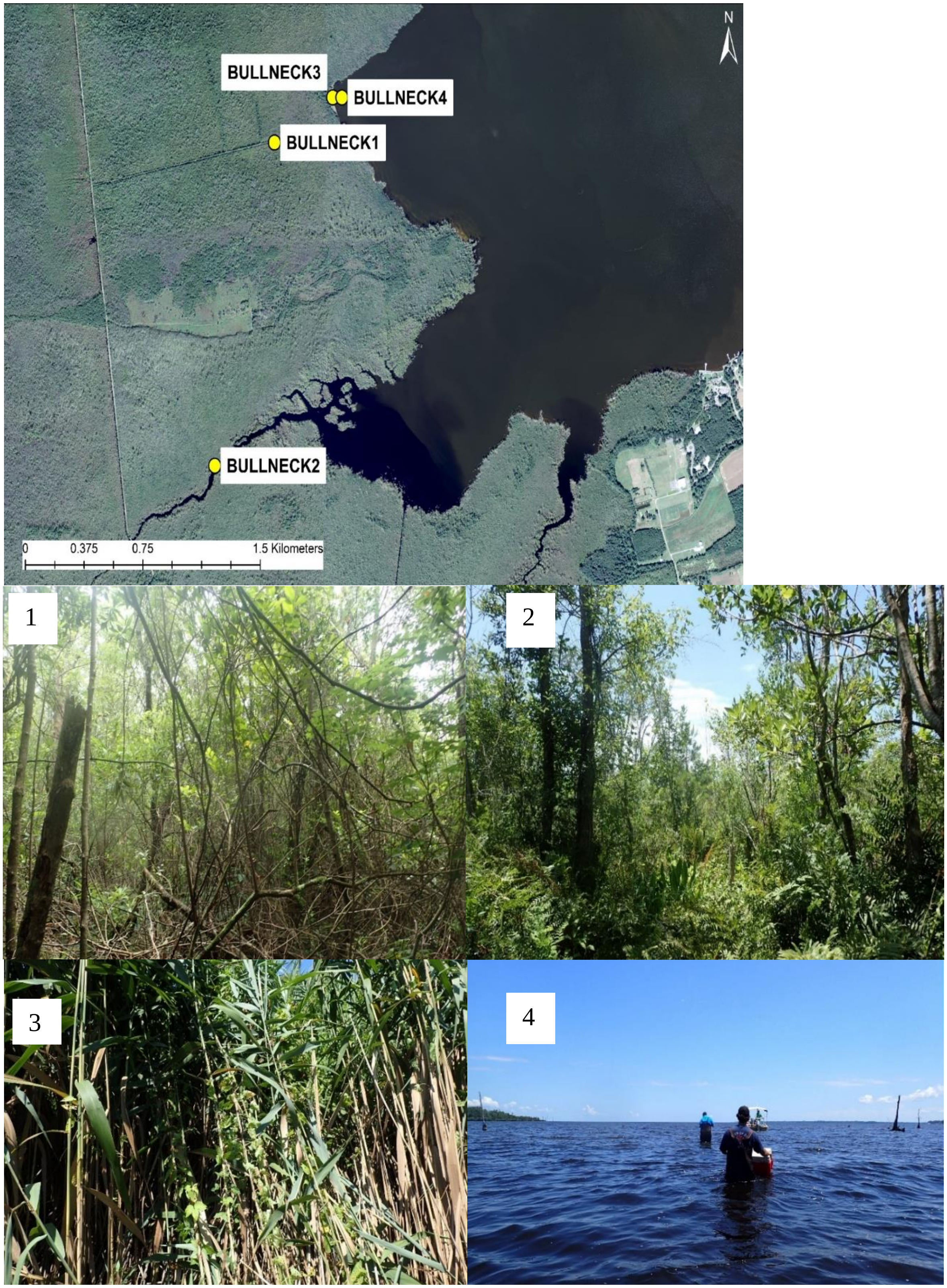
Appendix A

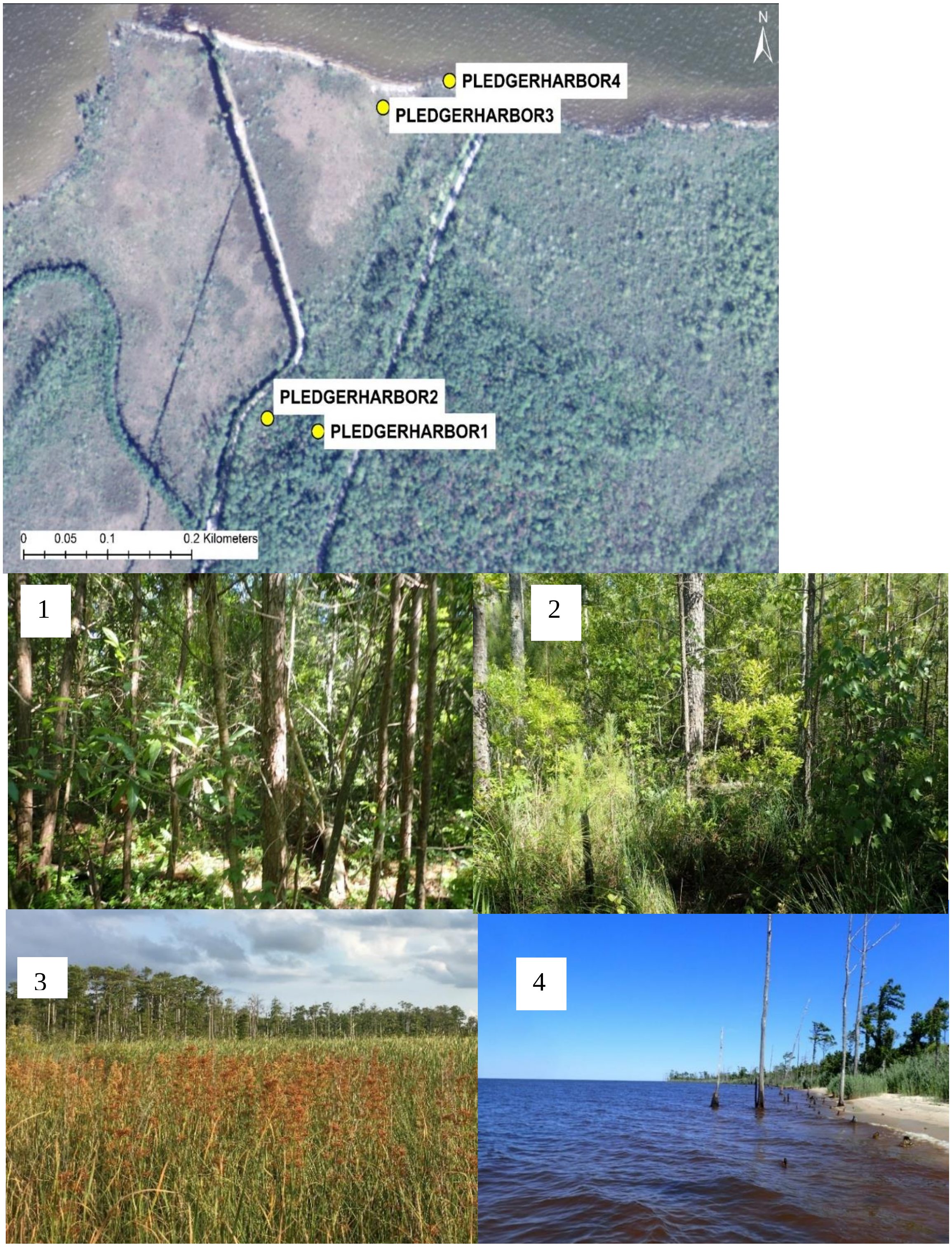
Labels 1-4 on following maps indicate Forest, Transitional, Marsh, and Open water sites respectively. On the TOWeR map, 1 is dry and 2 is flooded sites.

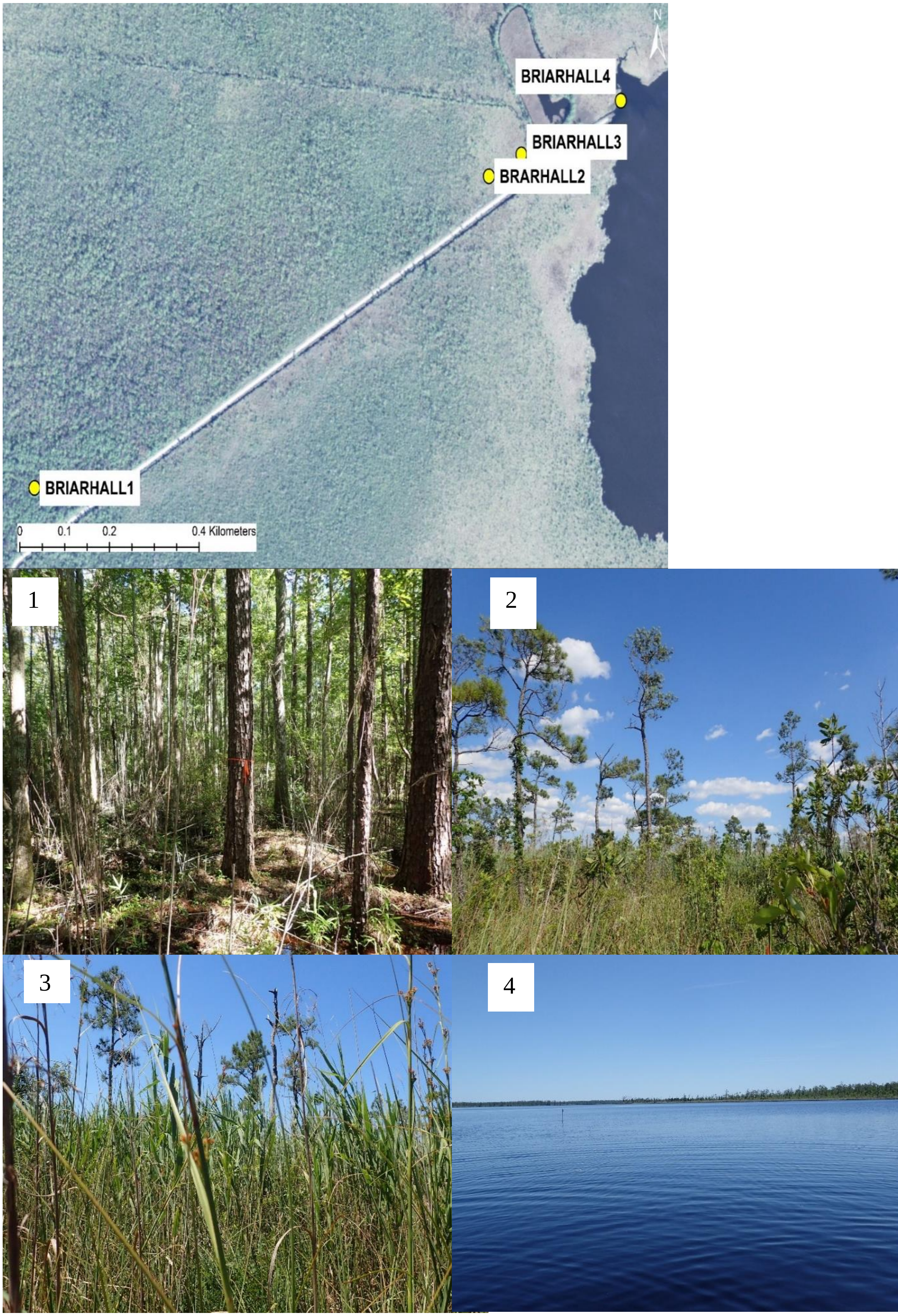


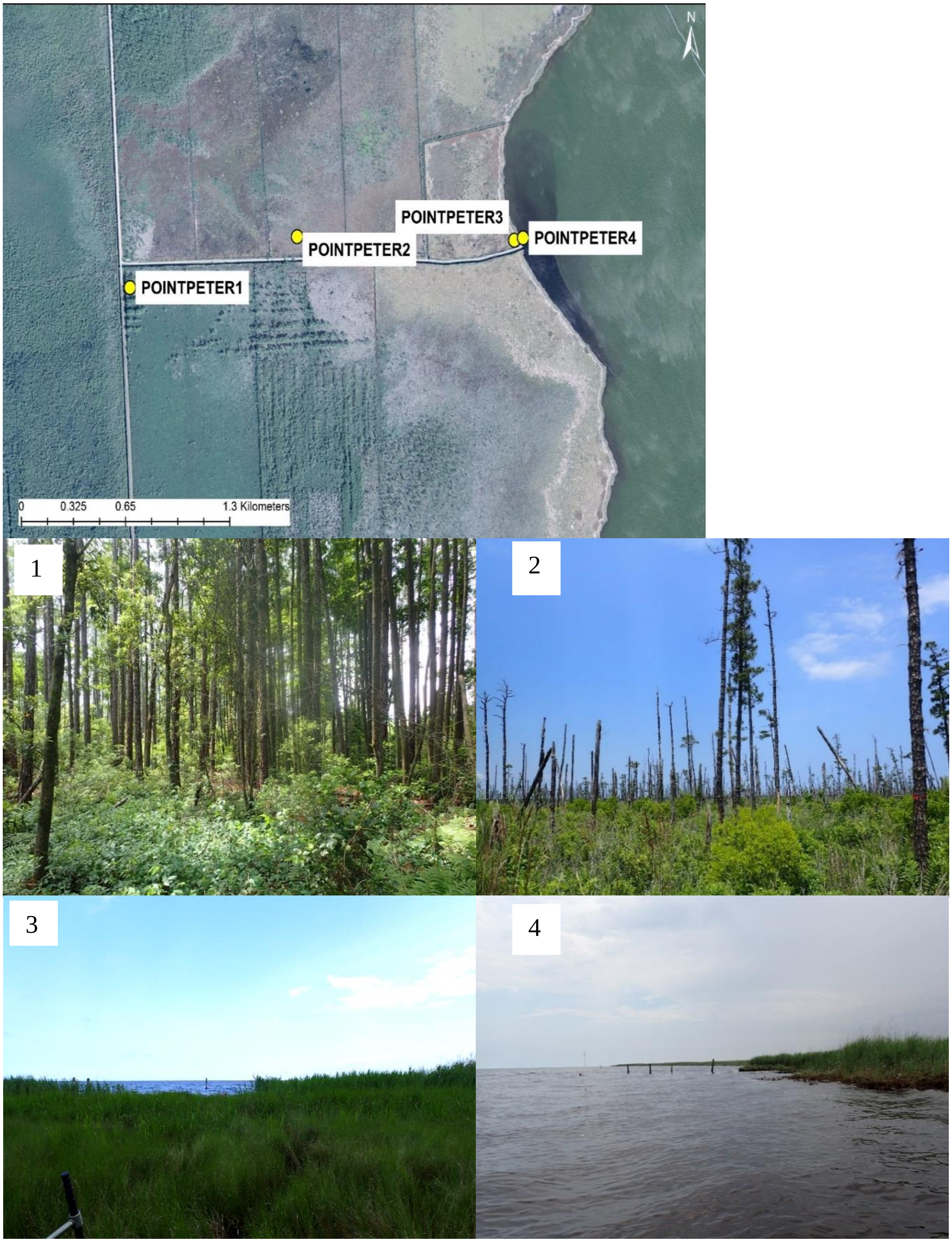


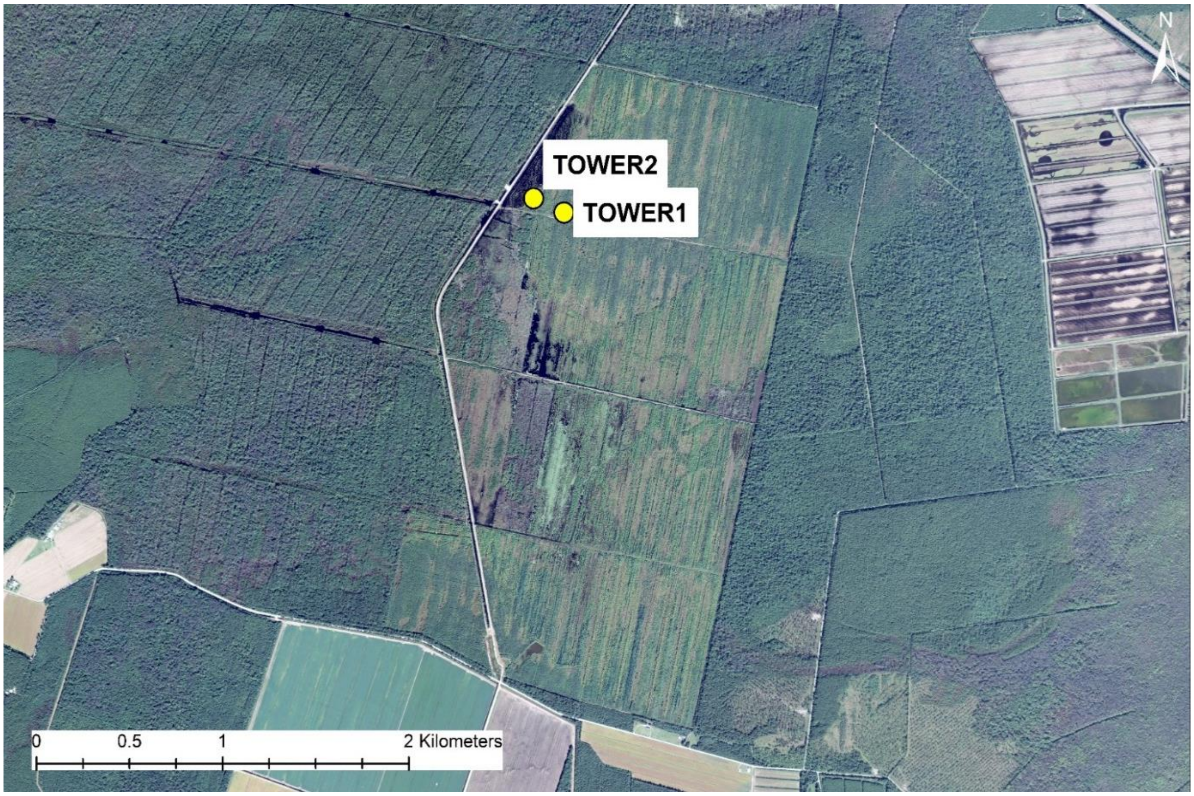
N
Albemarle Sound
Pledger Harbor
Bull Neck
TOWeR
Briar Hall
Croatan Sound
Point Peter
Greenville
Pamlico Sound
0
12.5
25
50 Kilometers


BULLNECK3
BULLNECK4
BULLNECK1
BULLNECK2
N
0
0.375
0.75
1.5 Kilometers
1
2
3
4


N
PLEDGERHARBOR4
PLEDGERHARBOR3
PLEDGERHARBOR2
PLEDGERHARBOR1
0
0.05
0.1
0.2 Kilometers
1
2
3
4

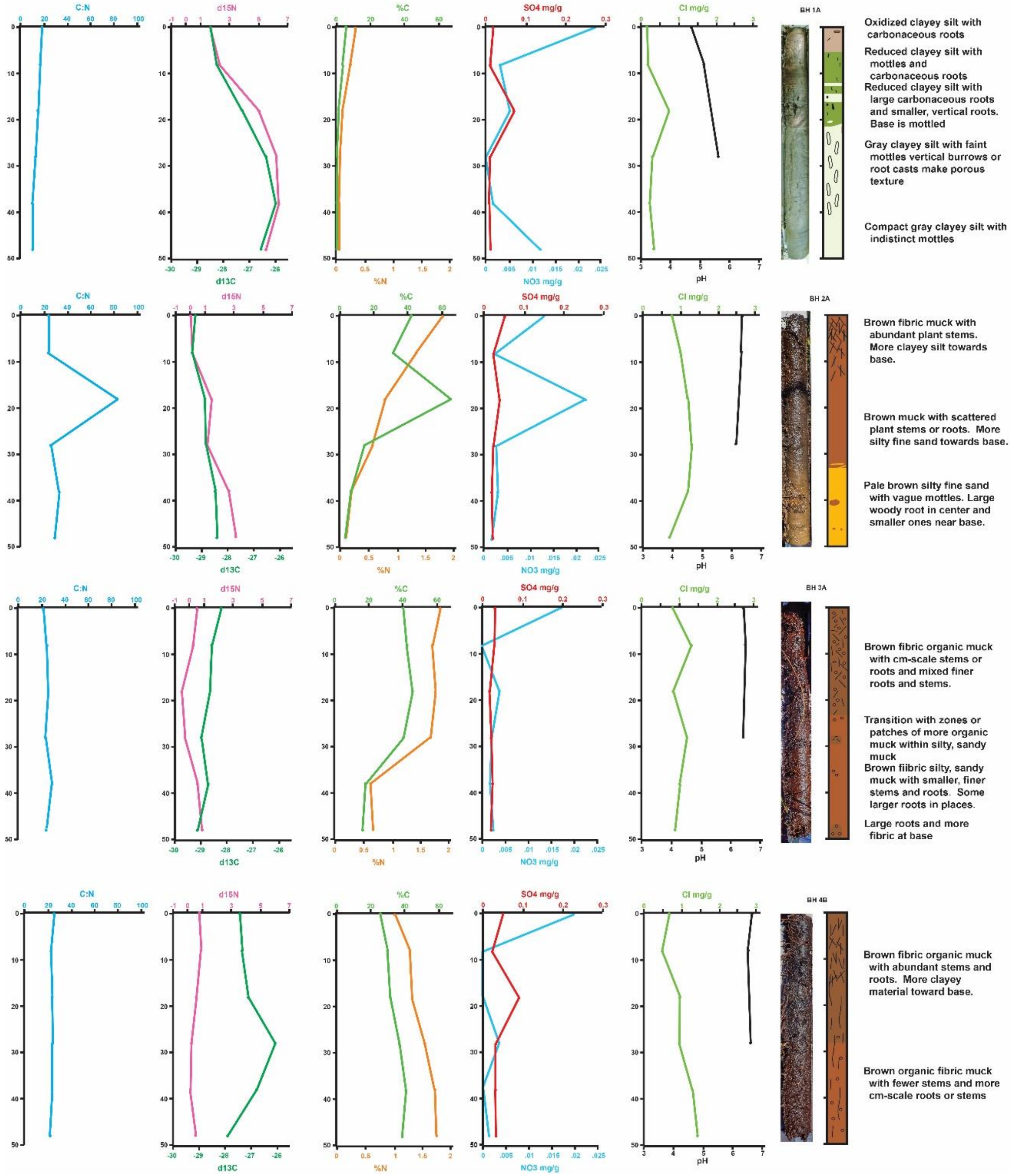

N
BRIARHALL4
BRIARHALL3
BRARHALL2
BRIARHALL1
0 0.1 0.2 0.4 Kilometers
1
2
3
4

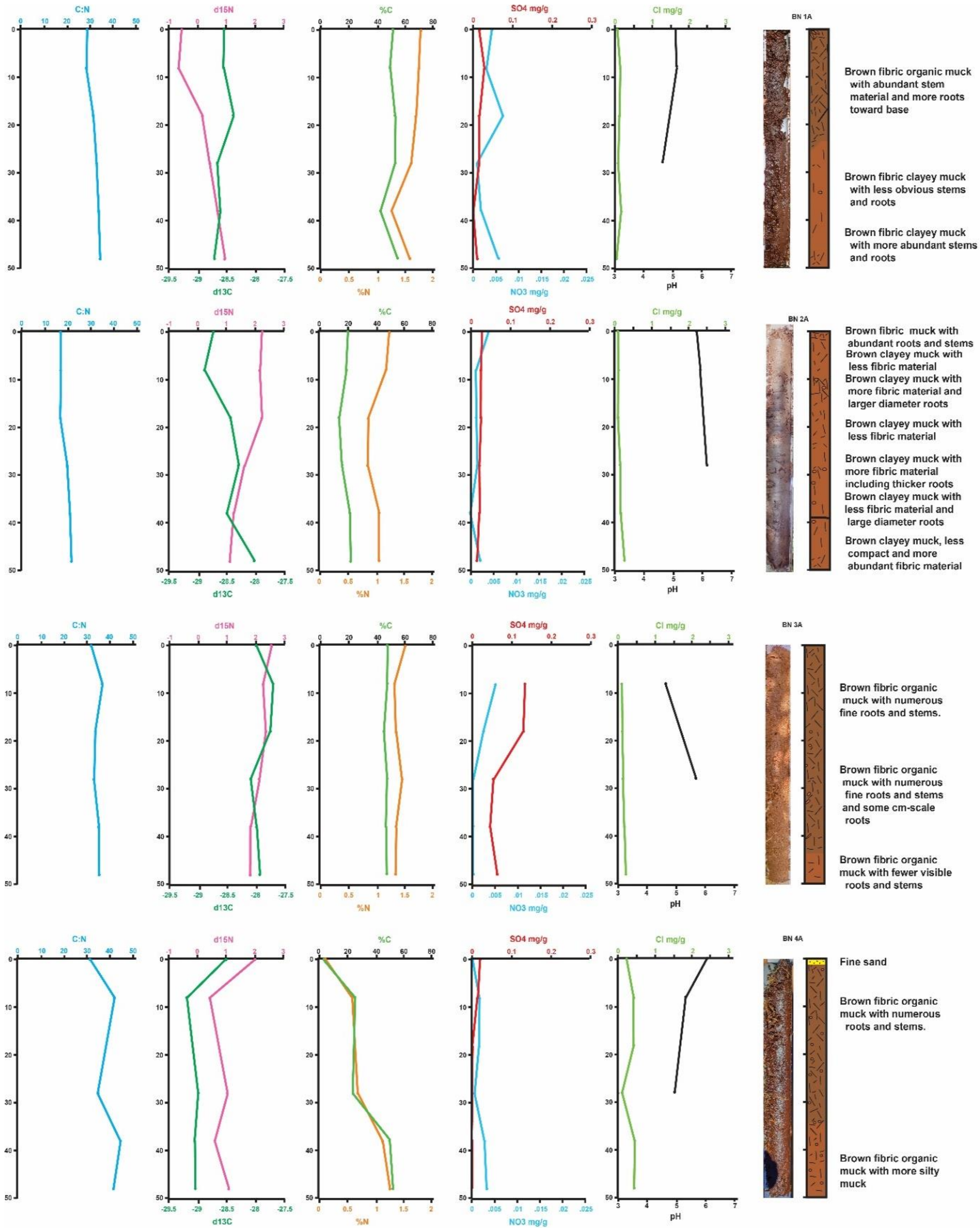

N
POINTPETER1
POINTPETER2
POINTPETER3
POINTPETER4
0 0.325 0.65 1.3 Kilometers
1
2
3
4

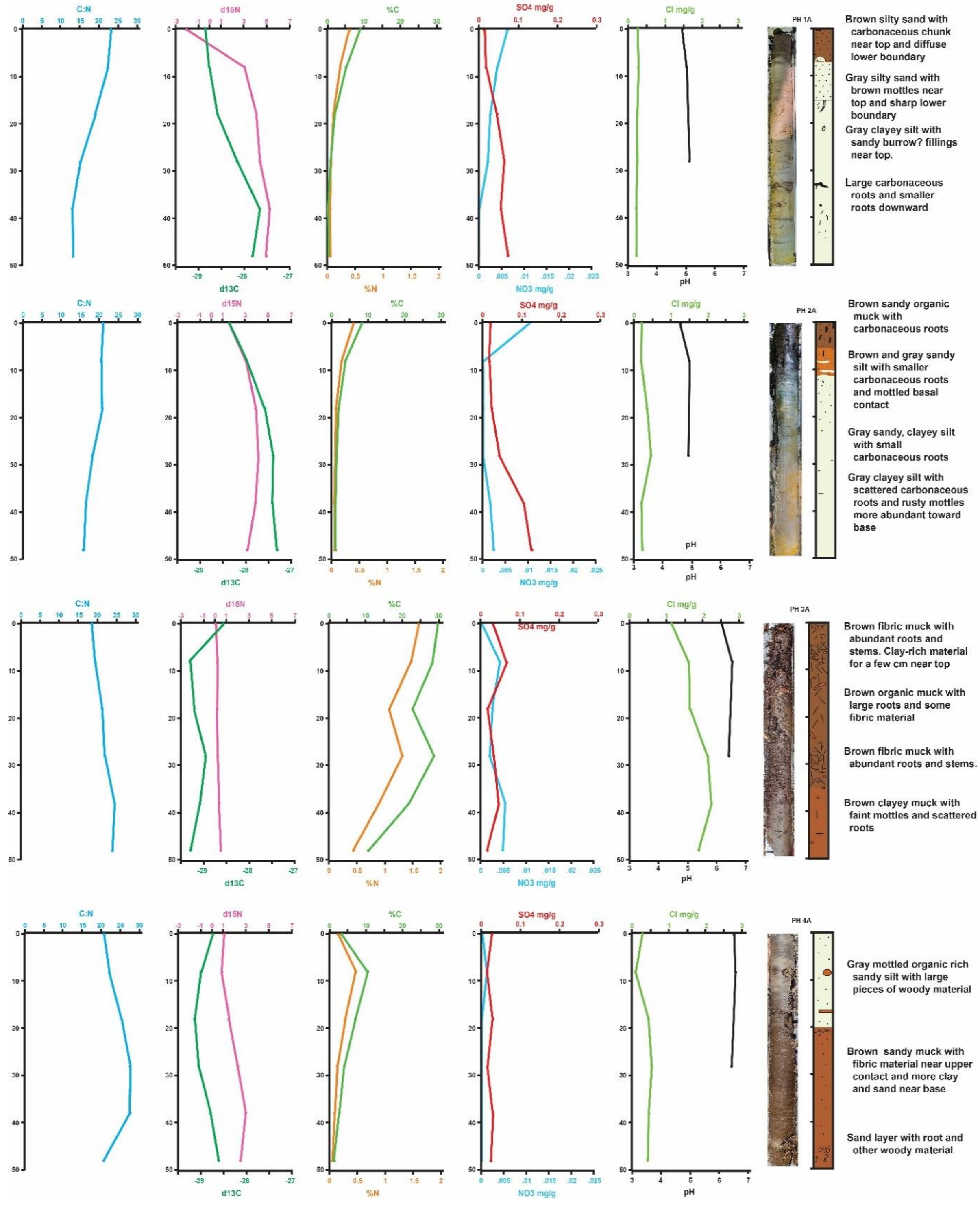

TOWER2
TOWER1
0
0.5
1
2 Kilometers
N

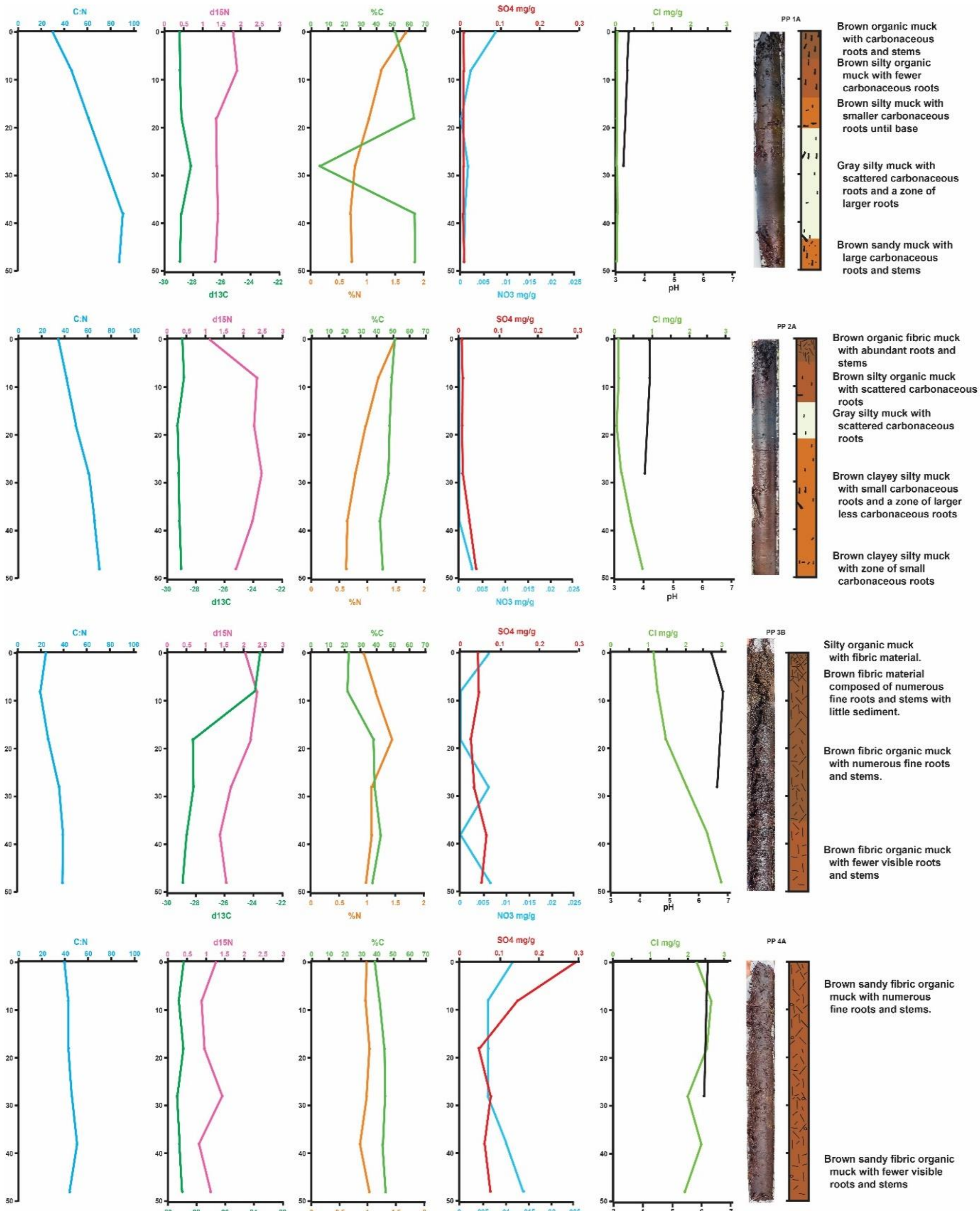
Appendix B

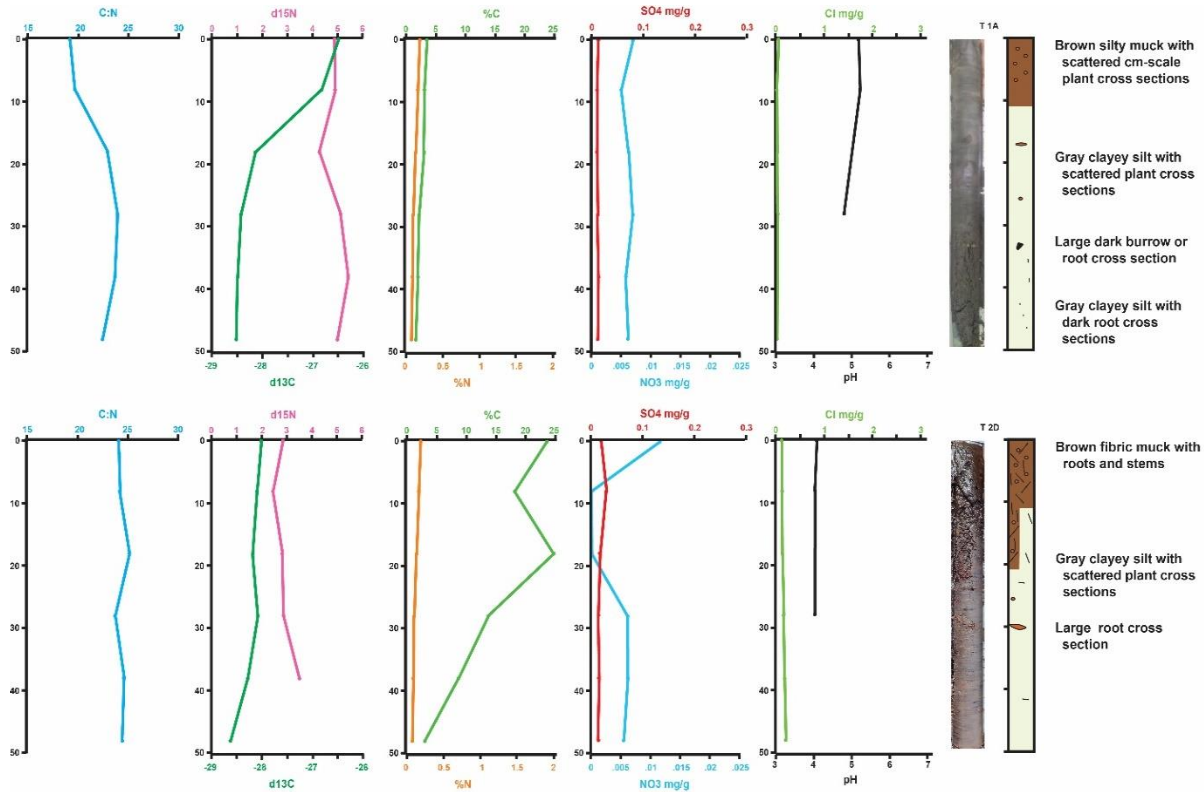
Soil profiles and analyses for each of the five transects Briar Hall (BH), Bull Neck (BN), Pledger Harbor (PH) Point Peter (PP) and TOWeR (T1and T2) are provided below. Each transect displays a photograph of the soil core, a schematic of the soil attributes, a soil description, and analyses with depth. Natural wetland sites include profiles for all four wetland types: 1 (forested wetland) 2 (transitional wetland) 3 (marsh) and 4 (open water). The TOWeR retored wetland transects includes profiles for the dry (T1) and the flooded (T2) sites. The illustration includes analyses of nutrients (horizontal scale) plotted with depth in centimeters (vertical scale), analyses include chloride concentration (Cl^-), sulfate concentration (SO_4^{2-}), pH, nitrate concentration (NO_3^-), percent carbon (% C), percent nitrogen (% N), isotopic ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in parts per thousand, and the ratio of carbon to nitrogen (C/N).


C:N
d15N
d13C
%C
%N
SO4 mg/g
NO3 mg/g
Cl mg/g
pH
BH 1A
Oxidized clayey silt with carbonaceous roots
Reduced clayey silt with mottles and carbonaceous roots
Reduced clayey silt with large carbonaceous roots and smaller, vertical roots. Base is mottled
Gray clayey silt with faint mottles vertical burrows or root casts make porous texture
Compact gray clayey silt with indistinct mottles
BH 2A
Brown fibric muck with abundant plant stems. More clayey silt towards base.
Brown muck with scattered plant stems or roots. More silty fine sand towards base.
Pale brown silty fine sand with vague mottles. Large woody root in center and smaller ones near base.
BH 3A
Brown fibric organic muck with cm-scale stems or roots and mixed finer roots and stems.
Transition with zones or patches of more organic muck within silty, sandy muck
Brown flibric silty, sandy muck with smaller, finer stems and roots. Some larger roots in places.
Large roots and more fibric at base
BH 4B
Brown fibric organic muck with abundant stems and roots. More clayey material toward base.
Brown organic fibric muck with fewer stems and more cm-scale roots or stems


C:N
d15N
d13C
%C
%N
SO4 mg/g
NO3 mg/g
Cl mg/g
pH
BN 1A
Brown fibric organic muck with abundant stem material and more roots toward base
Brown fibric clayey muck with less obvious stems and roots
Brown fibric clayey muck with more abundant stems and roots
BN 2A
Brown fibric muck with abundant roots and stems
Brown clayey muck with less fibric material
Brown clayey muck with more fibric material and larger diameter roots
Brown clayey muck with less fibric material
Brown clayey muck with more fibric material including thicker roots
Brown clayey muck with less fibric material and large diameter roots
Brown clayey muck, less compact and more abundant fibric material
BN 3A
Brown fibric organic muck with numerous fine roots and stems.
Brown fibric organic muck with numerous fine roots and stems and some cm-scale roots
Brown fibric organic muck with fewer visible roots and stems
BN 4A
Fine sand
Brown fibric organic muck with numerous roots and stems.
Brown fibric organic muck with more silty muck


PH 1A
Brown silty sand with carbonaceous chunk near top and diffuse lower boundary
Gray silty sand with brown mottles near top and sharp lower boundary
Gray clayey silt with sandy burrow? fillings near top.
Large carbonaceous roots and smaller roots downward
PH 2A
Brown sandy organic muck with carbonaceous roots
Brown and gray sandy silt with smaller carbonaceous roots and mottled basal contact
Gray sandy, clayey silt with small carbonaceous roots
Gray clayey silt with scattered carbonaceous roots and rusty mottles more abundant toward base
PH 3A
Brown fibric muck with abundant roots and stems. Clay-rich material for a few cm near top
Brown organic muck with large roots and some fibric material
Brown fibric muck with abundant roots and stems.
Brown clayey muck with faint mottles and scattered roots
PH 4A
Gray mottled organic rich sandy silt with large pieces of woody material
Brown sandy muck with fibric material near upper contact and more clay and sand near base
Sand layer with root and other woody material
C:N
d15N
d13C
%C
%N
SO4 mg/g
NO3 mg/g
Cl mg/g
pH


C:N
d15N
d13C
%C
%N
SO4 mg/g
NO3 mg/g
Cl mg/g
pH
PP 1A
Brown organic muck with carbonaceous roots and stems
Brown silty organic muck with fewer carbonaceous roots
Brown silty muck with smaller carbonaceous roots until base
Gray silty muck with scattered carbonaceous roots and a zone of larger roots
Brown sandy muck with large carbonaceous roots and stems
PP 2A
Brown organic fibric muck with abundant roots and stems
Brown silty organic muck with scattered carbonaceous roots
Gray silty muck with scattered carbonaceous roots
Brown clayey silty muck with small carbonaceous roots and a zone of larger less carbonaceous roots
Brown clayey silty muck with zone of small carbonaceous roots
PP 3B
Silty organic muck with fibric material.
Brown fibric material composed of numerous fine roots and stems with little sediment.
Brown fibric organic muck with numerous fine roots and stems.
Brown fibric organic muck with fewer visible roots and stems
PP 4A
Brown sandy fibric organic muck with numerous fine roots and stems.
Brown sandy fibric organic muck with fewer visible roots and stems



C:N
d15N
%C
SO4 mg/g
Cl mg/g
T 1A
Brown silty muck with scattered cm-scale plant cross sections
Gray clayey silt with scattered plant cross sections
Large dark burrow or root cross section
Gray clayey silt with dark root cross sections
d13C
%N
NO3 mg/g
pH
T 2D
Brown fibric muck with roots and stems
Gray clayey silt with scattered plant cross sections
Large root cross section

Appendix C

Excess ^{210}Pb (Xs ^{210}Pb) concentration, ^{137}Cs concentration, and bulk density for each of 18 cores is provided below. Where data is blank, no measure was taken. Where there is BD, measures were taken, but concentration was below detection.

Bull Neck		Forested				Transitional	
Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density	Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	5.31±0.4		0.09	1	12.41±0.4		0.24
3	4.3±0.39	2.81±0.36	0.12	3	14.22±0.45		0.24
5	4.3±0.39	2.8±0.13	0.13	5	14.45±0.45	2.02±0.14	0.27
7	2.76±0.38	2.66±0.16	0.19	7	12.58±0.41		0.25
9	1.97±0.37	2.75±0.25	0.15	9	11.29±0.38	1.82±0.07	0.27
13	0.7±0.35	1.52±0.12	0.19	13	11.43±0.36	3.37±0.15	0.25
17	0.02±0.35	1.49±0.24	0.15	17	9.85±0.34	3.84±0.14	0.26
21	0.2±0.35		0.14	21	8.73±0.31	4.49±0.11	0.31
25	0.74±0.38		0.11	25	8.24±0.3	3.96±0.11	0.3
29	0.14±0.36		0.14	29	5.01±0.21	4.66±0.16	0.28
				31		4.24±0.11	0.25
				33		3.65±0.09	0.24
				35		1.64±0.07	0.23
				41		0.47±0.08	0.23
				45		0.25±0.1	0.19
				47			0.22

		Marsh				Open Water	
Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density	Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	6.27±0.56		0.33	1	0.2±0.03		1.47
3	6.53±0.57		0.36	3	0.31±0.05		2.32
5	6.86±0.58	0.05±0.16	0.44	5	0.01±0.04		2.04
7	6.43±0.58		0.4	7	0±0.04		1.09
9	6.53±0.54		0.37	9	0.01±0.04		1.16
11		0.34±0.18	0.34				
13	7.52±0.55		0.4				
15			0.43				
17	7.97±0.55		0.47				
21		0.09±0.37	0.44				
25	5.53±0.54		0.43				
29	5.75±0.54		0.47				
31		0.4±0.32	0.46				
35		0.05±0.46	0.49				
41		0.34±0.32	0.42				
49		0.12±0.24	0.32				

Pledger Harbor		Forested				Transitional	
Depth	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**	**Depth**	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**
1	2.54±0.11	0.56±0.07	0.4	1	2.94±0.16	0.86±0.08	0.38
3	2.08±0.11	0.63±0.06	0.59	3	1.77±0.13	0.85±0.05	0.63
5	1.76±0.1	0.55±0.06	0.67	5	0.84±0.11	0.7±0.06	0.65
7	0.52±0.09	0.27±0.03	0.75	7	0.6±0.11	0.65±0.05	0.85
9	0.47±0.09	0.22±0.03	0.86	9	0.05±0.09	0.24±0.06	0.99
13	0.04±0.09		0.88				
17	0.06±0.09		1.21				
21	0±0.1		1.37				
		Marsh				**Open Water**	
Depth	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**	**Depth**	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**
1	5.67±0.3	1.38±0.32	0.09	1	0±0.07		0.52
3	3.3±0.27	2±0.21	0.1	3	0±0.1		0.47
5	3.13±0.27	2.67±0.08	0.1	5	0±0.07		0.5
7	2.74±0.27	0.99±0.21	0.11	7	0±0.1		0.46
9		0.37±0.13	0.12	9	0±0.08		0.49
				13	0±0.08		0.55

Briar Hall		**Forested**				**Transitional**	
Depth	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**	**Depth**	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**
1	0.64±0.22	0.3±0.03	0.47	1	4.8±0.19	4.54±0.15	0.11
3	0.5±0.23	0.25±0.02	0.6	3	3.46±0.18	4.05±0.21	0.09
5	0.12±0.22	0.19±0.03	0.65	5	4.11±0.17	3.21±0.38	0.1
7	0.13±0.22		0.67	7	4.11±0.19	2.75±0.29	0.1
9	0.19±0.22	0.38±0.06	0.79	9	3.9±0.15	2.43±0.32	0.13
11	0.09±0.22	0.3±0.06	0.92	11	2.99±0.17	1.56±0.24	0.13
13	0.16±0.22	0.12±0.04	0.97	13	1.66±0.12	0.94±0.15	0.28
15		0.06±0.02	1.18	15	1.24±0.13		0.3
				17	0.75±0.1		0.22

		Marsh				**Open Water**	
Depth	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**	**Depth**	**Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**
1	8.2±0.25	2.61±0.27	0.05	1	0.62±0.07		0.11
3	4.73±0.19	1.89±0.54	0.08	3	0.31±0.1	BD	0.11
5	2.95±0.14	1.65±0.25	0.08	5	0.18±0.07	0.08±0.21	0.12
7	2.63±0.13	0.82±0.24	0.07	7	0.09±0.1	BD	0.12
9	1.12±0.11		0.08	9	0.11±0.08		0.13
13	0.29±0.07		0.1	13	0.01±0.08		0.1
17	0.14±0.06		0.11				
25		0.04±0.09	0.14				

Point Peter

Forested

Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	4.67±0.25	0.82±0.17	0.11
3	4.13±0.23	0.53±0.18	0.14
5	3.56±0.37	0.33±0.13	0.15
7	2.07±0.13		0.16
9	1.1±0.1	0.21±0.11	0.19
11		BD	0.16
13	0.84±0.09		0.17
25	0.4±0.06		0.21
29	0±0.06		0.2

Transitional

Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	5.13±0.25	0.24±0.08	0.05
3	2.69±0.19		0.07
5	2.19±0.17		0.1
7	2.22±0.18	0.1±0.07	0.09
9	1.82±0.19		0.12
11		0.55±0.11	0.12
13	0.53±0.1	0.43±0.1	0.15
17	0.61±0.08		0.16
21	0.19±0.15		0.19

Marsh

Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	6.08±0.19		0.13
3	4.94±0.16	0.94±0.12	0.2
5	6.83±0.21	0.81±0.17	0.21
7	7.12±0.22	1.4±0.06	0.15
9	6.59±0.21	2.74±0.2	0.18
11		10.23±0.33	0.17
13	5.08±0.19	5.83±0.19	0.16
15		1.59±0.09	0.16
17	2.88±0.13		0.14
21	0.22±0.11		0.12
25	0±0.1		0.12

Open Water

Depth	Xs ^{210}Pb (dpm/g)	^{137}Cs (dpm/g)	Bulk Density
1	0.25±0.04		0.09
3	0.22±0.09		0.1
5	0.2±0.09		0.12
7	0.08±0.13	BD	0.11
9	0.09±0.07	0.13±0.13	0.11
13	0.05±0.09	BD	0.12
17	0±0.08		0.1

TOWeR Depth	**Dry Restored Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**	**Depth**	**Flooded Restored Xs ^{210}Pb (dpm/g)**	**^{137}Cs (dpm/g)**	**Bulk Density**
1	2.2±0.15	0.26±0.09	0.5	1	4.65±0.26		0.32
3	1.8±0.17		0.77	3	2.99±0.24		0.47
5	1.69±0.16	0.25±0.06	0.99	5	2.96±0.25		0.56
7	1.52±0.19		0.93	7	2.41±0.24		0.65
9	1.25±0.16	0.35±0.05	0.98	9		1.05±0.11	0.69
11		0.4±0.04	1.07	11		1±0.11	0.54
13	0.74±0.14	0.39±0.03	1.14	13	1.58±0.23	1.11±0.08	0.47
15			1.19	15		0.75±0.14	0.49
17	0.62±0.14	0.29±0.05	1.21	17	1.2±0.24	0.6±0.08	0.48
19		0.28±0.03	1.21	19		0.47±0.06	0.49
21	0.29±0.13		1.21	21	0.8±0.24	0.17±0.07	0.48