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Impacts of Land-Use Change on Sedimentation in Tidal Creeks of North Carolina, USA

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Abstract

Tidal creeks act as a gateway between uplands and marshes to estuaries and larger coastal waters. These smaller water bodies are influenced by freshwater flows running off the landscape and the constant ebb and flow of the salty ocean. These ecosystems are important habitat, act as an initial "filter" of water from the landscape to the ocean and as a buffer to storm surge inundation. The physical and biological dynamics of this ecosystem are intricately connected. Changes that occur at that landward (e.g., stormwater runoff, shoreline hardening, land clearing) and seaward (e.g., trawling, sea level change) ends of this system may alter the resilience of these habitats in the future.Changes in shoreline and land-use were coupled with tracers of the sedimentary record from three tidal creek systems (Oyster, Broad, and Hawkins Creek) of central coastal North Carolinato provide valuable data relevant to the management of coastal systems. There was a clear difference in development across the systems, highest in Hawkins and lowest in Oyster Creeks. Shoreline change rates were highly erosive in Hawkins Creek, with little change in the other basins. Sediment accumulation rates in all tidal creeks exceed that of relative sea level rise, leading to a slow infilling of the tidal basins. Organic matter tracers suggest some minor increases in organic carbon and nitrogen storage, particularly in the heads of the creeks, but no large fluctuations in the source of material being deposited over decadal timescales.Finally, the timing of the measured change in accumulation rates in Oyster and Broad Creeks may be related to development of the surrounding region.

Keywords: Land-use change; Primary nursery designation; sedimentation; Tidal creek; North Carolina; organic matter

1. Introduction

Estuarine systems are among the most productive and dynamic ecosystems on earth. Coastal and estuarine watersheds currently support 75% of the world's population and are still rapidly being developed (Paerl, 2006; Street et al., 2005). In North Carolina (NC) coastal plain counties, there has been a population increase of 32% from 1977 to 1997 and 16% from 1990-2000 (Street et al., 2005; Mallin et al., 2000). The growth in coastal areas has increased the anthropogenic effects on these systems, including the degradation of many water bodies due to increased amounts of land-based nutrients and other pollutants like heavy and trace metals, wastewater, herbicides, and pesticides (Paerl, 2006; Buzzelli et al., 2001; Hyland et al., 2000; Pearl et al., 1998; Phillips, 1997; Riggs et al., 1991; Schropp et al., 1990). Water quality was first addressed as a national problem in the 1970s with the passage of the Water Quality Pollution Control Act and the Clean Water Act (USEPA, 2006). In more recent legislation, a National Sediment Quality Survey (NSQS) was established to assess sediment chemistry, tissue residue, and toxicity in order to develop methods and protocols for the classification of contaminated sediments (USEPA, 2004).

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The United States Environmental Protection Agency (USEPA) required that the NSQS compile all existing data on sediment quality, chemistry, physical composition, geographic location and possible sources of pollutants, especially to identify contaminated sediments that pose a threat to human health or the environment (USEPA, 2004). A 1998 publication by the NSQS found that "there is contaminated sediment in all regions and every state" and "streams, lakes, harbors, near-shore areas, and oceans … have been impacted by heavy shipping traffic, contamination from upstream sources, and local municipal and industrial discharges" (USEPA, 2006). In the shallow coastal tributaries and estuaries, there is continuous exchange and deposition of particle-reactive organic materials between the water column and bed sediment (Giffin and Corbett, 2003). Because of this, there is a need to study the sediment dynamics of these systemsif we are to better understand their function as sediment sources or sinks, as well as their sedimentological characteristics.

Tributary creeks and sub-estuarine areas are often an important source for freshwater and organic matter input toan estuary or coastal system (Cooper et al., 2004; Lerberg et al., 2000). Many tributaries along the NCcoast also function as primary nursery areas for the commercial and recreational fishing industries (Street et al., 2005). The coastal and estuarine waters of North Carolina support extensive shellfish populations including, blue crab, northern quahog, eastern oyster, and shrimp fisheries (Mallin et al., 2000; Paerl et al., 1998). In North Carolina, estuarine waters currently support 90% of commercial harvest and 60% of recreational landings of fish with a ranking of fifth and second for commercial and recreation fishing along the Atlantic coast, respectively (Street et al., 2005).

Tidal creeks act as a gateway between uplands and marshes to estuaries and larger coastal waters. These smaller water bodies are influenced by freshwater flows running off the landscape and the constant ebb and flow of the salty ocean(Holland and Sanger, 2008). The upland areas of these watersheds are often popular locations for development due to the adjacent coastal landscape.These ecosystems are important habitat for commercial and recreation fishes, including seatrout, crevalle jack, flounder, spadefish, spot, black drum, blue crab, brown shrimp and white shrimp(Hackney et al., 1976; Shenker and Dean, 1979; Beck et al. 2001; Kneib, 1997). In addition, these creeks act as an initial "filter" of water from the landscape to the ocean and act as a buffer to storm surge inundation. The physical and biological dynamics of these ecosystem are intricately connected. Changes that occur at that landward (e.g., stormwater runoff, shoreline hardening, land clearing) and seaward (e.g., trawling, sea level change) ends of this system may alter the resilience of these habitats in the future. Rapid economic development and associated land-use change in these coastal areas can potentially increase point and nonpoint source pollution loading into these tidal creeks and nearby estuaries, influencing productivity, biodiversity and ecological functioning of these systems (Vitousek et al. 1997).Much of the previous research on tidal creek systems has focused primarily on freshwater discharge, water quality, macrobenthic communities, and the biodiversity (Webster et al., 2013; Corbett et al., 2007; Corbett et al., 2009; Gleeson et al.,2013; Voulgaris et al., 2004; Sanger et al.,2015; Washbum et al., 2011; DiDonato et al.,2009; Sanger et al., 2008). There has been much less focus on the response of sediment dynamics associated with land-use change, particularly development, in these critical coastal ecosystems.

Therefore, tobetter understand the changes currently occurring within NC tidal creeks and the drivers leading to these changes, this study was developed and designed to provide some preliminary data to further our understanding of sedimentation in tidal creeks. The working hypothesis of this study is that tidal creeks within a developed catchment will have an increased sediment accumulation rate and sediments indicative of upland erosion, whereasa "control" creek will have little change in sediment accumulation rate with sediments representative of local shoreline erosion. The objective of this study was to elucidatepotential impacts of land-use change on the sedimentation of three tidal creeks in North Carolina by: (1) measuring land use and shoreline change during recent decades; (2) calculating the rate of sediment accumulation via ^{210}Pb and ^{137}Cs and changes in sediment character (e.g. grain size, %C, %N, C:N, ^{13}C, and ^{15}N)at each site; and (3) evaluating the influence of land-use change to the sedimentation and sediment character of each tidal creek.

2. Study Area

2.1 Geologic Setting

The North Carolina coastal plain is comprised of marine terraces and paleoshorelines that lie roughly parallel to the modern shoreline. These units are a mixture of transgressive and regressive sequences that have been preserved in the landscape due to sea level fluctuations (Riggs and Ames, 2003; Phillips, 1992). The terraces and scarps that make up the lower coastal plain are the Pamlico Terrace (sea level to 6 m), Suffolk Scarp, Talbot Terrace (between 6 and 14 m), Walterboro Scarp, Wicomico Terrace (between 14 and 29 m), and is bounded on the west by the Surry Scarp (Phillips, 1992). The coastal zone of North Carolina is controlled by the underlying, inherited geology that separates the coast into distinct northern and southern provinces (Riggs and Ames, 2003; Riggs et al., 1995). The northern province, Cape Lookout to the Virginia border, is underlain by sediments dating from the Cretaceous (5.3 to 1.8 MY in age) and younger. One of the resultant features of this areas geology is deeply embayed estuaries with gentle slopes (Riggs and Ames, 2003). The Southern zone (south of Cape Lookout to the South Carolina border) is underlain by older geologic units (e.g., Cretaceous throughMiocene in age) and is characterized by a relatively steep land slope compared to the Northern zone.

The sediments found in typical coastal plain terraces and scarps are highly weathered sands and clays with very little labile material or minerals (Phillips, 1992). These sediments are classified as low erosion sediments due to their high infiltration capacity, low slopes, and the relatively low sediment yields seen in the coastal plain when compared to Piedmont sediment properties (Phillips, 1997, 1992). The floodplains adjacent to the coastal water bodies are broad areas that are frequently inundated and are important for sediment trapping (Langland and Cronin, 2003; Phillips, 1997).

2.2 Study Sites

The intent of this study was to select three tidal creeks based on variations in land-use change (Figure 1-4). Three creeks were chosen with significant variations in development, but no difference in nursery designation (i.e., all are considered Primary Nurseries and do not allow trawling operations): Oyster Creek, Broad Creek, and Hawkins Creek. Oyster Creek is north of Cape Lookout, off of Core Sound. This creek is surrounded by wetland with little development of the watershed or shoreline, but has a significant agricultural area just outside the watershed to the north and west (i.e., Open Ground Farms). Broad Creek is a large watershed with some development in the watershed and shoreline. Hawkins Creek is a small watershed with significant development within the watershed. Local residents around Hawkins Creek have noted changes within the basin, including significant infilling.

3. Background

3.1 Radionuclide Measurements in Recent Sediments

Several radionuclides, with varying half-lives, can be used to provide a chronology for sediment deposition/accumulation rates and to examine the extent of sediment reworking. The radionuclides used in this study include: ^{210}Pb and^{137}Cs.Lead-210 is a naturally occurring radioisotope that is part of the ^{238}U decay series, often used for age dating of sediments (Krishnaswamy et al., 1971; Ravichandran et al., 1995a; Patchineelam et al., 1999; Lewis et al., 2002). A disequilibrium occurs between ^{210}Pb and its parent isotope, ^{226}Ra ($t_{1/2}$ = 1602 years), by diffusion of ^{222}Rn ($t_{1/2}$ = 3.84 days). Some of the ^{222}Rn atoms that are formed by the decay of ^{226}Ra in soils diffuse into the atmosphere, eventually decaying to ^{210}Pb. The ^{210}Pb is removed from the atmosphere by precipitation or dry deposition,where it can be adsorbed

Figure 1. Three tidal creeks in eastern North Carolina, USA, were chosen as part of this study.

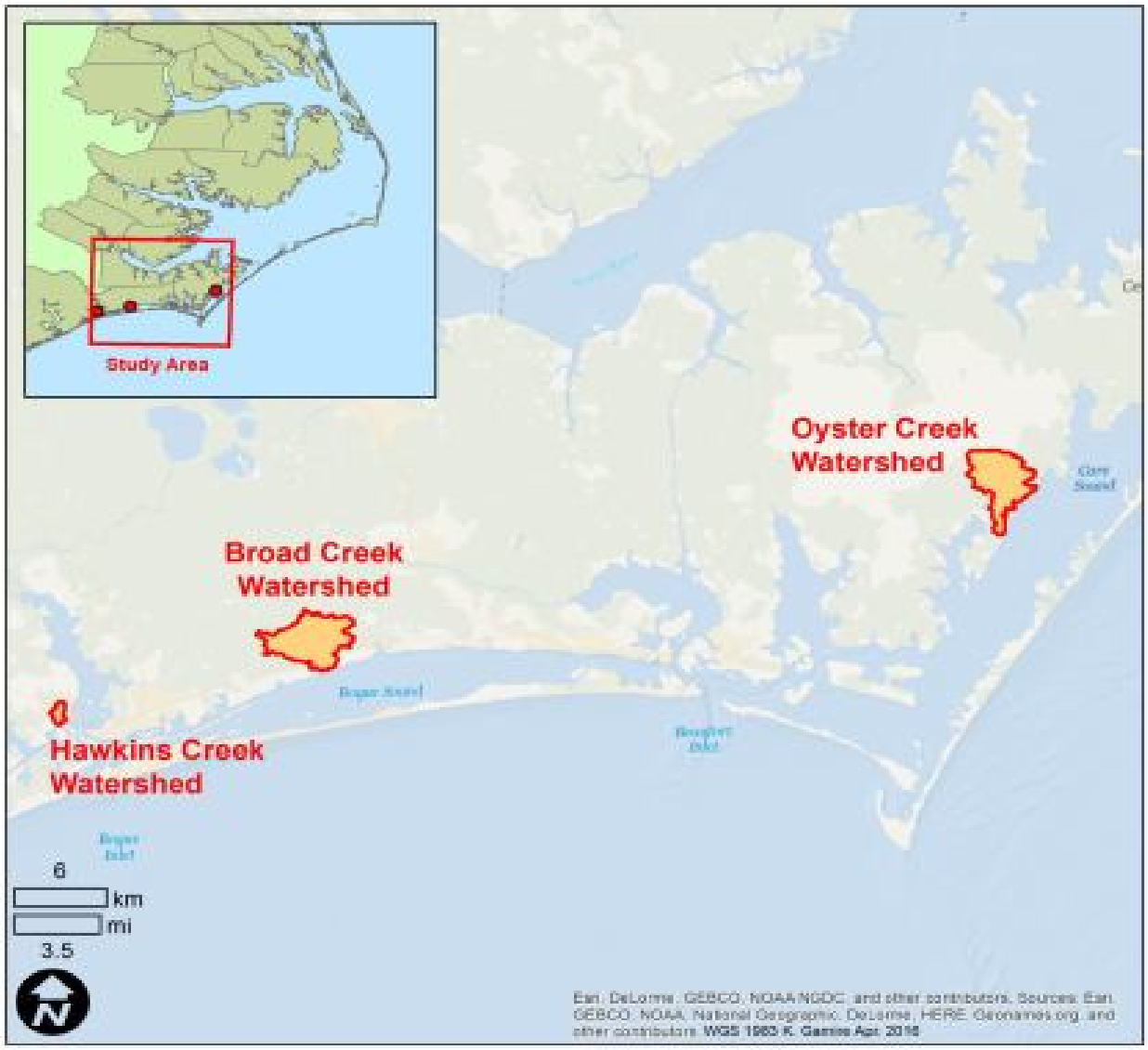


Figure 2. Oyster Creek watershed and sample locations. Shoreline change rates (1993-2012) were calculated at 50m spacing along the shoreline. Land-use and land-use change data are from NOAAC-CAP (https://coast.noaa.gov/dataregistry/earch/collection/info/ccapregional).

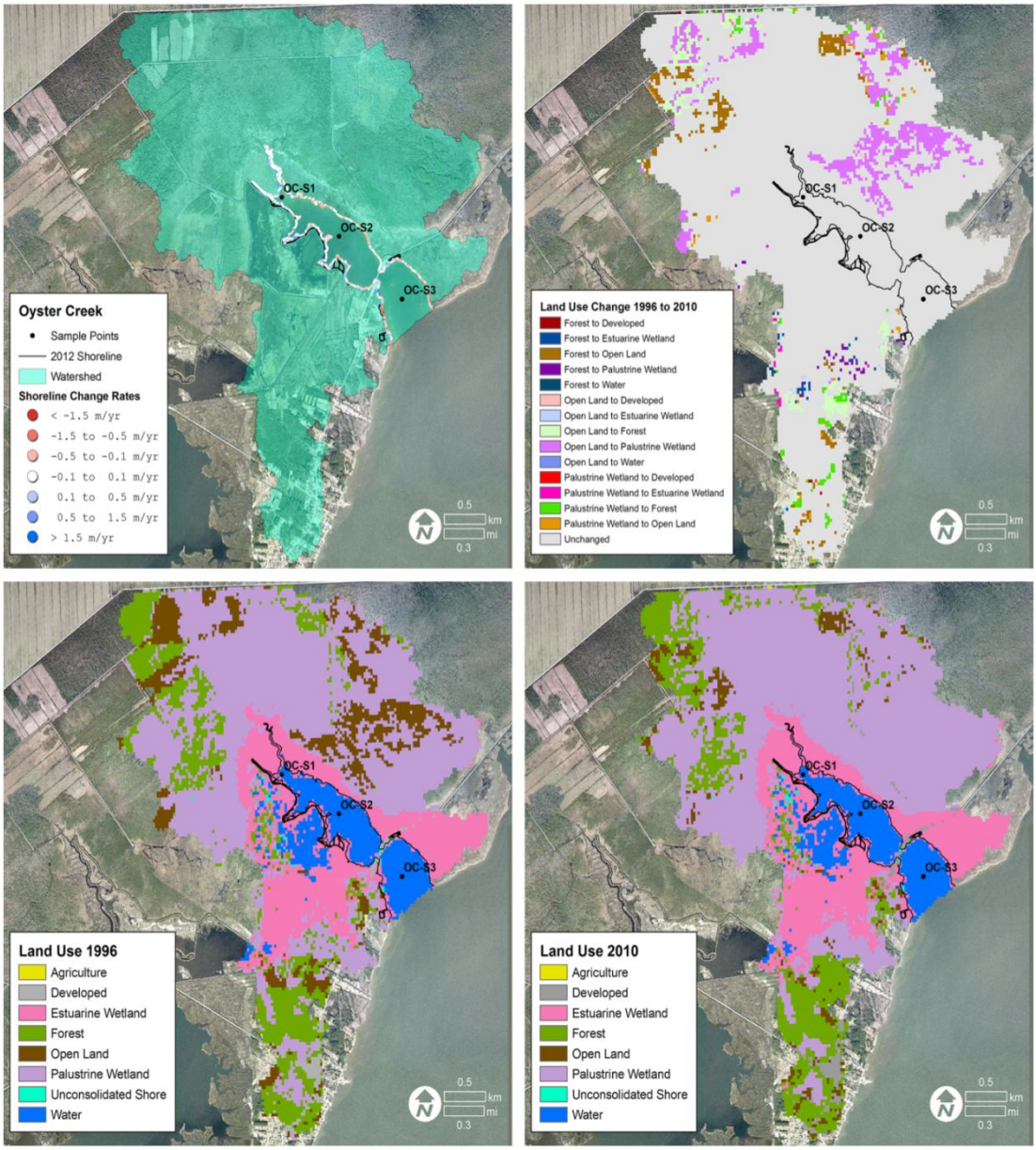


Figure 3. Broad Creek watershed and sample locations. Shoreline change rates (1993-2012) were calculated at 50m spacing along the shoreline. Land-use and land-use change data are from NOAA C-CAP (https: / / coast.noaa.gov / dataregistry / search / collection / info / ccapregional).

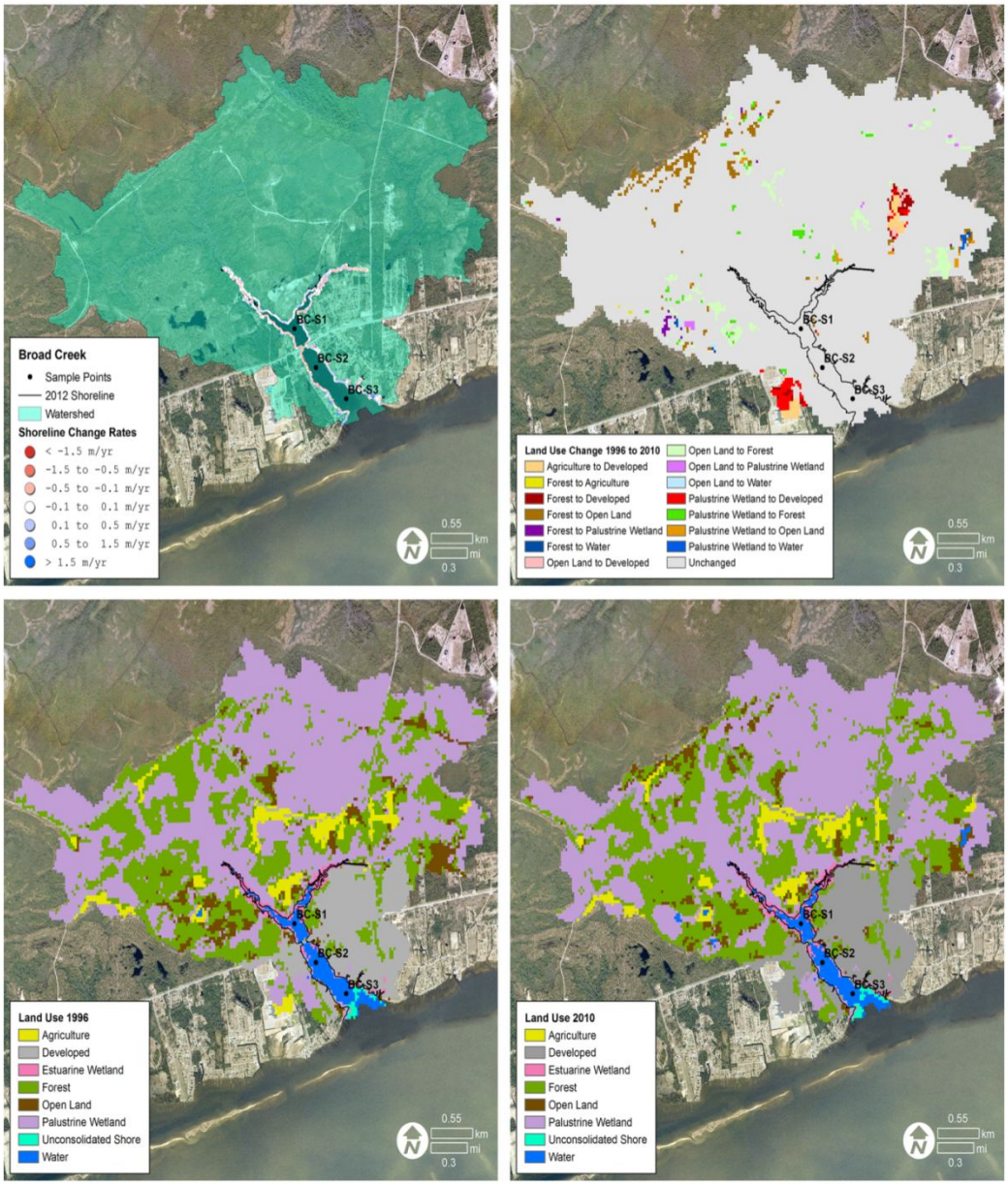
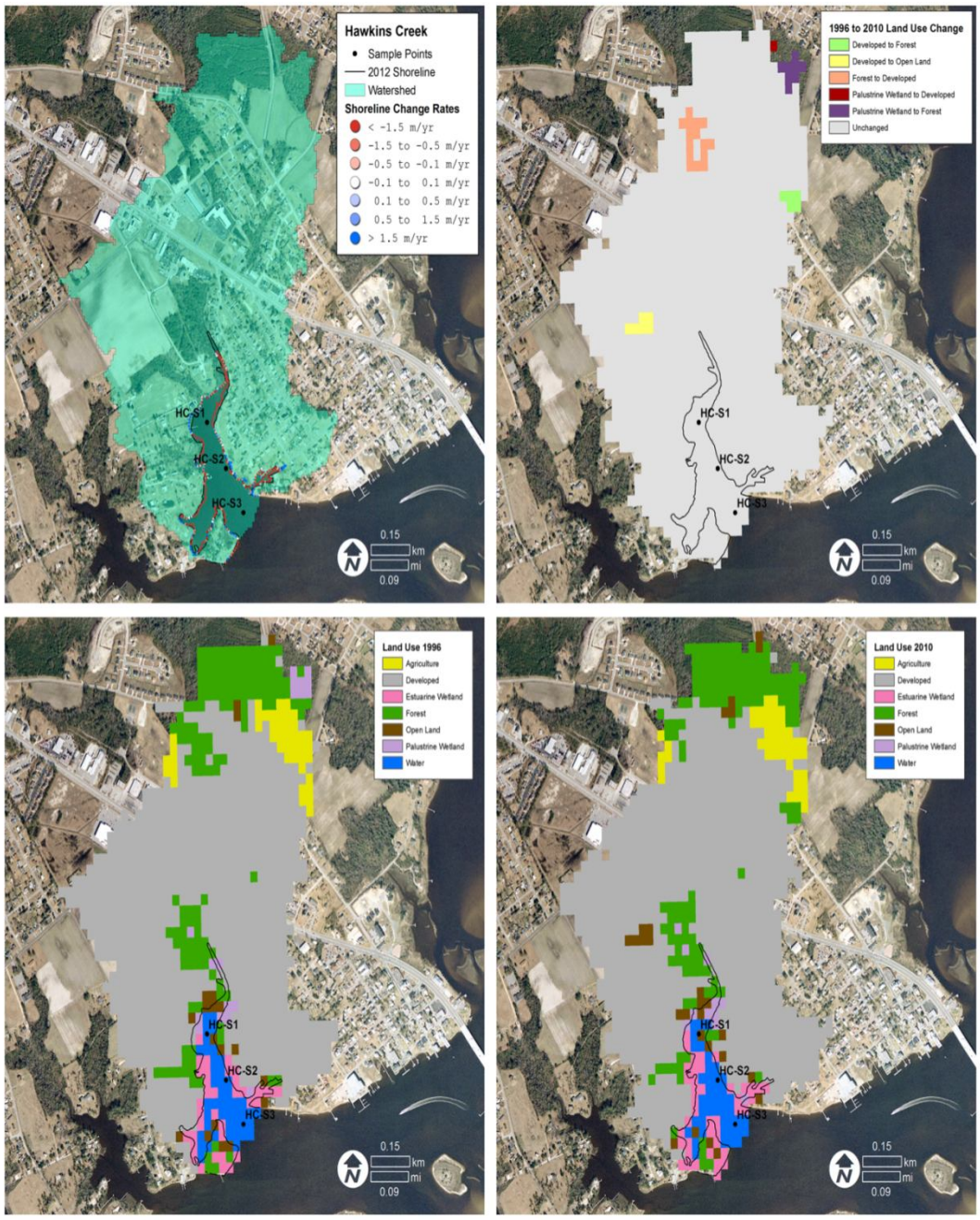


Figure 4. Hawkins Creek watershed and sample locations. Shoreline change rates (2010-2012) were calculated at 50m spacing along the shoreline. Land-use and land-use change data are from NOAA C-CAP (https://coast.noaa.gov/dataregistry/search/collection/info/ccapregional).



onto sediments in water bodies (Appleby and Oldfield, 1992). By subtracting the ^{210}Pb activity supported by ^{226}Ra from the total ^{210}Pb, excess ^{210}Pb (or unsupported ^{210}Pb) activity can be determined. A half-life of 22.3 years allows ^{210}Pb to be used for dating sediments up to approximately 120 years of age.Cesium-137 is an anthropogenic radionuclide that is a by-product of fission reactions. Atmospheric ^{137}Cs ($t_{1/2}$ = 30.1 years) derived from nuclear weapons testing was first detectible in 1953, with the maximum fallout occurring in 1963 in the northern hemisphere (Chumura and Kosters, 1994).

This provides the possibility of two dated horizons, one reflecting the initial early 1950s increase and the other the 1963 peak in ^{137}Cs fallout. This allows ^{137}Cs to be a viable stratigraphic marker in lake, marsh, and estuarine sediments (Pennington et al., 1973; Chmura and Kosters, 1994; Nyman et al., 1995; Cearreta et al., 2000; Donnelly et al., 2001a, b; Neubauer et al., 2002). Three assumptions must be made when using ^{137}Cs in the measurement of sediment accumulation in aquatic systems: 1) the ^{137}Cs entering the water body is quickly adsorbed to suspended material in the water column; 2) in cases where radiocesium is deposited in the catchment area of a water body, the radionuclide is firmly adsorbed on soil particles and any redistribution results chiefly from erosion and deposition; and3) once deposited in the sediment column the radionuclide is immobile and not affected by reworking or diffusional movement up or down in the substrate (Hutchinson, 1995).

3.2 Carbon and Nitrogen Stable Isotopes and C:N Ratios

The differences that exist among natural abundances of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes and atomic ratios of carbon to nitrogen in organic matter derived from different sources (i.e., terrestrial, anthropogenic, marine, etc.) make them valuable geochemical tracers (Matson and Brinson, 1990). When using stable isotopes in this manner, it is assumed that the isotopic distributions of organic matter are based on conservative isotopic ratios determined by physical mixing of end-member sources (Cifuentes et al., 1988). The isotopic value of carbon ($\delta^{13}C$ in ‰) is determined by

$$\text{Eq. 1} \qquad \delta^{13}C \text{ or } \delta^{15}N\ (‰) = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000$$

where R is the atomic $^{45}CO_2/^{44}CO_2$ ratio and the standard is carbonate from Belemnitellaamericana from the Cretaceous Peedee Formation of South Carolina (Smith and Epstein, 1971). Similarly, the isotopic composition of nitrogen ($\delta^{15}N$ in ‰) in a sample is expressed in Eq. 1, where R is the atomic $^{15}N/^{14}N$ ratio and the standard is atmospheric N_2 (Heaton, 1986; Thornton and McManus, 1994).Organic carbon can display a wide range of $\delta^{13}C$ values depending on the source of the organic matter.

Materials enriched in ^{13}C relative to ^{12}C are isotopically heavy and have more positive $\delta^{13}C$ values, while materials depleted in ^{13}C relative to ^{12}C are isotopically light, and have more negative $\delta^{13}C$ signatures. Variations in the $\delta^{13}C$ signatures for terrestrial and marine plant matter are related to the mechanism of CO_2 fixation used by the flora during photosynthesis (C_3 vs. C_4 photosynthetic pathway). Terrestrial plants tend to employ the Calvin-Benson (C_3) pathway, which produces an average $\delta^{13}C$ value of -27‰. The Hatch-Slack (C_4) pathway is used by many grasses and salt marsh plants and produces an average $\delta^{13}C$ value of -13‰ (Smith and Epstein, 1971; Waller and Lewis, 1979; Sherr, 1982; Benninger and Martens, 1983; Nordt et al., 1994; Hedges et al., 1997; Letrick, 2003). Studies have shown that the isotopic signature of carbon is not susceptible to significant alteration following deposition (Sherr, 1982; Nordt et al., 1994; Freudenthal et al., 2001; Letrick, 2003).Similarly, isotopic nitrogen ($\delta^{15}N$) values can be indicative of the biogeochemical cycling of nitrogen in estuarine sediments. Multiple processes occurring in the water column and sediments including ammonification, nutrient assimilation, nitrification, and denitrification, function to enrich the substrate in ^{15}N (Owens, 1987; Thornton and McManus, 1994). This enrichment is due to a preferential removal of the lighter ^{14}N relative to ^{15}N during organic matter degradation and assimilation processes. This is evidenced by food web observations which show greater enrichment at higher trophic levels (Freudenthal et al., 2001). Generally, $\delta^{15}N$ values for terrestrial nitrogen compounds range from -15 to +20‰ (Heaton, 1986). Salt marsh peats tend to have values ranging from -3 to 2‰. $\delta^{15}N$ values derived from anthropogenic activity tend to vary with the source. For example, nitrate from sewage and animal wastes tends to be highly positive, while nitrate and ammonia from fertilizers has a $\delta^{15}N$ signature near zero ‰.

As with $\delta^{13}C$ and $\delta^{15}N$, the molecular ratio of carbon to nitrogen is unique for many different types of organic matter. Generally, terrestrially-derived organic matter will have higher C:N ratios (12 or greater) than that of marine organic matter sources (10 or less) (Maksymowska et al., 2000). Much like $\delta^{15}N$, C:N ratios are subject to great alteration by degradation processes during transport. The majority of the time nitrogen will be removed preferentially to carbon, increasing the C:N ratio.

Comparisons between suspended organic matter C:N ratios and surface sediment C:N ratios invariably show that surface sediments have higher C:N ratios (Andrews et al., 1998; Middelburg and Nieuwenhuize, 1998). After sediment deposition, alteration of the C:N ratio can continue. The greatest alteration in C:N ratios often occurs in coarser sediments where bacteria can more readily degrade the particulate organic matter. A good correlation between C:N ratios and $\delta^{15}N$ values yields evidence that support a granulometric control over sediment diagenetic processes (Thornton and McManus, 1994).

4. Field Sampling and Analytical Methods

4.1 Sample Collection

Three stations in each tidal creek were occupied on January 6-7, 2016 starting near the creak head to the mouth. Two cores, one for geochemical analysis and the other for X-radiography, were collected at each site using a 10.2 cm (4-inch) direct push core sampler. Cores were primarily collected along their central axis of each tidal creek (Table 1). Cores OC-S1, OC-S2 and OC-S3 from the Oyster creekwatershed (Figure 1 and 2)were collectedin water depthsfrom0.8-1.8m. Broad Creek cores, BC-S1, BC-S2 and BC-S3,were collected in water depths of 1.0-1.3m (Figure 1 and 3). Finally, cores HC-S1, HC-S2 and HC-S3 from Hawkins Creek watershed in the south were collected indepths of 0.7-1.1m (Figure 1 and 4). Cores ranged in length from ~20 cm to 40 cm.Coresfor geochemical analysis were sectioned immediately into 2 cm intervals for the length of the core.Samples were returned to the laboratory and prepared for analysis. Cores collected for X-radiography were labeled, packed with foam discs and paper towels to preserve the sediment-water interface, and wrapped with plastic cellophane for transport to the laboratory. A PaxScan 4030R digital X-ray system was used to capture the images with VIVA software.

4.2 Grain-Size Analysis

Grain-size analyses were typically performed on sample intervals where porosity vials were collected. Hydrogen peroxide (30%) was added to ~5-15 g of relatively shell-free, wet sediment and allowed to sit for several days to remove all organic matter. The sediments were then transferred into 50 ml centrifuge tubes.

Table 1 Location of the sample site in Oyster, Hawkins and Broad Creek.

Site	Longitude(W)	Latitude(N)	Water depth (m)	Salinity
Oyster Creek				
OC-S1	76.46348°	34.82747°	0.8	35
OC-S2	76.45605°	34.82348°	1.1	35
OC-S3	76.44791°	34.81715°	1.8	35
Broad Creek				
BC-S1	76.94702°	34.72500°	1.0	32
BC-S2	76.94402°	34.72099°	1.3	34
BC-S3	76.93971°	34.71772°	1.2	34
Hawkins Creek				
HC-S1	77.12785°	34.68743°	0.7	33
HC-S2	77.12708°	34.68613°	0.7	33
HC-S3	77.12637°	34.68488°	1.1	33

The tubes were spun at 4000 rpm for 20 minutes and then any remaining peroxide and excess water decanted. The sediments in the tubes were stirred and about 20 ml of water was added to wash the sediments before they were centrifuged again at 4000 rpm for 20 minutes. The fluid was decanted and a mixture of the surfactant sodium hexametaphosphate (calgon) and water (0.6 g calgon/liter DI water) was added to the sediments to prevent flocculation of any clays. The calgon solution was added in an approximately equal volume as the quantity of sediment contained in the tubes. The samples were then shaken and remained in the solution for at least 24 hours prior to analysis.The sample grain-size distribution and median grain-size were determined on a Coulter LS 230 grain-size analyzer in the ECU sedimentology lab.

The instrument consists largely of 4 units: the optical module (houses the laser), the fluid module (sample well and sonicator), a 30 cell autosampler, and a computer. The LS 230 has the capability to measure particles in suspension from 0.4 to 2000 micrometers (μm) in size. A very small volume of sample (~3-6 drops) was loaded into a glass vial with an eyedropper, which was then inserted in the autosampler. The sample was emptied into the fluid module and sonicated. The optical module laser emitted a light with a wavelength of 750 nanometers (nm) into the sample cell, where particles suspended in the liquid diffracted the incident light in characteristic patterns dependent on their sizes. Values were averaged over the duration of the measurement, resulting in the true particle size distribution of the sample (Coulter Corporation, 1994). The percentage of light scattered out of the beam by the particles (obscuration) needed to be between 8 and 12% for a run to be considered valid. Either increasing or decreasing the sample volume was necessary to achieve values within this range.

4.3 Radionuclide Analysis

The potential of establishing a geochronology was evaluated by using short-lived radioisotopes including ^{210}Pb ($t_{1/2}$ = 22.3 years) and ^{137}Cs ($t_{1/2}$ = 30.1 years). The activities of ^{137}Cs was determined by direct gamma counting, while ^{210}Pb activities were obtained indirectly via alpha spectrometry counting of its granddaughter radionuclide ^{210}Po.For gamma spectrometry, a small volume of homogenized dried sediment was packed into petri dishes (~10-15 grams) or vials (~4-9 grams), prior to analysis. The packed vessels were then counted one of several high-resolution, low-background, high-purity germanium detector, coupled with a multi-channel analyzer. The detectors are calibrated regularly against a number of natural matrix standards (IAEA-300, 312, and 314) at different energies of interest. Samples were counted for ~24 hours.^{210}Pb activity was counted using alpha spectrometry to determine decadal accumulation rates. Samples (1-1.5 grams) were spiked with a yield determinate (^{209}Po) and partially digested in 8 N HNO_3 by microwave heating (method modified from Nittrouer et al., 1979). The $^{210,209}Po$ from the sample residues were electrodeposited onto nickel plated discs (modified from Flynn, 1968). The discs were then counted for >24 hours in an Ortec EG&G Octete Plus, eight channel alpha spectrometer.

Radionuclide activity is reported in dpm/g. Excess ^{210}Pb activities were determined by subtracting the supported ^{210}Pb, assumed to be the constant activity down core, from the total ^{210}Pb activity.A number of different models are used in trying to interpret downcore excess ^{210}Pb data. For this study, the sediment accumulation rate was calculated using the constant flux constant sedimentation model (CF:CS). This was done by applying a least-squares linear regression to the natural log of the ^{210}Pb activity. The slope of the regression divided by the ^{210}Pb decay constant (0.3108 yr^{-1}) gave the steady state accumulation rate in cm yr^{-1}. Similarly, mass accumulation rates (g $cm^{-2}yr^{-1}$) were calculated by a regression of the natural log of excess ^{210}Pb with increasing cumulative sediment mass (Corbett and Walsh, 2015).

4.4 Carbon / Nitrogen Stable Isotope and C:N Ratio Analysis

Sediment samples were analyzed for $\delta^{13}C$ and $\delta^{15}N$ stable isotopic ratios, organic carbon content, and nitrogen content by the Stable Isotope Laboratory at the University of California at Davis. Prior to sending samples to UC-Davis, the sediments were prepared by the acid fumigation method described in Harris et al. (2001). This procedure was necessary to remove any inorganic carbon that might otherwise lead to erroneous $\delta^{13}C$ values. This method involves an initial calculation of total carbon content in each sample, to ensure that the amount of carbon in the sample was within the acceptable working range for their instrument (800-1200 ug C). To obtain the correct sample weight for the procedure, it was assumed that total carbon content equaled 40% of the loss on ignition (Harris et al., 2001). The necessary amount of sample was carefully weighed into 8 X 5 mm silver capsules, with the capsules then placed in a 96 well microtitre plate. The samples were wetted with 50 ul of deionized (DI) water. The microtitre plate was then placed in a 5-liter desiccator along with a 150 ml beaker containing 100 ml of 12.1 M HCl for 6 hours. After the fumigation process was complete, the capsules were oven dried at 60°C until the sediments were dry. The capsules were then placed in a crimper plate, closed, and shipped to UC-Davis for analysis. The samples were analyzed on a Europa Hydra 20/20 continuous flow mass spectrometer following combustion at 1000°C in a Europa ANCA-GSL CN analyzer (Harris et al., 2001). Standard gases injected into the mass spectrometer before and after sample peaks allowed $\delta^{13}C$ (expressed relative to Vienna-Pee Dee Belemnite) and $\delta^{15}N$ (expressed relative to atmospheric N_2) values to be calculated.The precision of duplicate analyses was 0.2‰ for stable carbon isotopic composition.

4.5 Landuse and Shoreline Change Data Collection and Analysis

All aerial imagery was georeferenced and the shoreline digitized to evaluate shoreline change over time (Geis and Bendell, 2008). Previously digitized shoreline shapefiles from 2012 imagery were obtained from the NC Division of Coastal Management (http://portal.ncdenr.org/web/cm/).Additional aerial imagery (i.e., 1993)was obtained from the Carteret County Tax Office. Georeferencing required between seven and nineteen ground control points in a second-order polynomial transformation in Esri ArcMap to reference the image to a known coordinate system (Cowart et al., 2010, 2011). Once georeferenced, a zoom tolerance of between 1:300 and 1:1000 was utilized for heads-up shoreline digitization. The digitization process involved tracing the vegetated edge of the shoreline or the wet/dry line within the aerial image (Geis and Bendell, 2008; Cowart et al, 2010, 2011). The AMBUR package is a function-based program that uses scripts within the R software program to analyze moving boundaries (e.g., shoreline change) (Jackson et al., 2012). Shoreline shapefiles for the years of 1993 and 2012 were clipped in ArcGIS to encompass the same coverage area, and merged together into one shapefile. Within AMBUR, the focus area was selected and outer and inner baselines were created. Transects were cast 50 m apart and with a 500 m length, to analyze the shoreline envelope. Additional filtering of transects was completed to reduce poorly cast transects (e.g., not shore-perpendicular or intersecting other transects), and shoreline capture points were created for analysis. The placement of capture points accounted for changes in shoreline position for each time-step, and the end-point rate result was used to evaluate shoreline change rates (i.e., SCR) (Jackson, 2010 and Jackson et al., 2012).

5. Results

5.1 Land use and shoreline change

The land use and shoreline change of the three tidal creeks shows three very different systems (Figures 2,3, 4 and Table 2).Average shoreline change rates (SCR) were calculated for each study area based on the change in shoreline position between 1993 and 2012. Interestingly, Broad Creek was dominated by accretion (~53% of the points measured). The other two systems were dominated by erosion, but only Hawkins Creek had an SCR (-1.59 ±0.10 m/yr) significantly greater than the associated measurement error. Spatially, higher rates of erosion are observed near the mouth of Oyster Creek, while the only areas with significant erosion rates in Broad Creek are found in the central region of the system. High erosion rates are observed throughout Hawkins Creek, although erosion rates as high as ~10 m/yr are seen in the creek head.

Table 2. Summary of shoreline change rates (SCR) and 2010 land cover data for the three tidal creek watersheds.

	Oyster Creek	Broad Creek	Hawkins Creek
Area (km²)	13.5	15	1
Average SCR (m/y)[1]	-0.09 ±0.07	0.02 ±0.07	-1.59 ±0.10
Shoreline eroding (%)	55	47	70
Modified[2] (%)	<1	11	22
Land Use (%)[3]			
Agriculture	0.02	3.3	3.9
Developed	1.7	13.4	72.1
Estuarine Wetland	19.4	1.5	3.7
Forest	14.2	27.3	13.2
Open Land	0.5	3.5	5.2
Palustrine Wetland	52.8	48.0	1.0
Water	8.1	2.3	3.8

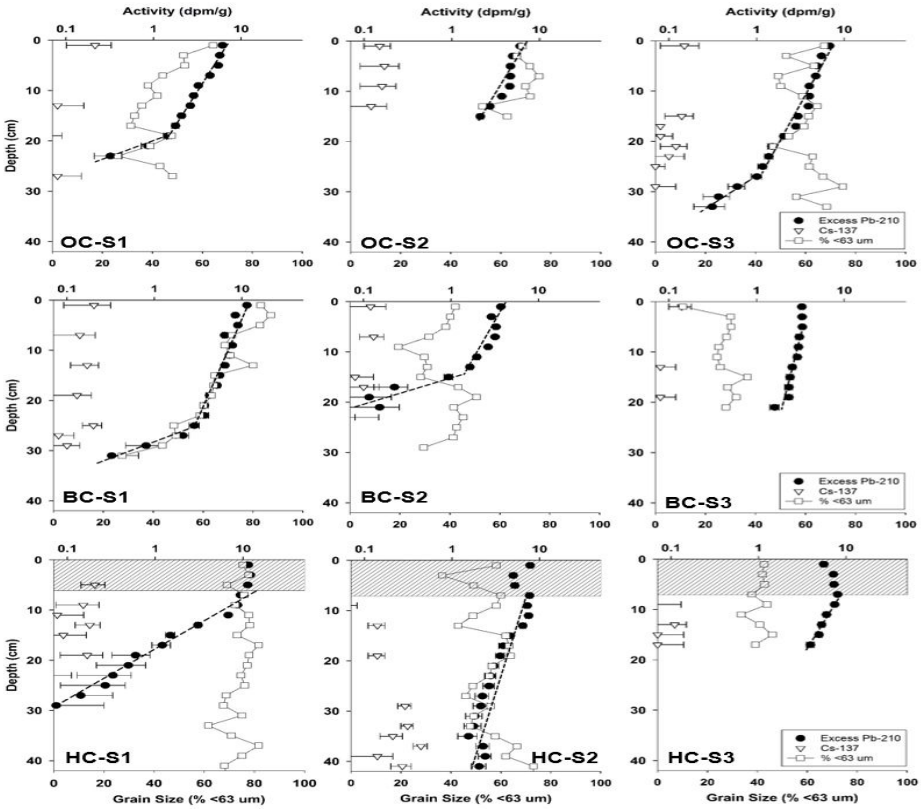
[1]Calculated as difference between digitized shorelines from 2012 and 1993.[2]Based on 2012 shoreline inventory.[3]NOAA C-CAP data from 2010.

The tidal creeks showed varying stages of development.Hawkins Creek watershed is the most developed (72%) followed by Broad Creek (13.4%) and the relatively undeveloped Oyster Creek (<2% developed). Collectively, the watersheds were mainly comprised of palustrine wetland, estuary wetland, forest, open land, and developed land, although it varied widely across the three systems. The Oyster Creek watershed area covered 13.5 km^2, dominated Palustrine and Estuarine Wetland (72% combined). The Broad creek watershed area (15.0 km^2) was the largest systemof thestudy. Broad Creek's land use was fairly diverse, not dominated by any one type (Table 2), although Palustrine Wetland was the largest in the watershed followed by Forest and Developed. Hawkins Creek is the smallest watershed (1 km^2) and is almost exclusively Developed and Forested.An attempt was made to use the NOAA C-CAP data collected in 1996 and 2010 to evaluate change in land cover. It should be noted that this amount of time is small, particularly since the communities likely experienced most change in the 1960-1970's like most of the NC coastal zone. However, some changes can be observed. In Oyster Creek, a minimal amount of area was converted to Palustrine wetland. The greatest changes were observed in Broad Creek with tracts of Forested, Palustrine, and Agriculture converted to Developed. Hawkins Creek saw very little change, likely given that most of the area was already developed.

5.2 Grain size and ^{210}Pb and ^{137}Cs chronology

The grain size (i.e., presented as the <63um fraction) varied widely among cores,ranging from 0% to 90% fine material (Figure5). Generally, grain size decreased from surface to depth in the upper of basin of Oyster and Broad Creeks (e.g., OC-S1 and BC-S1). The middle and lower basin sites of Oyster Creek show little variation in down-corefine material, ranging between 60 and 80%. Sand sizedmaterial dominated the middle and lower basin sites of Broad Creek with %fines <40% throughout most of the cores. Finally, grain size in the middle basin of Hawkins Creek (HC-S2) shows an increase in mud (i.e., decrease in sand) at the depth of 28-46 cm of the core. The outer creek (HC-S3) only has ~40% fines with little variability to the depth of the core. X-radiography provides visual evidence of grain size variations within a core and mixing.

Figure 5. Down-core profiles of excess ^{210}Pb, ^{137}Cs and percent grain size less than 63 um from cores collected in Hawkins Creek, Broad Creek and Oyster Creek.



80%. Sand sized material dominated the middle and lower basin sites of Broad Creek with %fines <40% throughout most of the cores. Finally, grain size in the middle basin of Hawkins Creek (HC-S2) shows an increase in mud (i.e., decrease in sand) at the depth

X-radiographs from most cores show some evidence of laminations within the cores (Figures 6-8). Care should be taken when interpreting hue variations between cores since adjustments to brightness and contrast are done individually based on the X-ray system. There is little evidence of macrofauna in any of the cores, except possibly the upper 5-10 cm of cores HC-S2 and HC-S3. Many cores have evidence (e.g., laminations) of minor mixing, although some of these laminations are limited to a small proportion of the core.Although there is limited evidence of biological mixing, the lack of sedimentary structure may indicate the presence of physical mixing. Cores BC-S1 and BC-S3 are difficult to interpret, with little change in sedimentary fabric downcore.The radionuclide data (e.g., ^{210}Pb, ^{137}Cs) were used in this study to present valuable information regarding recent sediment accumulation (Figure 5; Table 3). Again, sediment accumulation rates were calculated using the constant flux-constant sedimentation (CF-CS) model (Appleby and Oldfield, 1992). Unfortunately, thedown-core^{137}Cs activities were all within error of zero or within our systems minimum detectable activity, so could not be used to substantiate the ^{210}Pb accumulation rates and therefore are not included in Table 3.Generally, ^{210}Pb portrayed an exponential decline with depth in each core. However, several cores (e.g., OC-S1, OC-S3, BC-S1, and BC-S2) showed a significant break in slope (Figure 5). This rapid change in slope has been shown to represent a change in sedimentation rate with time (Appleby and Oldfield, 1992). As such, two rates are reported for these cores (Table 3), representing a rate for the deepersectionand one for the upper slope. Hawkins Creek cores were the only cores that presented evidence of sediment mixing or rapid deposition near the surface (i.e., near vertical ^{210}Pb profile), 0-8 cm.The accumulation rates of the three stations in Oyster Creek ranged from 0.37 to 0.47 cm/yr, the highest value in the central basin. The linear accumulation rate at OC-S1 increased from 0.08 cm/yrbetween 19 and 23cm to 0.37 cm/yrfrom 0-19cm. Similarly, OC-S3 changed from 0.16cm/yrbetween 27 and 33 cm to 0.43 cm/yrfrom 0-27cm. The sedimentation rates for BC-S1 were 0.63 and 0.08 cm/yrbetween 0-25cm and 25-32cm, respectively. Core BC-S2, from the central basin of Broad Creek, had a sedimentation rate of 0.52cm/yrbetween 0-14cm, with a clear reduction of rate to 0.08cm/yr below 14 cm. The highest sedimentation rate in Broad Creek was observed at the mouth (BC-S3) at 0.84 cm/yr. The sediment accumulation rates in Hawkins Creek appeared to be steady with depth. Rates for HC-S1, HC-S2 and HC-S3 were 0.14, 0.69 and 0.44 cm/yr, respectively.

Table 3. Sediment accumulation rates for sites within the three tidal creeks.

Site	**^{210}PbAccumulation**	
	cm y^{-1}	**g cm^{-2} y^{-1}**
Oyster Creek		
OC-S1	0.37±0.02 (0-19cm) 0.08±0.03 (19-23cm)	0.25±0.02
OC-S2	0.47±0.08	0.33±0.04
OC-S3	0.43±0.03 (0-27cm) 0.16±0.02 (27-33cm)	0.37±0.02
Broad Creek		
BC-S1	0.63±0.05 (0-25cm) 0.08±0.03 (25-32cm)	0.33±0.02
BC-S2	0.52±0.11 (0-14cm) 0.08±0.03 (14-22cm)	0.50±0.11
BC-S3	0.84±0.13	0.99±0.16
Hawkins Creek		
HC-S1	0.14±0.02	0.10±0.01
HC-S2	0.69±0.08	0.52±0.06
HC-S3	0.44±0.03	0.41±0.03

Figure 6. Oyster Creek x-radiographs and interpretation. Dark colors are more x-ray opaque (i.e., less x-rays pass through the core) and represent a relative increase in bulk density.

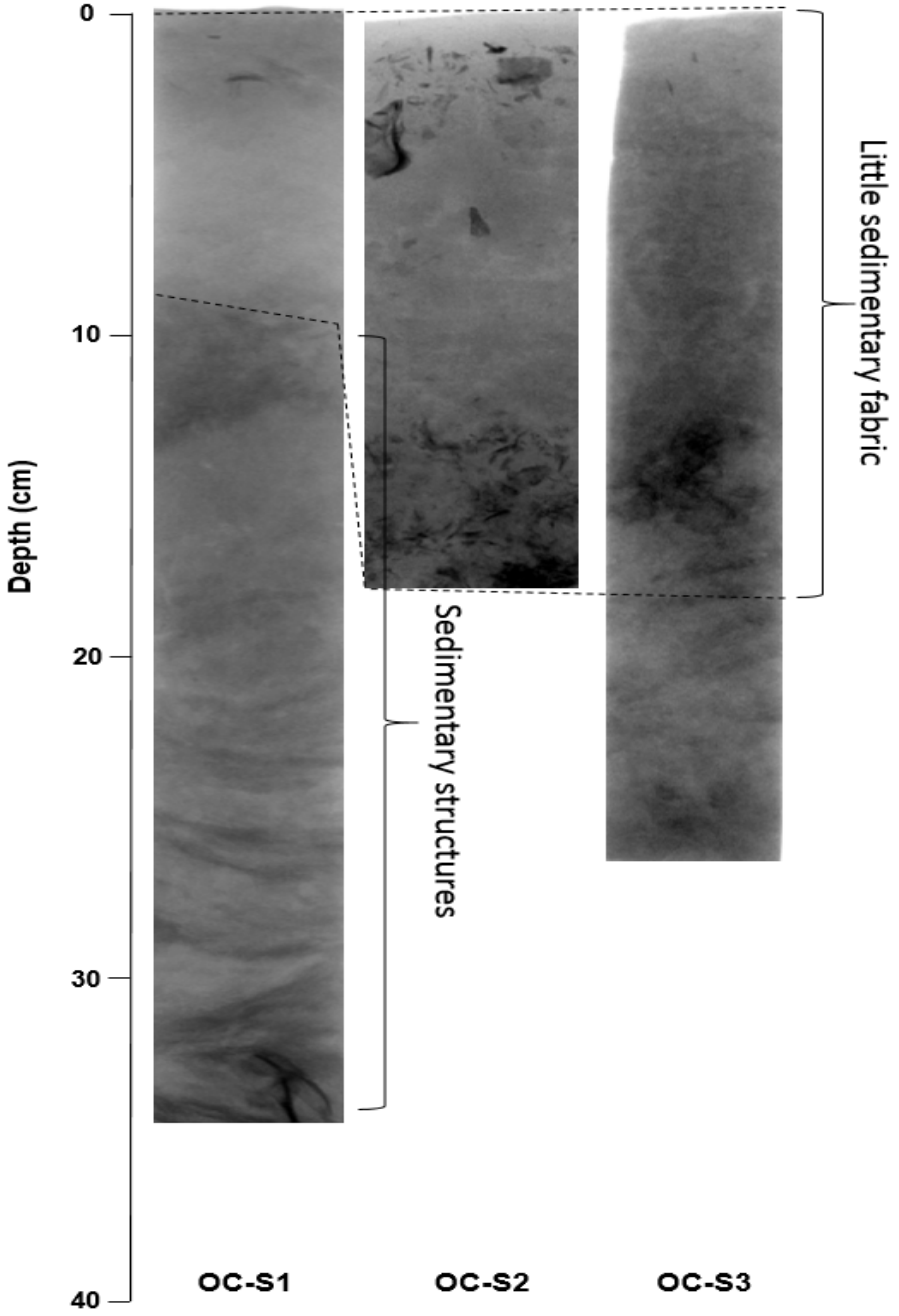


Figure 7. Broad Creek x-radiographs and interpretation. Dark colors are more x-ray opaque (i.e., less x-rays pass through the core) and represent a relative increase in bulk density.

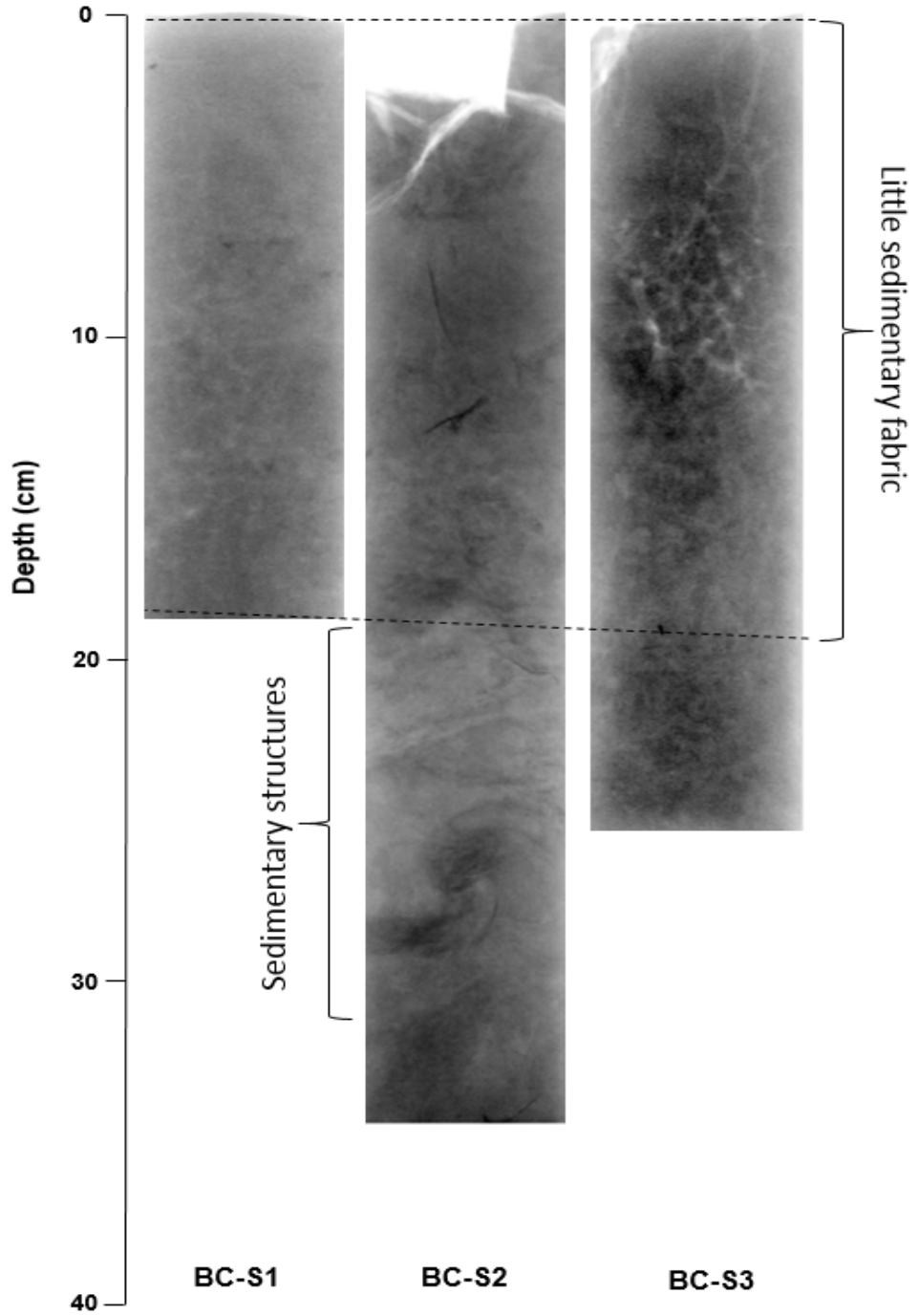
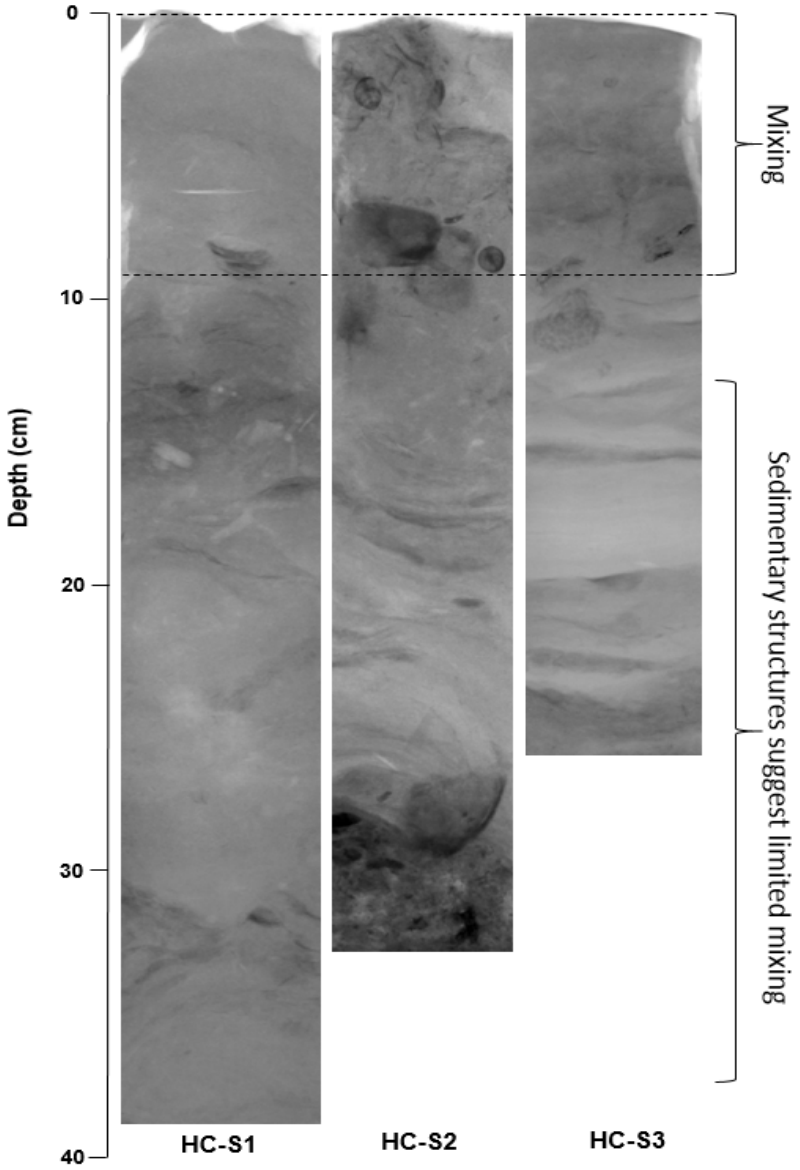


Figure 8. HawkinsCreek x-radiographs and interpretation. Dark colors are more x-ray opaque (i.e., less x-rays pass through the core) and represent a relative increase in bulk density.



5.3 Organic Matter Tracers

Samples were analyzed for a suite of organic matter tracers ($\delta^{15}N$,$\delta^{13}C$, %TC, %TOC, and C:N) in an attempt to evaluate changes in deposition setting (Figures 9-11). Generally, %TOC and %TNdecreases and $\delta^{13}C$ becomes less negative from the head of the stream (Stations S1) to the mouth (S3) in all creeks. In the head of Oyster Creek, TOC and TN indicated increasing trends of vertical distribution, both tracers increase slowly from depths 29cm to 11cm and then more pronounced from 11cm to the surface. The $\delta^{13}C$values vary between -26‰ to 24‰ with no significant trend with depth. The content of $\delta^{15}N$ increases slightly (3.0‰ to 3.8‰) from the bottom to the surface. In contrast, TOC/TN ratio decreasesfrom the bottom to the surface. CoresOC-S2 and OC-S3 had very little change with depth in most of the parameters measured, although absolute values between the cores did vary. The one important caveat is the downcore enrichment of ^{13}C in core OC-S2 with a significant change from -21‰ (1 cm) to -17‰ (15 cm), and the C:N decreasing downcore from 12.9 to 18.1.In the head of Broad Creek (BC-S1), the contents of TOC and TN portrays a trend of significant increase from the core bottom to surface.

The $\delta^{13}C$ varied from -25‰ to -23.6‰ with no discernable trend. The stable isotope $\delta^{15}N$ variedbetween 1.7‰ to 3.7‰, generally increasing up-core (i.e., past to present). Core BC-S2 showed an increase in $\delta^{13}C$ (-24 to -19‰) up-core with an interesting "spike" at 15 cm. Similarly, C:N decreased downcore from 15 to 20. Parameters in core BC-S3 show relatively stable values throughout the core.In the head of Hawkins Creek (HC-S1), the TOC and TN contents increasesup-core, with an inflection around 18 cm. The $\delta^{13}C$ decreases up-core from -17 to -21‰. The $\delta^{15}N$ varies with depth with no discernable trend.The C:N ratiois fairly stable except for a slight inflection around 18 cm. Cores HC-S2 and HC-S3 showed little downcore variability

Figure 9. Downcore organic matter analysis of cores collected on Oyster Creek. Year is calculated by dividing the sample depth by the accumulation rate and subtracting the value (i.e., age) from the sampling date.

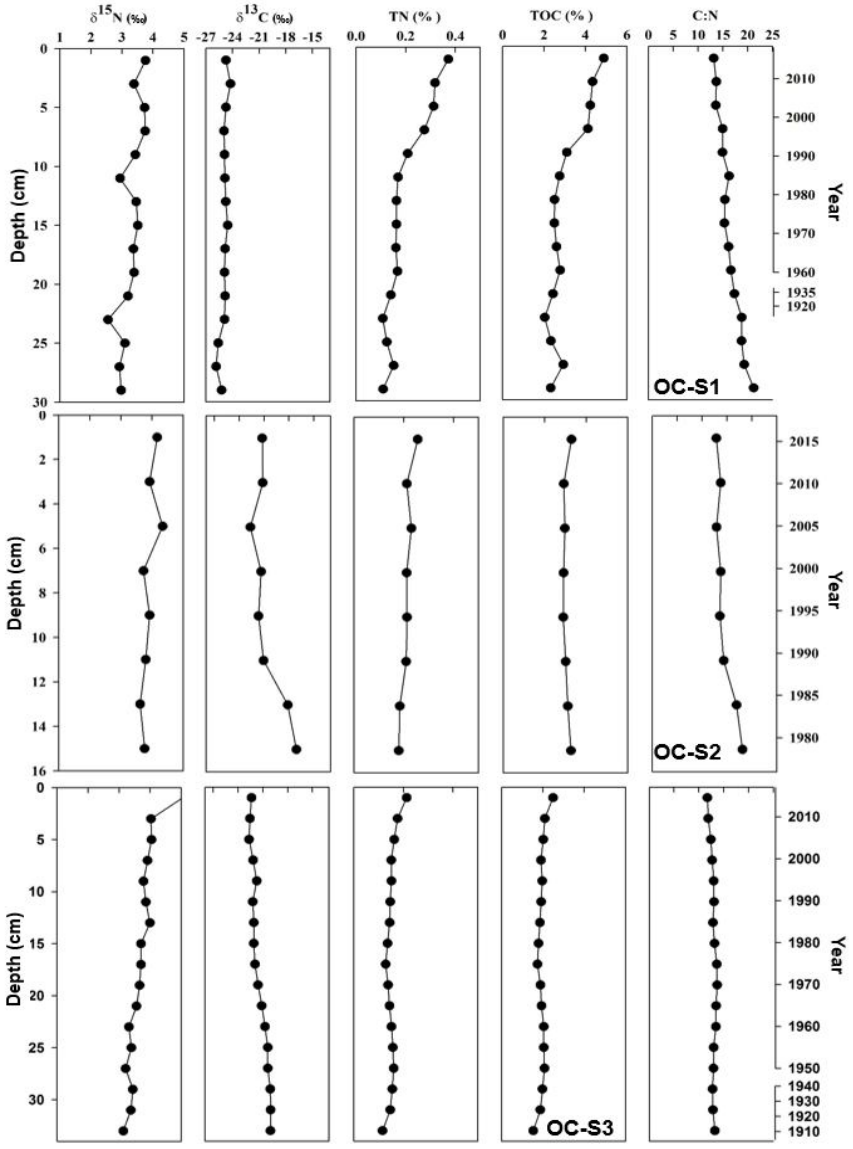


Figure 10. Downcore organic matter analysis of cores collected on Broad Creek. Year is calculated by dividing the sample depth by the accumulation rate and subtracting the value (i.e., age) from the sampling date.

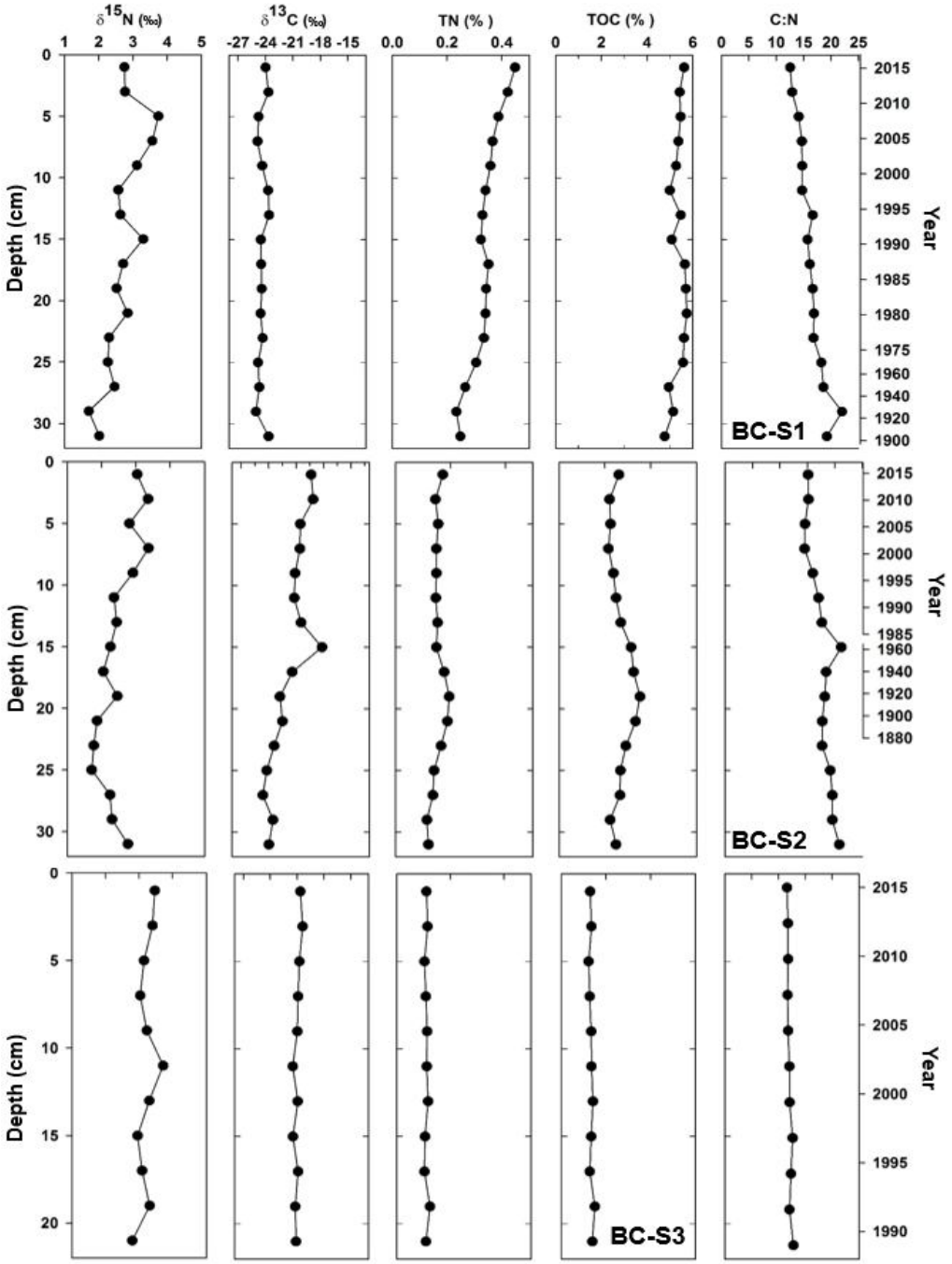
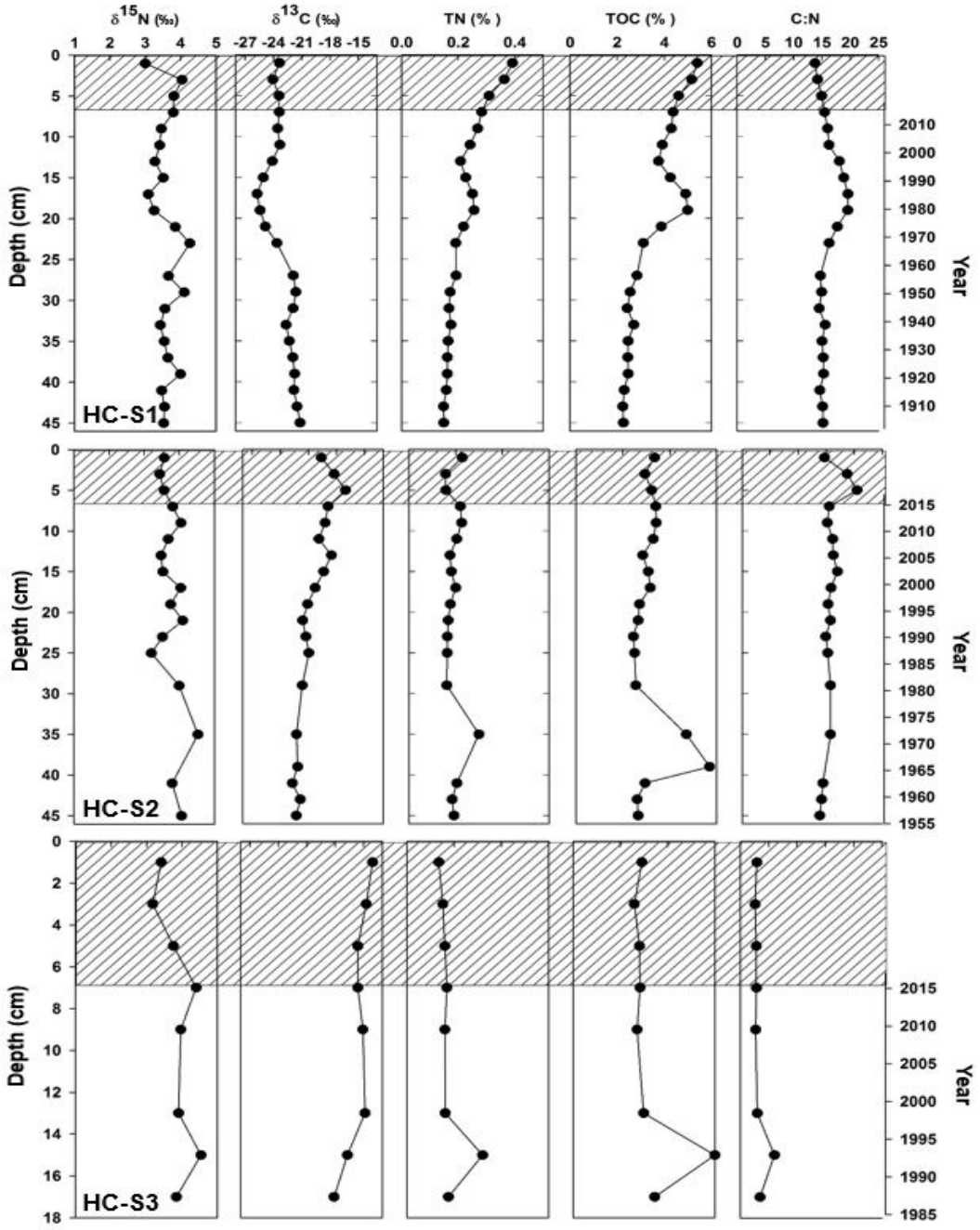


Figure 11. Downcore organic matter analysis of cores collected on Hawkins Creek. Hatched area represents the mixed layer (see Figure 5). Year is calculated by dividing the sample depth by the accumulation rate and subtracting the value (i.e., age) from the sampling date.



in all a parameters, although absolute values varied between sites. The only other discernable fluctuation inHC-S2 was an anomalous "bump" in most parameters between 30 and 40cm. Parameters in core BC-S3 show relatively stable values throughout the core. However, like the other cores in Hawkins Creek, there is an anomalous "bump", occurring around 15 cm in HC-S3.

6. Discussion

Studying sediment dynamics within coastal tributaries and estuaries is important because sediment is cited as the most prolific water pollutant (USEPA, 2006, 2004). It is commonly found that sediments introduced into coastal systems are associated with enrichments of terrestrially-based nutrients and other sediment associated pollutants like heavy and trace-metals, herbicides, and pesticides. These constituents can lead to the degradation of the water quality of these coastal systems (Cooper et al., 2004; Benninger and Wells, 1993; Riggs et al., 1991). The sedimentary record can provide valuable data relevant to the management of coastal systems. This is important because estuarine and coastal areas provide a significant source of revenue for states like North Carolina. This study presents evidence for sediment trapping in tidal creeksalong central NC, as well as detailed chronologies of organic matter accumulation.

6.1 Nature of Sediment Accumulation

Modeling of ^{210}Pb downcore data has several inherent assumptions, as outlined in the methods. Although rates of sediment accumulation have been calculated for each core, the lack of viable ^{137}Cs data (likely associated with cation exchange due to high salinity) reduces the confidence in the calculated rates. Future work should consider including ^{239,240}Pu as an alternative independent chronometer to substantiate the ^{210}Pb accumulation rate results. A notable concern with the rates is the high sand content and downcore grain size variability in several cores, particularly OC-S1 and BC-S1. This change in grain size can influence ^{210}Pb bound to the particles, leading to different modeling interpretations. This may have some influence on cores OC-S1 and BC-S1, but likely not the other sites. A re-evaluation of these two sites taking into account the change in downcore grain size would suggest even higher rates of accumulation. We use those presented in Table 3 as a conservative estimate. Sediment accumulation is dependent on the balance between sources, sinks, the transport of material between the two, and the availability of accommodation space. Sources include suspended material in river discharge, shoreline erosion and tidal transport from the sea. Currents and waves may resuspend bottom material and transport it out of the basin on an ebb tide or higher river discharge (i.e., a sink). Finally, accommodation space can be gained in coastal systems through the rate of relative sea level rise (SLRr). Systems at equilibrium will often have rates of sediment accumulation within error of local SLRr (Corbett et al., 2007). This study cannot provide information on the processes that have led to the measured accumulation, only the net product of these drivers.

Relative sea level rise measured at Beaufort, NC is 2.89 +/- 0.36 mm/yr (NOAA, 2017). Modern rates of sediment accumulation in each tidal creek exceeds that of local SLRr, except for a single site in Hawkins Creek (HC-S1; Table 3). Rates in Oyster Creek are less variable across the system relative to the other two sites and are close to other accumulation rates reported in that same region (Benninger and Martens, 1983; Giffin and Corbett, 2003; Corbett et al., 2007). In addition, the rate of SLRr north of Cape Lookout is likely higher than that measured at Beaufort (NOAA, 2017). Regardless, given the excessaccumulation ratesrelative to the rate of sea level rise, the basins do appear to be in-filling (e.g., shallowing), albeit relatively slowly. From a resident's perspective, a change in depth of a few centimeters over a decade would likely not be noticeable. However, this preliminary assessment does suggest more data should be collected to better evaluate the spatial variability across the system.

Variations in accumulation rates do not appear to be directly related to variations in land-use. The highest percent coverage of developed land was found in the Hawkins Creek watershed. However, the highest rate of sediment accumulation was measured in the mouth of Broad Creek. Although the size of the watershed is likely an important consideration when considering the sediment yield of the associated watershed. Hawkins Creek is more than an order of magnitude smaller than the other two systems, yet has accumulation rates of comparable magnitude with the greatest variability (0.14 – 0.69 cm/yr).Finally, it should be noted that several of the sites in Oyster and Broad Creek appear to show a change in the rate of sediment accumulation (Table 3; Figure 5). This may be a function of changes in land use or a product of hydrodynamic variations in the basins. The two cores in these basins that did not show a change in rate (OC-S2 and BC-S3) likely did not penetrate deep enough into the seafloor to observe the change. The timing of this rate change occurred in the 1950-60's and 1970-90's in Oyster and Broad Creek, respectively. Unfortunately, this timeframe extends beyond readily available land use data, so a direct connection is not easily determined. However, one could look to the timing of the development of Open Ground Farms (1950-70's) near Oyster Creek and Morehead City/Swansboro (1960's to present) near Broad Creek.

6.2 Historic Accumulation of Organic Matter

Organic matter tracers can provide some understanding of sediment source or changes in source. As expected, all creeks show the most terrestrial signature ($\delta^{13}C$ approaching -28‰) at the head of the system, typically moving toward more marine (-21‰) signature near the creek mouth. Most organic tracers showed little change with time (i.e., downcore), indicating no significant shifts in sediment source over the timescale indicated (i.e, ~25 to 120+ years). The most prevalent change across the systems is an increase in the %C and %N deposited during the last several decades. This increase has occurred during a period of fairly constant accumulation, indicating an increased flux of organic C and N to the sea floor. This is most notable in the head of Hawkins Creek where organic carbon flux has increased from ~2.5 mg cm^{-2} yr^{-1} to 5.5 mg $cm^{-2}yr^{-1}$. This increase in organic carbon load could ultimately impacttheoverlying water column oxygen dynamics and benthic biomass.

7. Summary

From the results of this study, the following statements can be made relating to sedimentation rates, land use, and organic matter accumulation in tidal creeks along central NC:

1. The limited shoreline and land use data available made it difficult to quantitatively evaluate change in all the tidal creeks. Recent shoreline change rates are highly erosive in Hawkins Creek, with little change in the other basins.
2. Sediment accumulation rates in all tidal creeks exceed that of SLRr, leading to a slow infilling of the tidal basins. Organic matter tracers suggest some minor increases in organic carbon and nitrogen storage, particularly in the heads of the creeks, but no large fluctuations in the source of material being deposited over decadal timescales.
3. Timing of the measured change in accumulation rates in Oyster and Broad Creeks may be related to development of surrounding areas (i.e., Open Ground Farms and Morehead City/Swansboro, respectively).

Additional information on modern and historic sediment delivery to the system would be beneficial in evaluating changes to the system. Specifically, gathering historic data on stream flow and sediment discharge to the streams of interest would be an added benefit to understanding accumulation in the receiving basin. However, only focusing on the sediments does not provide insight into the drivers that lead to the ultimate accumulation of material. Additional focus on the biogeochemical transformations of the material in route to deposition/accumulation would better link the sediments to the biological community and productivity. Other studies have shown the impact of development in tidal creek watersheds to detrimental changes in the benthic biological community. Linking sediment delivery, quality, and dynamics to land use change and biological diversity/productivity would be a next logical step in better managing these system.

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