Site Profile of the

North Inlet - Winyah Bay National Estuarine Research Reserve

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Photo of F. John Vernberg by George Cathcart, taken at the dedication ceremony of the Hobcaw Barony Discovery Center, September 2009.

The North Inlet - Winyah Bay National Estuarine Research Reserve (NERR) Site Profile document is dedicated to Professor Emeritus F. John Vernberg, Director of the Belle W. Baruch Institute for Marine and Coastal Sciences from 1969 to 1996. Dr. Vernberg guided and inspired the development of an internationally recognized and respected research program centered in the North Inlet estuary. His success in establishing one of the first of the National Science Foundation's Long-Term Ecological Research sites (1980) and then the North Inlet -Winyah Bay NERR (1992) has enabled hundreds of scientists, staff, and students to conduct the studies that comprise the remarkable collection of scientific contributions described in this volume.

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Preface: Organization of the Profile

This comprehensive document covers the environmental setting, history of human use, and geology and ecology of the North Inlet – Winyah Bay National Estuarine Research Reserve (NI-WB NERR or the Reserve.) It has been prepared to increase awareness of the Reserve's spectacular natural resources, the successful private-state –federal partnership that assures continued protection of local lands and waters, and especially the internationally recognized base of scientific knowledge associated with the research conducted in the estuaries that comprise the Reserve. Literally hundreds of researchers, technical assistants, and students have contributed to this volume through their studies over more than 40 years. We could not list all of the published authors and successful graduate degree recipients in this profile, but references to almost all of their work can be found at the website of the Belle W. Baruch Institute for Marine and Coastal Sciences, University of South Carolina, which operates the Reserve: **www.baruch.sc.edu**. The website is also a good source of information about research and teaching facilities available at the Baruch Marine Field Laboratory, opportunities for visiting scientists, and on-going studies in the North Inlet – Winyah Bay NERR.

The site profile is designed primarily for investigators interested in conducting work in the NI-WB NERR and provides a summary of the current state of knowledge about North Inlet and Winyah Bay. We hope that students, teachers, coastal decision makers, and interested citizens will also find the maps, facts and figures, and references to further reading helpful in their study, enjoyment, and stewardship of these local estuaries and watersheds. Supplemental background information on some topics is included in **Appendix A** and is organized by sections as they appear in the main text of the document.

Initial efforts to develop a site profile began many years ago. Changes in priorities, schedules, and staff personnel slowed the process, but it was the sheer volume of relevant information about the local environment that had been generated by scientists over the decades that made this an especially daunting project. The resulting summary of that knowledge reveals that, although we know a great deal, much still needs to be understood and done before we achieve the goal of balanced environmental integrity and human needs, so critical to the mission of the NI-WB NERR. It is not enough to protect sections of the coast or conduct research. Success relies on the communication of useful information to citizens and those who make decisions that affect the environment at the home, city, county, state, regional, and federal levels. The education programs sponsored by the Reserve are often based on the results of studies conducted here and throughout the world's coastal systems. We encourage residents and visitors to the area to participate in our education programs and contribute to maintaining a long and balanced future for our estuaries and coastal communities.

Acknowledgements

Primary recognition and thanks goes to the Belle W. Baruch Foundation, which has carefully managed and defended the 16,000 acres of Hobcaw Barony to insure its outstanding ecological well-being and value for research and education in perpetuity. Their support of the NI-WB NERR and its programs has resulted in a productive partnership in conservation, environmental monitoring and research, and both academic and public education programs.

With the continued funding support of the Reserve by the National Oceanic and Atmospheric Administration (NOAA) and the oversight and collaboration we have enjoyed with the NOAA Estuarine Reserve Division (ERD) in the Office of Ocean and Coastal Resource Management, the NI-WB NERR has grown to be a productive and well-respected source of information and instruction within the state and region. We thank the South Carolina Department of Health and Environmental Control's Office of Ocean and Coastal Resource Management for all of their services and support since the late 1980's when establishment of a NERR at North Inlet- Winyah Bay was still only a concept. It was the initiative of the former University of South Carolina Baruch Institute Director Dr. F. John Vernberg and the support of Senator Ernest Hollings and Governor Carroll Campbell that resulted in the nomination and official designation of the Reserve in 1992. For the vision of these champions and the help from many others involved in creating the Reserve, we are grateful.

Much of the planning, writing, and editing of this document were accomplished by Drs. Dennis M. Allen and Robert J. Feller, with additional writing and editing provided by Reserve Manager Wendy Allen. Dr. Jennifer Plunket, Stewardship Coordinator for the Reserve, also contributed to the final editing and formatted the document for publication. The leadership and support of the Baruch Institute Directors, Dr. F. John Vernberg, Dr. Madilyn Fletcher, and Dr. James T. Morris, are also gratefully acknowledged. Significant input and contributions of text, figures and images were provided by several former and current NI-WB NERR, Baruch Institute, and Baruch Foundation staff members over the years including Lee Brockington, Dr. Chris Buzzelli, Dr. Bob Gardner, Paul Kenny, Anne Miller, Ginger Ogburn-Matthews, Jeffrey Pollack, Dr. Erik Smith, Laura Schmidt, Beth Thomas, Dr. Anna Toline, and Leigh Wood. We also gratefully acknowledge Dr. Marie Bundy and Bree Murphy for their careful review of this document on behalf of NOAA. This was truly a huge team effort and we thank all who helped along the way.

Researchers met at Hobcaw House in 2007 to share data and experiences in North Inlet and Winyah Bay. Some investigators have conducted studies in North Inlet for more than 40 years.

The NI-WB NERR Program: Genesis, Rational, and Mission

PRE-NERR PROGRAMS ON SITE: USC-BARUCH INSTITUTE RESEARCH AND EDUCATION

The establishment of a long-term agreement between the Belle W. Baruch Foundation and the newly formed Belle W. Baruch Institute for Marine Biology and Coastal Research at the University of South Carolina (USC) in 1969 marked the beginning of a productive partnership in education and research that continues today. The Institute's name was later changed to the Belle W. Baruch Institute for Marine and Coastal Sciences. In the 1960's, individual scientists from other South Carolina institutions explored and described some of the flora and fauna of what is recognized today as the NI-WB NERR near Georgetown, South Carolina. Multidisciplinary research and formal academic and continuing education programs were not organized until the early 1970's when the USC and Clemson University (which started a forestry program on Hobcaw Barony in 1968) established research-oriented facilities on site. With interests in estuarine ecology and coastal marine sciences, USC researchers began monitoring environmental conditions and conducting experimental research in North Inlet. Campus-based (in Columbia, SC) and resident scientists were successful in attracting funding from state, federal, and private programs. Large grants from the US Environmental Protection Agency (EPA) and the National Science Foundation (NSF) provided the opportunity to gain insights into how the estuarine-salt marsh ecosystem at North Inlet is structured and functions in relation to the surrounding watershed and coastal ocean. The Outwelling Study, conducted in the late 1970's, involved dozens of investigators from different disciplines and hundreds of students. This study demonstrated a net flux of dissolved and particulate materials to the ocean thus supporting the notion that much of the rich productivity of the estuary is exported and helps to nourish the relatively impoverished nearshore ocean (Dame et al., 1986) and generated several other hypotheses that were investigated in subsequent years. In

The Outwelling Study, conducted in the late 1970's, involved dozens of investigators from different disciplines and hundreds of students.

1980, the first estuarine site in NSF's Long-Term Ecological Research (LTER) Program was established in North Inlet. Long-term time series collections of physical features of the water and atmosphere, microbes, water chemistry, algae, marsh plants, benthos, zooplankton, fishes, birds and many other ecosystem variables were measured regularly, and process-oriented research and ecological modeling were conducted.

The North Inlet LTER program ended in the early 1990s as the NI-WB NERR was becoming established. In the years preceding the Reserve's designation, approximately $15M in research funding had supported more than 250 research projects and led to the publication of more than 900 scientific papers and books. Hundreds of USC and visiting investigators from all over the world conducted studies within the North Inlet portions of the Reserve, making this one of the most intensively studied and well-understood estuaries in the world. The significance of these contributions to science was enhanced by the recognition that measurements were made within a relatively pristine coastal system, thus reflecting natural variability in the patterns and processes being measured. As a consequence, the value of these multi-decadal databases is increasing as society seeks an understanding of the impacts of sea level rise and other aspects of global climate change. **Appendix B** lists USC Baruch and NI-WB archived and web published databases for biological, water chemistry and meteorological, and water quality data.

By 1992, more than 200 graduate students had completed Master's theses and PhD dissertations that involved research in North Inlet, and many hundreds of USC's undergraduate Marine Science Program majors had spent time at the site. Field trips and the use of materials and data in classrooms served to expand the value of the site for formal environmental education. Starting in the late 1970s, USC Baruch Institute staff organized community-based education programs such as coastal ecology classes for children, teacher training courses, public lectures by scientists, and discussions on environmental issues. Constituting the first public environmental education programs in the Georgetown area, these helped increase awareness of our coastal systems and the value of protected areas and research within them.

Professor Bruce Coull and one of the first of hundreds of USC marine science classes to study life in North Inlet.

Baruch scientists celebrate completion of cruise #150 as part of the LTER project.

National Estuarine Research Reserve System and the North Inlet – Winyah Bay NERR

The National Estuarine Research Reserve System (NERRS) was created by the Coastal Zone Management Act (CZMA) of 1972, as amended, 16 U.S.C. Sec. 1461, to augment the Federal Coastal Zone Management (CZM) Program. The CZM Program is dedicated to comprehensive, sustainable management of the nation's coasts. The reserve system is a network of protected areas established to promote informed management of the Nation's estuaries and coastal habitats. The reserve system currently consists of 28 reserves in 23 states and territories, protecting over one million acres of estuarine lands and waters (Figure 1).

As stated in the NERRS regulations, 15 C.F.R. Sec. 921.1(a), the National Estuarine Research Reserve System mission is:

> *The establishment and management, through Federal-state cooperation, of a national system of estuarine research reserves representative of the various regions and estuarine types in the United States. National Estuarine Research Reserves are established to provide opportunities for long-term research, education, and interpretation.*

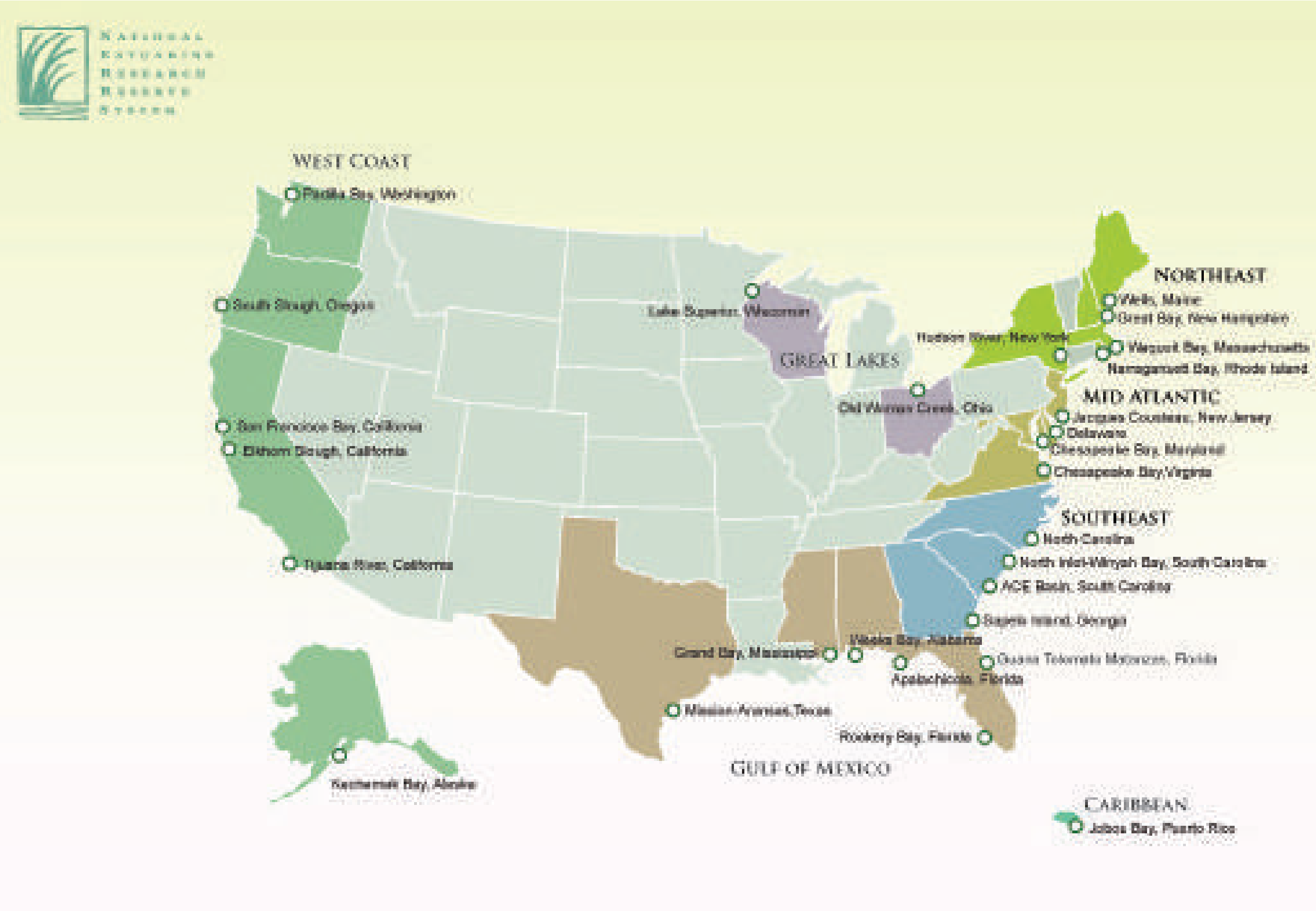


Figure 1. Location of the 28 Reserves in the National Estuarine Research Reserve System.

Federal regulations, 15 C.F.R. Sec. 921.1(b), provide five specific goals for the reserve system:

1) *Ensure a stable environment for research through long-term protection of National Estuarine Research Reserve resources;*

2) *Address coastal management issues identified as significant through coordinated estuarine research within the System;*

3) *Enhance public awareness and understanding of estuarine areas and provide suitable opportunities for public education and interpretation;*

4) *Promote Federal, state, public and private use of one or more Reserves within the System when such entities conduct estuarine research; and*

5) *Conduct and coordinate estuarine research within the System, gathering and making available information necessary for improved understanding and management of estuarine areas.*

The North Inlet – Winyah Bay National Estuarine Research Reserve (North Inlet – Winyah Bay NERR or NI-WB NERR or the Reserve) was designated in 1992 and is located in Georgetown County, South Carolina, about 30 miles south of Myrtle Beach and 50 miles north of Charleston (Figure 2). It encompasses 18,916 acres of tidal marshes and wetlands, much of which is on Hobcaw Barony, the 16,000 acre property of the Belle W. Baruch Foundation, a private, 501 (c) (3) operating foundation that manages its lands in perpetuity for conservation, research and education. The NI-WB NERR is administered by the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina that has facilities on the main university campus in Columbia, SC and on Hobcaw Barony.

The North Inlet – Winyah Bay NERR is in the South Atlantic subregion of the Carolinian biogeographic region in NOAA's Biogeographic Classification Scheme. The Reserve includes portions of two separate but connected estuaries: North Inlet, a small ocean-dominated estuary that is minimally impacted by human activities, and Winyah Bay, a classic estuary fed with freshwater by four major rivers. Both of these estuaries are described in more detail in other chapters of the site profile. The Reserve boundary has not changed since designation in 1992 (Figure 3). The core area of the Reserve is estimated at 11,173 acres and the buffer area is 7,743 acres, bringing the total acreage to 18,916 acres. A detailed description of these boundaries is contained the NI-WB NERR Management Plan (2011).

The University of South Carolina Belle W. Baruch Institute for Marine and Coastal Sciences operates the Baruch Marine Field Laboratory (BMFL) on Hobcaw Barony.

The Reserve wing of the BMFL houses a classroom, library, laboratory and offices. The NI-WB NERR is administered by the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina.

Looking south over North Inlet. Hobcaw Beach is in the forground. Image courtesy of Dr. Erik Smith.

Looking southwest over North Inlet and the Baruch Marine Field Laboratory. The bridges over Winyah Bay are in the upper left. Image courtesy of Dr. Timothy A. Mousseau.

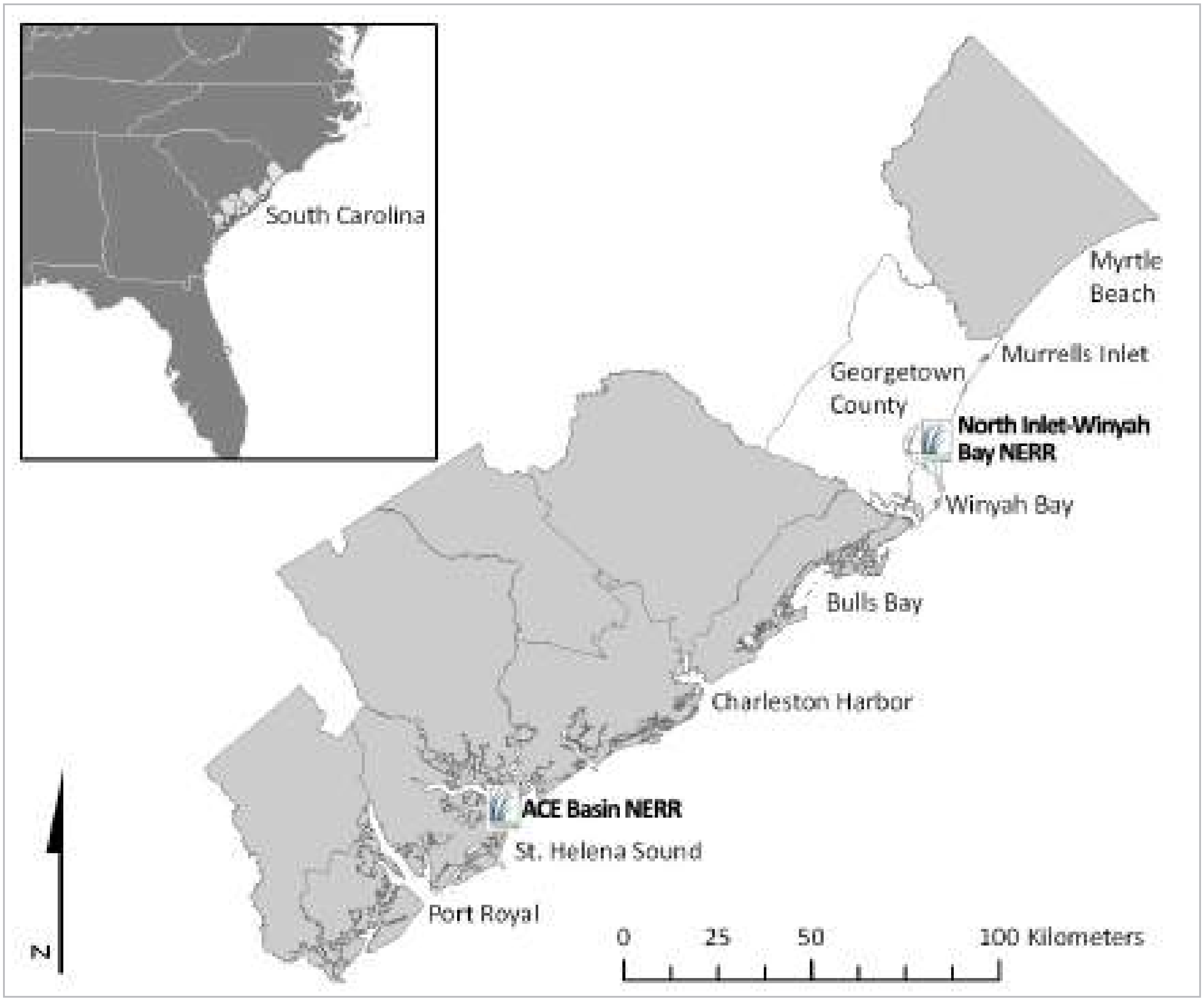


Figure 2. Location of the North Inlet-Winyah Bay National Estuarine Research Reserve in Georgetown County, South Carolina.

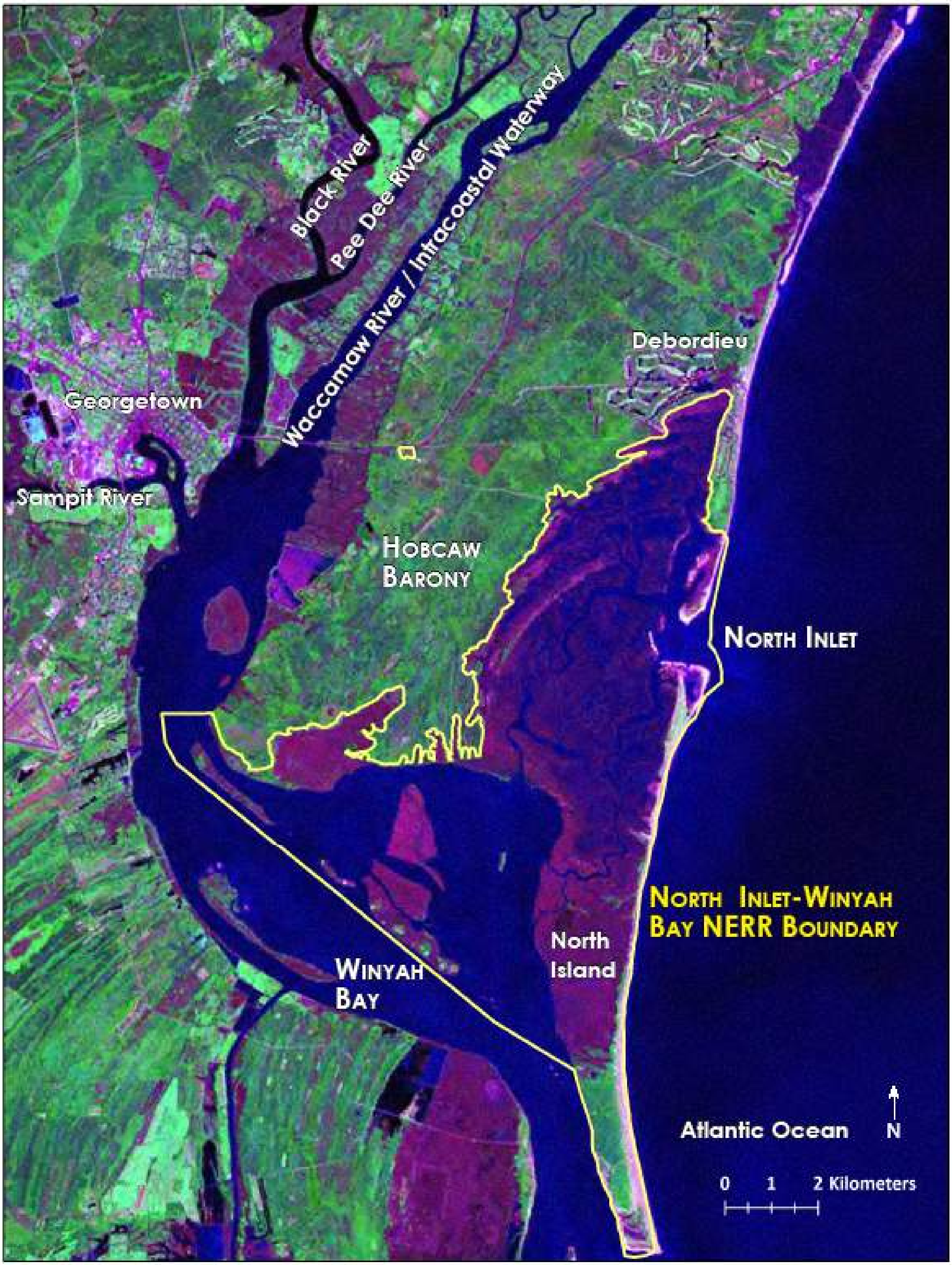


Figure 3. Boundary of the North Inlet-Winyah Bay National Estuarine Research Reserve.

» Reserve Milestones since Designation

There have been a number of significant milestones for the NI-WB NERR since it was established in 1992. The program has grown from a small staff of five individuals including a Manager, Research Coordinator, Education Coordinator and two research technicians to nine full-time and two part-time staff members. New positions were established over the years including a full-time Stewardship Coordinator (2001), a Coastal Training Program Coordinator (2003), and a full time Education Specialist (2007.) The research and monitoring program has also grown from a Research Coordinator and two technicians to a Research Coordinator and three full-time research specialists and one part-time research assistant. The Reserve also shares a system administrator with the Baruch Marine Field Laboratory and NERRS Centralized Data Management Office (CDMO).

Significant improvements to Reserve facilities have occurred since 1992. The NI-WB NERR was successful in securing a NOAA construction award to complete a 4,500 square-foot addition to the Baruch Marine Field Laboratory in 2002 that serves as the Reserve headquarters. NOAA construction funds were also used to enhance educational facilities on site including construction of a salt marsh boardwalk and renovations to the Kimbel Lodge, a conference building used for public education and Coastal Training Program events. Most recently, the Reserve received a series of NOAA construction awards to plan and build an education center in cooperation with the Belle W. Baruch Foundation. This joint-use facility, the Hobcaw Barony Discovery Center, was completed in 2009. It has approximately 12,000 square feet of space and includes a large exhibit area, classroom, audio-visual room and offices for Reserve and Baruch Foundation education staff. Staff members of the NERRS CDMO also occupy space in the staff wing of the center. A screened outdoor classroom adjacent to the Kimbel Pond and Lodge was also completed in 2009.

Although the North Inlet site was already well known for its research productivity before the Reserve was established, the NI-WB NERR has provided a stable platform for additional research and long-term monitoring. The Reserve's research and monitoring program has also experienced significant growth since 1992. Milestones include the successful establishment of the NERR System-wide Monitoring Program (SWMP) at our site (1993) and subsequent expansion of this program, including two monitoring sites that are linked via satellite for real time data transmission. While the Reserve has continued long-term biological monitoring for zooplankton, nekton and benthos, programs established prior to designation, it has also initiated new monitoring programs. In 2005, the Reserve established a series of permanent sampling transects in North Inlet for long-term biomonitoring of emergent marsh vegetation according to NERRS protocols; this was expanded in 2007 to include measures of sediment elevation change and porewater chemistry. These efforts position the Reserve to act as a sentinel site for salt marsh response to climate change and sea level rise in an area where marsh transgression of the uplands is not impeded by coastal development. In 2005 the Reserve also began routine monitoring of microplankton metabolism, designed to complement the SWMP nutrient monitoring program and track the ecological response of subtidal creeks to variability and change in salt marsh productivity. Within the broader watershed, the Reserve has been an active member of the multi-agency Long Bay Workgroup since its inception in 2004, examining the occurrence and mechanisms of hypoxia formation along the northern portion of the South Carolina coast.

The Reserve serves thousands of school aged children each year and provides a variety of classes, seminars and other public events to engage adults and families in learning about estuaries and the discoveries being made by scientists in the Reserve. The addition of the marsh boardwalk in 1997 and a salt marsh trail designed in 2011 provide increased access and opportunities for visiting groups to learn about salt marshes. Both access areas are used regularly by the Reserve in its education programs for K-12 students and members of the public and also by the Belle W. Baruch Foundation during public tours of the Hobcaw Barony property, conducted

2-4 times a week. The completion of the Hobcaw Barony Discovery Center in 2009 was a major milestone for the Reserve and enhances presence and visibility in the local community. The Reserve also enhanced its visibility with the creation of a website (**www.northinlet.sc.edu**) and an electronic newsletter, *Estuaries Illustrated*, that inform people about Reserve research, monitoring, stewardship and education activities.

The completion of the Hobcaw Barony Discovery Center in 2009 was a major milestone for the Reserve and enhances presence and visibility in the local community.

The midden tank is a popular exhibit at the Hobcaw Barony Discovery Center.

The transition of coastal issue workshops for decision-makers to a fully-implemented Coastal Training Program (CTP) in 2003 represented another significant milestone for the Reserve. The CTP addresses coastal information and management needs of local community leaders, environmental planners and engineers, and other coastal decision-makers. Current findings from scientific research and best management practices are shared during training events and field demonstration projects. This training program has been very well received by the local communities that it serves and has resulted in more informed decisions and actions being taken by planners and local governments such as using pervious alternatives for parking spaces.

The Reserve has also experienced success in the areas of resource management and stewardship. The Reserve worked with other conservation partners to develop the Coastal and Estuarine Land Conservation Program (CELCP) for South Carolina. One of the bigger success stories in this realm has been through working with the Beach Vitex Task Force. The Reserve helped form this group in 2002, remains an active member and maintains the task force website. Efforts of the task force have kept the invasive plant beach vitex from achieving its potential reputation as the “kudzu of the coast.” Education efforts combined with research, town and county imposed ordinances prohibiting the planting of beach vitex, and voluntary and mandatory eradication efforts by individual property owners and communities, have contributed to this success story.

» Reserve Mission and Goals

The original Reserve management plan published in 1992 was updated in 2011 and provides a framework for the Reserve to continue to address NERRS and site-based priorities. The mission of the NI-WB NERR as defined in the 2011-2016 Management Plan is:

> *"To promote stewardship in the North Inlet and Winyah Bay watersheds through science and education"*

This mission supports the vision of sustainable and ecologically productive estuaries. The Reserve identified three goals on which to focus its research, education and stewardship efforts over the next several years that will help achieve this mission and vision. These goals, listed below, along with strategies to achieve them are also described in the NI-WB NERR Management Plan (2011).

- Understand and minimize the impacts of coastal growth on water and habitat quality and ecological communities
- Understand the impacts of naturally occurring short-term, stochastic and long-term, large-scale climate events on coastal ecosystems and human communities
- Understand and reduce the impacts of invasive species and habitat loss on biodiversity

» Resource Management and Responsible Authorities

The NI-WB NERR works in cooperation with the Belle W. Baruch Foundation (BWBF) and other partners to ensure that the resources in the Reserve are managed and protected to the fullest extent possible. Authority for resource protection within the Reserve resides with a number of different state and federal agencies. Public access and use of the upland portions of the Reserve is restricted by the BWBF. Visitors authorized by the BWBF, Baruch Institute or the Reserve, including scientists, students, and special groups, may enter through the electronic gate at the main entrance of Hobcaw Barony. Scientific permit requests are carefully reviewed through the system in place at the Baruch Institute of USC. The Baruch Institute obtains a permit each year from the SC Department of Natural Resources (SCDNR), Marine Resources Division, to collect biological samples in the North Inlet and Winyah Bay area. If new research projects are not covered by this permit, the investigator will have to obtain a special permit from the appropriate governmental agency such as the SCDNR, United States Fish and Wildlife Service (USFWS) or NOAA. Approved permits must be in possession of permit holders at all times when in the field sampling. In addition to state and federal permits, written permission must be obtained from the BWBF prior to conducting research on the Hobcaw Barony property. This system is in place to protect the environmental integrity of the Baruch Foundation's holdings and to ensure that new studies will not interfere with existing projects. These policies have not impeded research in any substantive manner but some lead time is required to process requests before research projects can begin. Persons interested in conducting new research should contact the Reserve for additional information on the approved policies and procedures.

NERR System-wide Monitoring Program and other Monitoring at the NI-WB NERR

The National Estuarine Research Reserve System (NERRS) provides a mechanism for addressing scientific and technical aspects of coastal management problems through a comprehensive, interdisciplinary, and coordinated approach. Research and monitoring programs, including the development of baseline information, form the basis of this approach. Reserve research and monitoring activities are guided by the research and monitoring plan 2006-2011 which identifies goals, priorities, and implementation strategies. This approach, when used in combination with the education and outreach programs, will help ensure the availability of scientific information that has long-term, system-wide consistency and utility for managers and members of the public to use in protecting or improving natural processes in their estuaries.

Prior to the mid 1990s each reserve operated its research and monitoring program independently. The NERR System-wide Monitoring Program (SWMP) was designed and implemented at all reserves in 1995 and provides standardized data on national estuarine environmental trends while allowing the flexibility to assess coastal management issues of regional or local concern. The principal mission of the monitoring program is to develop quantitative measurements of short-term variability and long-term changes in the integrity and biodiversity of representative estuarine ecosystems and coastal watersheds for the purposes of contributing to effective coastal zone management. The program is designed to enhance the value and vision of the reserves as a system of national references sites. The program also takes a phased approach and focuses on three different ecosystem characteristics, described below.

1) **Abiotic Variables:** The monitoring program currently measures pH, conductivity, salinity, temperature, dissolved oxygen, turbidity, water level and atmospheric conditions. In addition, the program collects monthly nutrient and chlorophyll *a* samples at four SWMP stations and monthly diel sampling at one SWMP station. The chlorophyll and nutrient data are collected by hand or, in the case of diel sampling, by automated instruments. These data are submitted to a centralized data management office.

2) **Biotic Variables:** The reserve system is focusing on monitoring biodiversity, habitat and population characteristics by monitoring organisms and habitats as funds are available.

3) **Watershed and Land Use Classifications:** This component attempts to identify changes in coastal ecological conditions with the goal of tracking and evaluating changes in coastal habitats and watershed land use/cover. The main objective of this element is to examine the links between watershed land use activities and coastal habitat quality.

These data are compiled electronically at a central data management "hub", the NERRS Centralized Data Management Office (CDMO) at the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina, located at the NI-WB NERR. The CDMO provides additional quality control for data and metadata and compiles and disseminates the data and summary statistics via the Web (**http://cdmo.baruch.sc.edu**) where researchers, coastal managers and educators can readily access the information. The metadata meet the standards of the Federal Geographical Data Committee.

» Implementation of the System-Wide Monitoring Program at the North Inlet –Winyah Bay NERR

Routine environmental monitoring within North Inlet has occurred, in some fashion, since 1980, when a National Science Foundation Long-Term Ecological Research Site was established (LTER; 1980-1993). Abiotic variable monitoring under the evolving NERRS SWMP auspices began at the NI-WB NERR in 1993, with the establishment of two long-term water quality monitoring sites, one in North Inlet (Oyster Landing site) and one in a tidal creek of Winyah Bay (Thousand Acre Marsh site). A third long-term monitoring site was added in 1998 (Debidue Creek), and the fourth site in 2001 (Clambank Creek site). The location of the four SWMP stations is shown in Figure 4. At each station, YSI 6600 EDS data loggers are continuously deployed to record pH, conductivity, salinity, temperature, dissolved oxygen, turbidity, and water level data at 15 minute intervals, as per NERRS SWMP protocols. The 15 minute data from Oyster Landing and Debidue Creek stations are transmitted on an hourly basis to the NOAA Geostationary Operational Environmental Satellites (GOES) to provide near real-time data.

Figure 4. Location of the four System-wide Monitoring Program (SWMP) stations, vegetation biomonitoring transects, and fauna monitoring sites in the North Inlet-Winyah Bay National Estuarine Research Reserve.

Four System-wide Monitoring Program (SWMP) stations are located in the NI-WB Reserve at Clambank Creek (top left), Oyster Landing (top right), Debidue Creek (bottom left) and Thousand Acre.

Routine nutrient and chlorophyll *a* monitoring was initiated at each of the four sites at the same time the stations were established for long-term water quality monitoring. Nutrients and chlorophyll *a* are sampled at exactly 20 day intervals, more frequently than the NERRS-recommended "approximately monthly intervals." This decision, approved by the NERR SWMP Oversight Committee and NERRS Data Management Committee, was made so as to minimize sampling bias with respect to spring – neap tidal periodicity over the annual cycle. On these 20 day intervals, both duplicate low tide grab sampling and diel sampling (2 hr and 4 min intervals over 26 hr) of water are conducted at each of the four stations. This sampling is accomplished through the deployment of ISCO model 3600 automated water samplers at each of the four stations. In addition to the currently the required dissolved inorganic nutrients (NH_4^+, NO_2^-, NO_3^- and PO_4^{3-}) and chlorophyll *a*, the Reserve has also been measuring a suite of elective nutrients. To date, this includes dissolved organic carbon, total suspended solids, organic and inorganic suspended solids (determined by difference before and after combustion at 450°C), as well as total nitrogen and total phosphorus in both the particulate and dissolved phases, which allow organic nitrogen and phosphorus fractions to be determined as the difference between total and inorganic fractions.

Meteorological conditions at North Inlet have been measured by the Baruch Marine Field Laboratory since 1982. In 1997, meteorological measurements were modified slightly to conform to the newly established NERR SWMP protocols for meteorological data collection. The NI-WB weather station is located at Oyster Landing, adjacent to the long-term water quality and nutrient monitoring station. Air temperature, wind speed and direction, relative humidity, barometric pressure, rainfall, total short-wave global radiation (280 - 2800 nm wavelengths) and photosynthetically active radiation (400-700 nm wavelengths) are recorded. Sensors are all located on an electrically grounded aluminum tower at a height of approximately 3.5 meters. Sensors are connected to a Campbell Scientific CR-1000 data logger that records the meteorological conditions every 5 seconds continuously throughout the year, producing 15 minute, hourly, and daily averages of the data parameters.

» Other Monitoring Programs Conducted by the Reserve

ESTUARINE FAUNA MONITORING

Routine monitoring of dominant estuarine fauna in North Inlet began in the early 1980s with a grant from the National Science Foundation's LTER program. This monitoring was continued by the Reserve beginning in 1993. The on-going goals of this program are: to quantify the long-term composition and abundance of estuarine fauna within the Reserve in order to characterize and understand short-term variability and long-term changes in the abundance and community composition of both resident and transient estuarine species; to provide researchers and resource managers reference data from a relatively pristine estuary for comparisons with anthropogenically-impacted estuarine sites; and to provide baseline data for other faunal research conducted within North Inlet.

The components of the Reserve's fauna monitoring program include:

Zooplankton: Defined by two size fractions: a 153 micrometer mesh net towed obliquely through the water column collects copepods and small invertebrate larvae; and a 365 micrometer mesh net mounted on an epibenthic sled collects the larvae of fishes, shrimps and crabs as well as other large zooplankton. 153 micrometer tows are collected in duplicate. 365 micrometer tows are collected in triplicate. Samples have been collected biweekly since 1981 at mid-ebb tide in Town Creek and have been identified to lowest practical taxa and life stage.

Nekton: Comprised of resident and transient fishes, shrimps and crabs greater than 20 mm long. From 1984 until fall 2011, biweekly (spring, summer and fall) or monthly (winter) collections were made using a combination of seining a drainage pool at low tide and/or enclosing a one acre area of flooded marsh at high tide and collecting all fauna leaving the area with the ebbing tide in a 0.25 inch mesh net. Sample catches were processed for species richness, individual species abundance and biomass, individual species lengths, and total catch abundance and biomass. This very labor-intensive sampling was conducted in the Oyster Landing basin, adjacent to the Reserve's long-term water quality, nutrient and weather monitoring station. Since fall 2011, the project was scaled back to examine phenology and growth of transient species to this basin through a biweekly seining effort conducted April – November.

Benthos: Two size fractions of animals that live in the sand or mud have been made at the same locations in North Inlet since 1972 (meiofauna) and 1981 (macrofauna). Biweekly samples of macrobenthos (> 0.5 mm) were collected from 1981-1992, and then quarterly from 1992 to the present. Meiofauna (<0.5 mm > 0.063 mm) samples were collected at two sites and analyzed through 1994. Although macrofauna continue to be sampled on a quarterly basis to maintain continuity in the dataset, neither the Reserve nor the Baruch Marine Field Laboratory currently has the personnel and resources needed to process the archived samples.

SALT MARSH EMERGENT VEGETATION MONITORING

As part of the biological component of the NERR System-Wide Monitoring Program, the Reserve initiated a long-term vegetation monitoring program

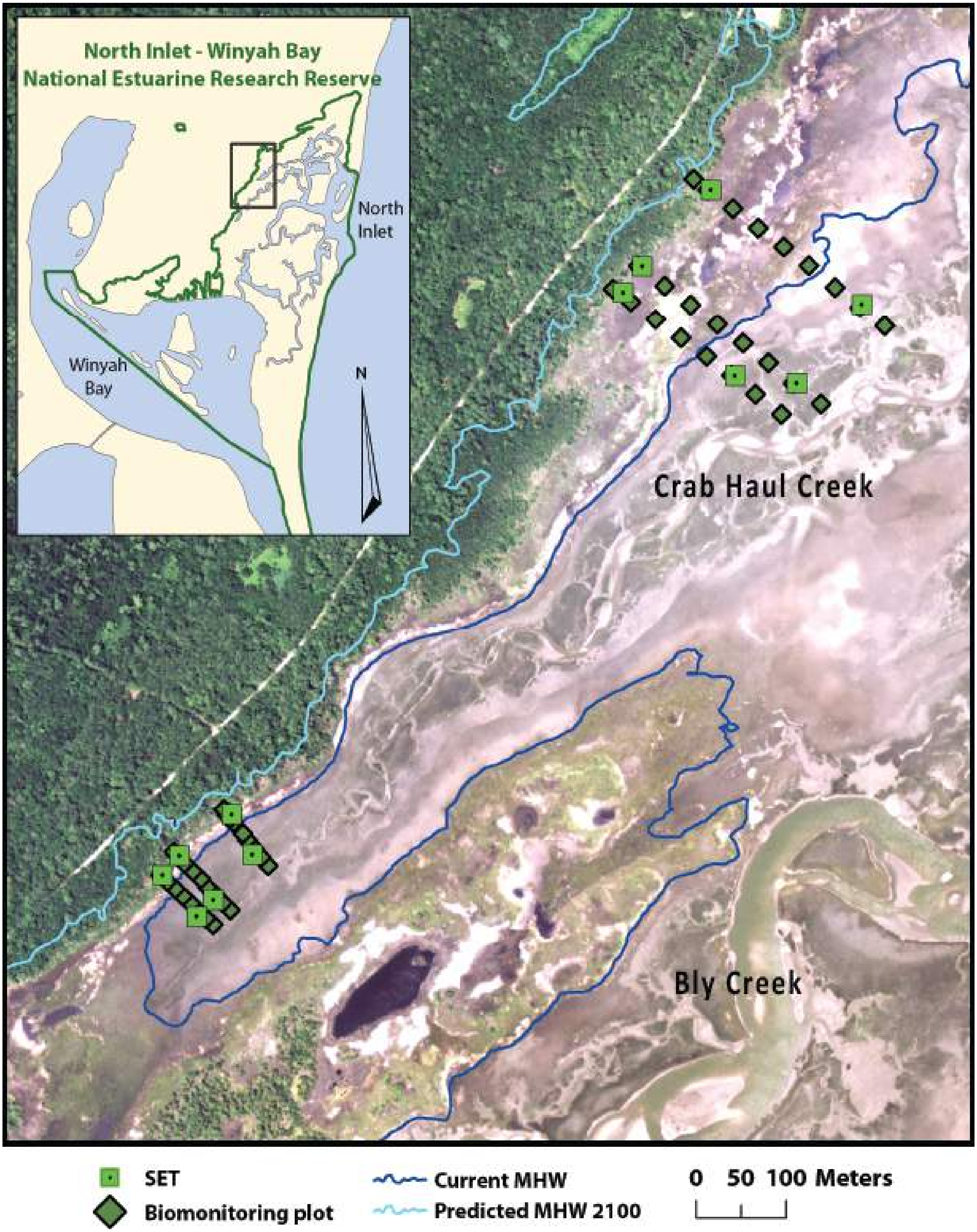


Figure 5. Long-term emergent vegetation monitoring plots and infrastructure in the Crab Haul Creek basin in North Inlet.

in 2005. The long-term goal of this program is to assess the effects of rising sea level on the spatial dynamics of emergent vegetation communities within the salt marshes of the North Inlet –Winyah Bay NERR. Specifically, this project seeks to quantify how salt marsh macrophyte community structure (species composition, relative abundance) varies along an elevation gradient, from creek bank to upland forest edge, in response to long-term changes in tidal height and flooding frequency due to sea level rise. In accordance with established NERRS protocols, a stratified sampling approach using fixed transects and repeated measurements within permanent sample plots are employed. Two segments have been established along the central axis of upper Crabhaul Creek, upstream of the Oyster Landing long-term water quality, nutrient and weather monitoring station and NOAA/NOS tide gauge (Figure 5). Within each segment, 3 fixed transects were randomly established from creek bank to the western, upland edge of the marsh platform. Each segment delineates a total of 25 permanent sampling plots. Groundwater wells and porewater equilibrators are installed adjacent to each permanent plot. Sediment Elevation Tables (SETs) have been installed adjacent to plots at the lower and upper ends of each transect. Vegetation sampling includes: percent cover for each species or cover category; species' shoot/stem density; species' maximum canopy height, which is conducted annually at the end of the growing season. Water table height and salinity at low tide is sampled biweekly, porewater chemistry (nutrients, dissolved organic carbon, and sulfide concentrations) is sampled monthly during summer, SET measurements are conducted bimonthly.

A long-term monitoring program will help to assess the effects of rising sea level on the spatial dynamics of emergent vegetation communities within the salt marshes of the North Inlet –Winyah Bay NERR.

MICRO-PLANKTON METABOLISM MONITORING

The Reserve conducted a program to quantify and understand the short-term variability and potential for long-term change in water column respiration and heterotrophic production rates through a combination of routine field measurements and manipulative experiments during the period July 2005 – December 2012. The focus of this effort was on the tidal creeks and open-water portions of the estuary because these represent the conduit for material exchanges between the land-margin and coastal ocean. Routine sampling was conducted on both ebbing and flooding tides at the Oyster Landing site in conjunction with the 20-day water chemistry sampling. The goal of this program was to quantify the role of the pelagic microbial community in the biogeochemical dynamics of carbon, nutrients and oxygen in the creek waters of North Inlet. This information will help improve understanding of how key ecological processes within the ecosystem respond to long-term changes associated with climate change, salt marsh productivity and organic export associated with sea level rise.

Geographic and Cultural Setting

The Region and South Carolina Coast

North Inlet-Winyah Bay NERR is located in Georgetown County, SC, about 50 km (30 mi) south of Myrtle Beach and 80 km (50 mi) north of Charleston (see Figure 2 presented in an earlier chapter). The entire length of the South Carolina coastline stretches approximately 300 km (180 mi) and includes more than 4,800 km (nearly 2,900 miles) of shoreline. Approximately 80,000 ha (200,000 acres) of marshes occur along this coast. A full range of Southeast coastal systems, including river-dominated estuaries (e.g., Winyah Bay, Santee), coastal lagoons and sounds (e.g., Bulls Bay, Port Royal), and ocean-dominated salt marsh systems (e.g., North Inlet and Murrells Inlet) can be found along the South Carolina coast.

South Carolina has four major watersheds that terminate at the coast, the Savannah, the Santee, the A.C.E. and the Pee Dee. Winyah Bay is in the northernmost Pee Dee watershed (Figure 6). The main rivers in central South Carolina meet the ocean at Charleston Harbor Estuary. Several smaller rivers drain through the ACE Basin NERR. The Savannah River Basin drains some of southern SC. Although the most conspicuous estuaries on the SC map are associated with major rivers, tidally-dominated estuarine waterways and marshes are far more numerous on the SC coast than those which receive most of their water from rivers.

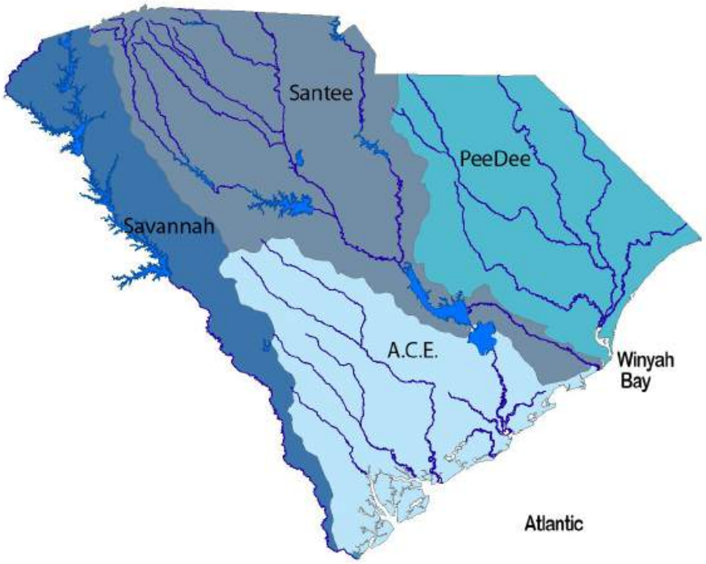


Figure 6. The four major watersheds of South Carolina.

According to NOAA's Biogeographic Classification Scheme, the NI-WB Reserve is in the South Atlantic subregion of the Carolinian biogeographic region. Other southeastern NERR sites include the NC NERR, the ACE Basin NERR about 150 km (90 mi) south of the NI-WB NERR in SC, the Sapelo Island NERR near Brunswick, GA, and the GTM NERR near St. Augustine, FL (Figure 7).

Figure 7. Southeast Reserves and major rivers and urban areas of the southeast. The Winyah Bay watershed is highlighted in blue.

The North Inlet and Winyah Bay Estuaries

The Winyah Bay watershed lies mostly on the coastal plain of South Carolina (Figure 7). The sloped landscape accounts for a steady movement of riverine waters towards the sea. In terms of watershed size, Winyah Bay is the third largest estuary on the east coast of the US after the Chesapeake Bay (VA) and Pamlico-Albemarle (NC) complexes. The entire Winyah Bay watershed is approximately 18,000 square miles (4.7 million hectares or about 12 million acres). It accounts for about 20% of North Carolina's and 25% of South Carolina's land areas. The watershed is mostly rural forested and agricultural lands. Five primary river systems comprise the basin (Figure 8). With origins in the Blue Ridge Mountains of North Carolina, the Pee Dee – Yadkin River system drains the largest portion of the watershed (>85%); the (Great) Pee Dee is the largest river associated with Winyah Bay. The Lynches River lies to the west of the Pee Dee and drains a portion of east central SC. The Black and Sampit Rivers, which merge with the Pee Dee further downstream, drain coastal SC counties. The Little Pee Dee lies to the east of the Pee Dee and drains a portion of northeastern SC. The Waccamaw River originates from Lake Waccamaw in eastern NC and parallels the coastline. All of the rivers merge within 50 km (30 mi) of the coast and form an expanse of forested wetlands and marshes at the headwaters of the open water body known as Winyah Bay.

Winyah Bay is oriented along a northwest-southeast axis. The estuary is about 30 km (18 mi) long and ranges in width from 1 to 7 km (0.6 – 4.2 mi) (Figure 8). The surface area is approximately 15,500 ha (about 40,000 acres). Mean depth is 4.2 m (14 ft) and the deepest areas are associated with the shipping channel that traditionally was maintained at 8.2 m (27 ft). This federally-authorized channel extends from the Port of Georgetown about 29 km (17 mi) to jetties at the mouth of Winyah Bay. Various types of tidal wetlands and impounded marshes border Winyah Bay downstream of the US Highway 17 bridges.

The North Inlet watershed is comparatively small, comprising approximately 38 square kilometers (3800 ha or just under 15 square miles). Most of the uplands are forested and only about 2% of the watershed is developed (Figure 8). Freshwater runoff into the tidally-dominated North Inlet is through numerous small streams and groundwater. The bar-built type estuary at North Inlet encompasses approximately 3,300 ha (8,250 acres). Salt marsh cordgrass (*Spartina alterniflora*) dominates the system, but other types of marshes occur around the upland borders and on the southern border where North Inlet intersects with the Mud Bay section of Winyah Bay (Figure 8). Mud Bay is an expansive shallow lagoonal area north and east of the main axis of Winyah Bay. Several large marsh islands and historic dredge spoil islands lying along the navigation channel separate Mud Bay from the rest of the open water of Winyah Bay.

The Black and Pee Dee Rivers (left) and the Waccamaw River (right) enter Winyah Bay just north of Georgetown.

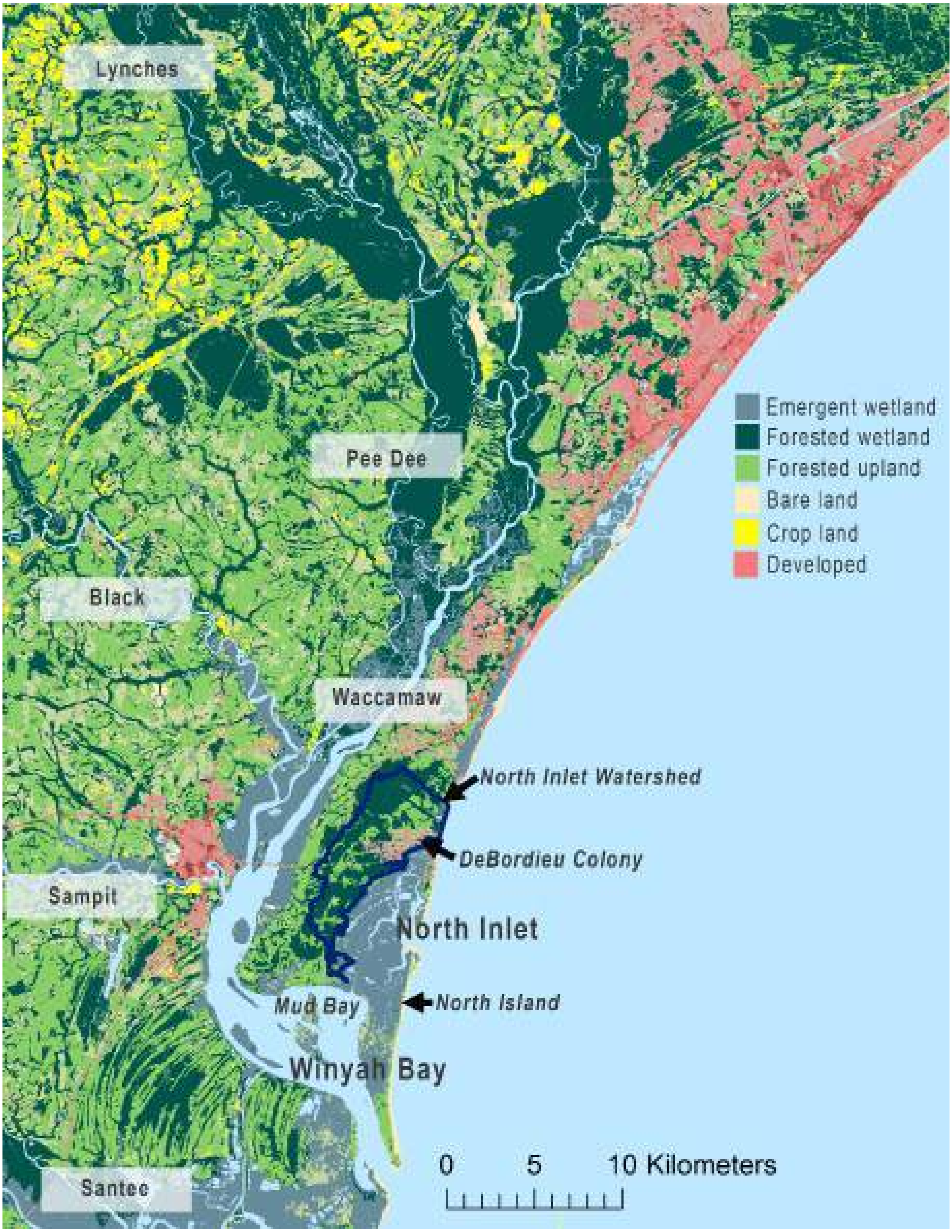


Figure 8. Rivers and landcover in the Winyah Bay and North Inlet watersheds.

Historic Land and Water Use

The peninsula where the North Inlet – Winyah Bay NERR is located was called "hobcaw" by local Native Americans. Meaning "between the waters," the term refers to the forested uplands being bordered by the Waccamaw River and Winyah Bay on the west and by the Atlantic Ocean on the east. The land supported the seasonal villages of the Waccamaw tribe. They hunted whitetail deer, black bear and wild turkey in the forests and harvested fish, oysters, clams, shrimp and crabs from the marshes.

The first contact with Europeans was most likely in 1526 when Spanish voyagers arrived with families, slaves and livestock and, according to most scholars, created a settlement on the shores of Hobcaw. The Spanish were unsuccessful. The English established the colony of Carolina in 1670 with Charleston as its capital and by 1700 had created Indian trading posts on the rivers of present day Georgetown County, one of which was located on Hobcaw's bluff overlooking Winyah Bay.

In the 18th century, Englishmen sought and were awarded land grants. Native Americans were displaced into present day Horry County, SC, and North Carolina. Hobcaw Barony was granted by King George to Lord Carteret, one of South Carolina's eight Lords Proprietors. The grant, called a "barony," stretched from the river to the sea and included swamps, marshes, woods and dunes. As the colony prospered, the tract was sold and subdivided into 14 separate, individually named plantations which first produced timber and naval stores, such as pitch, tar and turpentine, and within a few more years, high yields of indigo and rice.

By the time of the Civil War, Georgetown County grew more rice than any other place in the world except the area around Calcutta, India. At Hobcaw Barony, the plantations were owned by men whose names are prominent in local history, and the land was worked by slaves whose descendants still live in the area. Remnants of the plantation era survive as extant slave cabins, ruins of a rice mill and cemeteries. Maps, deeds and plats provide evidence of main houses, churches, summer cottages, boundary ditches and rice fields.

The rice era changed significantly following the emancipation of slaves and with growing competition from rice growers in western states. A series of unusual storm events at the turn of the 19th century ended rice production, and landowners sought to create revenue by harvesting timber and leasing their land to hunters.

In 1904, Bernard M. Baruch, a native South Carolinian and Wall Street financier, hunted over the rice fields and salt marshes of Hobcaw Barony with a group of northern hunters. He spontaneously offered to purchase the land. By 1907, Baruch was able to buy 11 of the original 14 tracts from various

Above: Friendfield Village Cabins, circa 1905 - courtesy of the Belle W. Baruch Foundation. Right: Friendfield church 2013.

The original Baruch winter home, the Old Relick (top), burned to the ground in 1929, and was replaced by Hobcaw House (bottom). Photos courtesy of the Belle W. Baruch Foundation.

owners to reassemble most of the original barony. He established a winter retreat for his family at Hobcaw, away from the pressures of city life in New York and away from the decisions he had to make as a presidential advisor in Washington. Each winter between Thanksgiving and Easter, family and guests hunted the land for duck, deer, turkey, quail, dove, and wild hog. Local men were hired as plantation managers, hunting guides and maintenance supervisors and moved their families to live on the barony. Freed slaves, their children and grandchildren continued living in four remaining slave villages and were hired by Baruch as boatmen, farmers, stable hands, cooks and maids. Goods and equipment were bought locally and boats ran regularly between Georgetown and Hobcaw Barony.

The Baruchs entertained hunting parties regularly and guests included congressmen, military officers, Broadway and Hollywood personalities, journalists, poets and musicians. In 1932, Winston Churchill arrived by yacht and in 1944, President Franklin D. Roosevelt stayed nearly a month for a much-needed health vacation. In addition to hunting, the guests enjoyed fishing, riding, oyster roasts, wild game dinners, drinking and storytelling.

In December 1929, a fire burned the Baruch winter home to the ground, leaving only ashes and fire-scarred live oaks that still overlook Winyah Bay today. Hobcaw House, a brick, concrete, and steel structure, was constructed on the same site the next year. Mr. Baruch sold the northern half of Hobcaw to his eldest child, Belle, in 1935 and by 1956, Belle had acquired all of Hobcaw Barony.

As a young child, Belle had enjoyed the forests and the waters of the family's winter retreat and became a sailor and equestrian, competing internationally in the 1920's and 30's. She became a pilot at age 40 and regularly flew from New York to Hobcaw. While in residence, she flew over the marshes of Hobcaw and guarded them against poachers. Through her protection of the fauna and habitats, Hobcaw was transformed from a hunting locale to a wildlife refuge. She entertained on a small scale and shared the property with a close circle of friends.

When Belle became very ill at age 64, she focused on the future of her property. She created a trust and directed trustees to hold the property in perpetuity for the purposes of research and education in the fields of forestry, wildlife and marine science. Her further stipulation was that the property should serve as an outdoor laboratory for researchers from universities and colleges located in South Carolina. Her death in 1964 began an era of long-term research that continues today. The Belle W. Baruch Foundation owns and operates the private tract and encourages its use by researchers, educators, students, and historians. An excellent summary of Hobcaw Barony history that includes historic photographs is found in *Plantation Between the Waters – A Brief History of Hobcaw Barony* by Lee G. Brockington (2006).


Belle and her father Bernard Baruch at the Old Relick, circa 1925 - courtesy of the Belle W. Baruch Foundation

CURRENT LAND AND WATER USE

South Carolina is among the fastest growing states in the nation. Population projections calculated by the SC Budget and Control Board's Office of Research and Statistics indicate that South Carolina's population will increase by over one million new residents by 2015, with rapid development at the periphery of the state's larger metropolitan areas and coastal resort/tourism centers (South Carolina Population…[cited 2010]). The state has roughly 182 miles of beaches and 200,000 acres of saltwater marshes that attract almost 30 million tourists annually.

A National Resource Inventory report released in 2000 indicated that between 1992 and 1997, 15.8 million acres of South Carolina's land were converted from farms and woodlands to a developed land status (U.S. Department of Agriculture, 1997). Land was converted at six times the rate of population growth during that period, a rate of development that was the 9th fastest in the nation despite ranking only 40th among states in land area. Development directly affects habitat quality and ecological communities as buildings and infrastructure replace natural areas, and also has indirect effects which are often overlooked and may be difficult to quantify. Runoff from impervious surfaces carries sediment and toxic chemicals into ditches and small streams that feed into the waterways. The infilling of isolated wetlands compounds the runoff problem as the water-holding and filtration capacity across the landscape is reduced. Development also forms barriers to the movement of species and materials between protected natural areas, creating a fragmented landscape which may diminish ecosystem functioning.

The North Inlet watershed is currently largely undeveloped. The land within the watershed is classified by the NOAA Coastal Change Analysis Program (C-CAP) as estuarine emergent wetland (29%), palustrine forested wetland (25%) and evergreen forest (18%). Only about 2% of this watershed is classified as low or medium intensity development. DeBordieu Colony is a gated residential community just north of the NERR, with high-end residential homes, condominiums, an 18-hole golf course, private docks and a boat ramp. Also in the North Inlet watershed is the gated community Prince George with properties both east and west of Highway 17. This development includes beach front and riverfront home sites and a private access boat slip and ramp on the Waccamaw River. The University of South Carolina Development Foundation also owns about 1,200 acres of forest, former rice fields and tidal marsh within the Prince George tract. An additional planned development just north of DeBordieu, Bannockburn, will also be within the North Inlet watershed. Clemson University's Baruch Institute for Coastal Ecology and Forest Science has initiated a pre- and post development impact study on this property.

Calculations of land cover based on the C-CAP data show that the majority of land in the 18,000 square mile Winyah Bay watershed is palustrine forested wetland (23%), evergreen forest (22%), cultivated land (19%), and scrub/shrub (12%). Approximately 3% of the land area is classified as low to high intensity development (Figure 9).

Within the City of Georgetown and Georgetown County, land use is much more diverse (with associated anthropogenic impacts), including large industries such as International Paper Company, 3V Chemical, a cargo port facility, a steel mill,

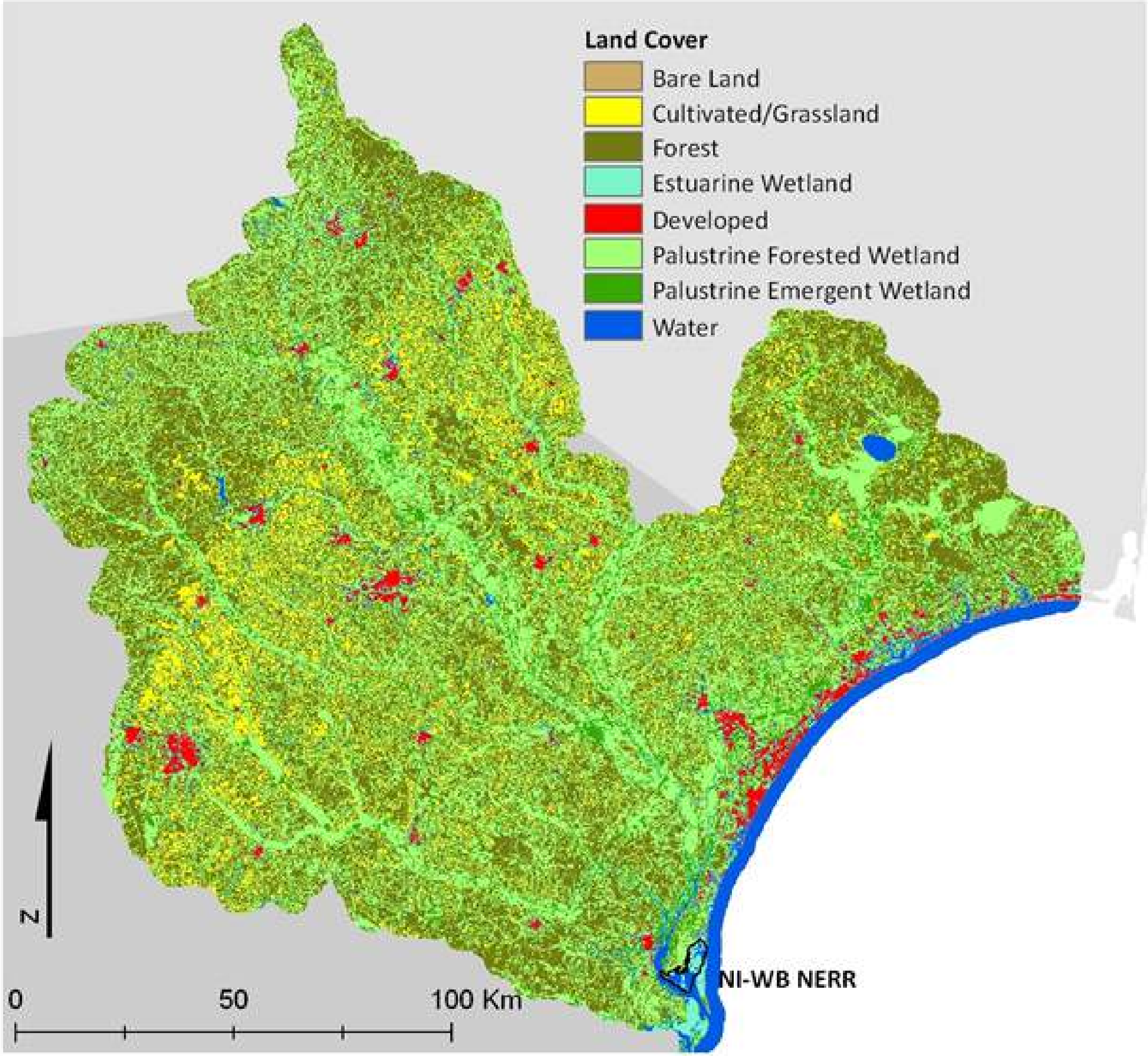


Figure 9. Coastal Change Analysis Program land use/land cover classification in the Winyah Bay watershed.

several marinas, and municipalities and associated infrastructure - including a variety of mixed-use businesses and single and multi-family residences. The Atlantic Intracoastal Waterway follows a portion of the Waccamaw River and maintenance dredging of this waterway and also the shipping channel for the Port of Georgetown is conducted on a periodic basis.

The population of Georgetown County reached 63,520 in 2010 according to the U.S. Census Bureau. The population of the county increased by 9.5% between 1980 and 1990, by 20.5% between 1990 and 2000, and by 13.8% from 2000 to 2010. Current projections by the Waccamaw Regional Council of Governments anticipate that the County of Georgetown will increase its 2000 population an additional 30.1% by the year 2030 (Waccamaw Regional … [cited 2010]). The Waccamaw Neck, the narrow strip of land between the Waccamaw River and the Atlantic Ocean which includes the resort towns of Pawleys Island, Litchfield Beach, and Murrells Inlet, is one of the fastest growing areas of Georgetown County. A 2003 population estimate of the Waccamaw Neck included 16,000 residents, a number that has tripled in the past 30 years.

NOAA C-CAP data were used to generate land cover changes from 1996 to 2001 within the Winyah Bay watershed. The majority of changes were from evergreen forest to shrub/scrub (21% of total change), from shrub/scrub to evergreen forest (14% of total change), from palustrine forested wetland to palustrine shrub scrub wetland (13% of total change) and from evergreen forest to grassland (11% of total change). These changes probably reflect forestry practices. About 3% of the total land change in the Winyah Bay watershed was undeveloped land to developed land. In comparison, within the Waccamaw Neck area adjacent to the NI-WB NERR, about 39% of the total land cover change was from undeveloped land to developed land.

Land management activities on Hobcaw Barony are designed to maintain a diverse and mixed age forest and conserve the rich historic sites. The pine and hardwood forest is managed by the Belle W. Baruch Foundation (BWBF) for research, long-term health, and wildlife. The BWBF harvests timber on Hobcaw periodically to improve forest health and to generate some revenue to support its operations including the continued protection and maintenance of the property. Buildings on Hobcaw Barony include research and education facilities associated with the Baruch Institutes of the University of South Carolina and Clemson University, the Hobcaw Barony Discovery Center and Baruch Foundation office, the Kimbel Conference Center, and several dormitories and visiting scientist cottages. Historic buildings including Hobcaw House, Bellefield House, numerous historic cottages, cemeteries, earthen fortifications, a rice mill, slave villages, and other sites are associated with Hobcaw Barony's designation as a registered National Historic Site.

Much of the history and current culture and economy of Georgetown County is associated with its abundant and diverse water resources. The City of Georgetown was one of the first ports in the Southeast region. Large volumes of lumber, cotton, rice, and other coastal products were exported, especially during the 1700's and 1800's. Today, the ship channel in Winyah Bay and the Sampit River provides a corridor for the movement of large commercial ships between the ocean and city of Georgetown. The Intracoastal Waterway provides protected access for commercial barges and recreational boats into Winyah Bay from the north and south.

The Harborwalk connects businesses in historic downtown Georgetown to the waterfront on the Sampit River. The harbor is also a popular stop over for boaters traveling the Intracoastal Waterway.

Local boaters use the extensive rivers and tidal marsh systems within Georgetown County for fishing, hunting, and general recreational enjoyment. In Winyah Bay and North Inlet, recreational fishers enjoy catching a variety of fishes, especially red drum, speckled sea trout, and flounder. Oysters, clams, shrimps, and blue crabs are also sought after resources by area residents and visitors. The recreational fishing industry in South Carolina was valued at over $441 million in 2009 (NOAA, 2011). The commercial shellfish industry in South Carolina contributed over 14 million dollars to the economy in 2010, with white shrimp being the most important in terms of value, followed by blue crabs and then oysters (National Ocean and Economics Program, 2012).

Belle Baruch's vision for preserving a large tract at the southern end of the Waccamaw Neck was noteworthy in the 1960's, and her legacy becomes more remarkable with each passing year as more and more of the coastal area becomes developed. Although Hobcaw Barony is one of only a few protected properties on the north side of Winyah Bay, a contiguous set of large tracts of land south of North Inlet are also protected and provide additional opportunities for research and education. Immediately adjacent to Hobcaw is the Tom Yawkey Heritage Preserve managed by SCDNR that includes North Island, South Island and Cat Island. Other properties in the protected chain include Santee Coastal Reserve, the Cape Romain National Wildlife Refuge, and Capers Island. Together, these properties comprise more than 50 miles of protected coastline.

There is a delicate balance between managing growth, development and tourism that drive South Carolina's economy while sustaining the natural resources that support these economic activities. Faced with this rapid growth scenario, the NI-WB NERR is committed to better understanding the impacts of coastal growth and to promoting stewardship of the resources in the North Inlet and Winyah Bay watersheds.

Shrimping continues to be an important part of the economy in coastal South Carolina.

Environmental Setting

CLIMATE AND WEATHER PATTERNS

General descriptions of climate, weather, storms and hurricanes for the state of South Carolina and the state's Lowcountry (coastal plain), including Georgetown County, were derived from the South Carolina State Climatology Office's website unless otherwise noted.

» Climate Controls

South Carolina's climate is classified as warm temperate – subtropical. Geographical features that most strongly influence the state's climate are its southerly latitude, low elevation, near proximity to warm waters of the Gulf Stream, and the blocking effect of the Appalachian Mountains which reduce the eastward flow of cold air from the interior of the United States during winter. Four seasons are recognized. Summers tend to be hot and humid whereas winters are short and mild. Variance in day length causes distinct differences in daytime heating and nighttime cooling among seasons. At the summer solstice, the sun is nearly overhead at solar noon, and the maximum zenith angle is approximately 79.5°. At winter solstice, the sun is low in the southern horizon at solar noon, and the maximum zenith angle is approximately 23.5°.

Coastal South Carolina has less extreme summer and winter temperatures than inland areas. Because land and water heat and cool at different rates, sea breezes cool the coast during the summer and warm the coast during the winter. During summer, the weather is dominated by a maritime tropical air mass known as the Bermuda High which brings moist air inland from the ocean waters of the Gulf Stream. At the land-sea interface, the air rises and forms a "sea-breeze front" where thunderstorms may extend up to 30 kilometers (20 mi) inland. This convergence zone is where the cooler air mass from the sea meets the warmer air from the land.

» Temperature

Along the coast, the onset of the spring warming is usually evident by mid-March, and warm temperatures (25 – 32 °C (77 – 90 °F)) are typical by mid-May. Summer humidity and heat commonly persist through September and into October. November brings relief from high temperatures. From December through March, daytime maximum temperatures (1981 - 2010) were about 15 °C (60 °F) in Georgetown (Station 2E). Freezing nighttime temperatures are not unusual from December through March but sustained periods that create ice are unusual. Surface ocean temperatures range from about 7 - 30 °C (45 – 85 °F) during the year.

The ‘Valentines’ storm on February 13, 2010 blanketed the marsh and boardwalk near the Baruch Marine Field Laboratory.

» Precipitation and Drought

In South Carolina, there is no discernible wet or dry season; alternating periods of heavy and light precipitation occur throughout the year with averages of two inches or more typical for every month. The state also has high year-to-year variability in precipitation; the main cause of high seasonal and interannual variability is the strength and geographic placement of the Bermuda High. As high pressure continues over the area, solar radiation increases, which in turn increases the temperature, which then decreases the cloud cover, thereby reducing the probability of substantial precipitation. When precipitation occurs during periods of drought, however, it is highly localized with low accumulation and the rainfall generally evaporates within 24-hours (Guttman and Plantico, 1987).

There is approximately a one in four probability of a drought somewhere in South Carolina at any time. Droughts are sometimes alleviated by a tropical cyclone. In 1954, Hurricane Hazel ended an extreme drought in eastern South Carolina, although drought conditions continued in western sections. In 1990, the remnants of Hurricane Klaus and Tropical Storm Marco ended an extreme drought. Historically, severe droughts have had adverse impacts on the people and economy of South Carolina. Periods of dry weather have occurred in each decade since 1818 (Hirschboeck, 1991). The most damaging droughts in recent history occurred in 1954, 1986, 1990, and 1998-2002, 2007-2008, 2011-12. The 1986 drought was severe and was accompanied by weeks of record or near-record high temperatures and record high demand for water in July. Less severe droughts were reported in 1988, 1993, and 1995. The adverse impacts on the people and economy were made especially clear during the drought of 1998-2002 that impacted agriculture, forestry, tourism, power generation, public water supplies, and freshwater fisheries. More recent detailed drought information for the Georgetown area comes from the SC State Climatology Office: Georgetown County was in a moderate drought in June 2007; drought status continued and was upgraded to severe in September 2007 through January 2008. The next moderate drought in Georgetown County lasted from June 2011 through April 2012.

In coastal South Carolina, precipitation tends to be greater in summer than in winter, but the pattern varies considerably from year-to-year. This is, in large part, due to the frequency and intensity of “sea-breeze front” thunderstorms, tropical storms or hurricanes during summer and autumn, and the frequency and intensity of El Niño/Southern Oscillation (ENSO) events (known as El Niños) during the winter and spring. In the Lowcountry, short-lived snowfall events are rare, occurring on average once every three years.

» Wind

Wind directions and velocities vary with the passage of weather systems, but the prevailing directions for the state and coast tend to be either from the northeast (during the cooler months) or southwest (during the warmer months). Upper air winds (those more than 1500 meters above mean sea level) are usually southwest to northwest in winter and spring, south to southwest in summer, and southwest to west in autumn. Average surface wind speeds for all months range between 6 and 10 miles per hour. The Appalachian Mountains have a strong influence on the prevailing surface coastal wind direction during all seasons but have a more pronounced effect in the winter, summer, and autumn. During winter, most low pressure cyclones that affect the state pass to the south of the mountains. As these systems move around the mountains, the winds are generally southwest. As the low pressure moves over the Atlantic Ocean, the winds shift to the northeast. During summer, air flows north along the western edge of the Bermuda High from the Gulf of Mexico. Quite often the mountains form the western extent of the Bermuda High. The Bermuda High also contributes to air stagnation, especially during the summer. Stagnant air is caused by very light winds that tend to be rather disorganized in direction. During autumn, winds are from the northeast because the mountains form the southern edge of the predominant continental high pressure pattern known as a “wedge”. This circulation generates northeast winds as the air wraps around the center of the high pressure in a clockwise fashion.

» Evaporation

The rate of evaporation of moisture from the ground influences weather, and the highest rates in South Carolina (> 65 inches, 1650 mm per year) are found along the lowcountry. Georgetown County’s annual rate is approximately 60 inches (data from 1961-1990). Evaporation measurements are expressed as the number of inches of water that evaporate from an evaporation pan per day, month, or year. Rate of evaporation is strongly influenced by wind velocity. With the increased frequency and intensity of droughts in the low country, evaporation rates are very important to estuarine ecosystems. With high evaporation rates and low rainfall, porewater salinity and geochemistry of marsh soils can change so dramatically that large expanses of saltmarsh cordgrass die-offs have been observed (Brown and Pezeshki, 2007). These dies-offs or diebacks have been observed more frequently and along the entire east coast within the last decade.

A former NI-WB NERR Research Coordinator stands next to what remains of an old loblolly pine which was impacted by a tornado formed from TS Gordon in 2000.

» Lightning

Thunderstorms and associated lightning are regular occurrences in the lowcountry, especially on warm afternoons and evenings from May to November. As of 2011, the National Weather Service (NWS) ranks South Carolina 18th in the number of reported lightning deaths (total of 99) since 1959 (Holle, 2012). The majority of lightning injuries and deaths occur on small boats without cabins.

» Tornadoes

In the period from 1950 through 2012 South Carolina saw 924 confirmed tornadoes, an average of 15 tornadoes per year. From 1994 to 2012 the annual average was 28 tornadoes per year. This dramatic increase is primarily attributable to the implementation of the National Weather Service’s advanced NEXRAD Doppler radar system which is able to pinpoint state-wide tornadic vortex signatures, unlike previous NWS radar systems. The majority, 81%, of South Carolina’s tornadoes are short-lived EF-0 and EF-1 tornadoes. Stronger more destructive EF-3 and EF-4 tornadoes are rare, but occur with a consistent annual frequency of 2-4 per year. There is no record or evidence of an EF-5 tornado, the strongest and most devastating on the EF scale, ever touching down in South Carolina.

Tornadoes have touched down in South Carolina during every month of the year; however, they are most likely in the spring and fall. During spring, tornadoes result from active cold fronts and pre-frontal squall lines. During November and December, active cold fronts can spawn tornadoes. Tornado frequency is at a minimum from October to January. In South Carolina, tornadoes are more likely to touch down during the afternoon and early evening; but, they can also touch down late at night and during the early morning hours. Fortunately, the strongest tornadoes occur in the afternoon and early evening when television and radio warnings are most effective. Many late season tornadoes are triggered by decaying tropical storms that make landfall in or near South Carolina. These tropical tornadoes can significantly add to the annual tornado average. Although tornadoes are rare in eastern Georgetown County, water spouts are not uncommon in the coastal ocean adjacent to the NI-WB NERR. Most are small and short-lived; however, a large water spout in Winyah Bay made landfall on the western side of the Hobcaw peninsula (just west of the North Inlet – Winyah Bay Reserve) during Tropical Storm Gordon in 2000 and destroyed more than 30 acres of old growth forest.

» Winter and Coastal Storms

The most intense winter storms generate high northeasterly winds and extreme high tides along the coast. They can occur anytime from autumn through early spring. Wave action, flooding, and beach erosion peak during this period. An especially severe storm system on January 1, 1987, produced gale force winds and abnormally high tides that caused an estimated $25 million worth of damage to South Carolina barrier island properties. In December 1989, the lowcountry experienced its first white Christmas on record, with more than six inches (15 cm) of snow that lasted for several days.

» Hurricanes (Tropical Cyclones)

In the western Atlantic basin, hurricane season is typically from June through November, with peak activity in August and September. Tropical cyclones are infrequent along the South Carolina coast. Depending on the storm's intensity, speed, and proximity to the coast, tropical cyclones can be disastrous. The major coastal impacts from tropical cyclones are storm surge, winds, flooding, precipitation, and tornadoes. Storm surge refers to the increase in the level of the ocean as water is pushed forward in front of the advancing wind field. Hurricanes can have lasting impacts on the geomorphology of local barrier islands, forests, crops, and local economies.

Hurricanes are characterized by wind speeds exceeding 64 knots (74 miles per hour) and central

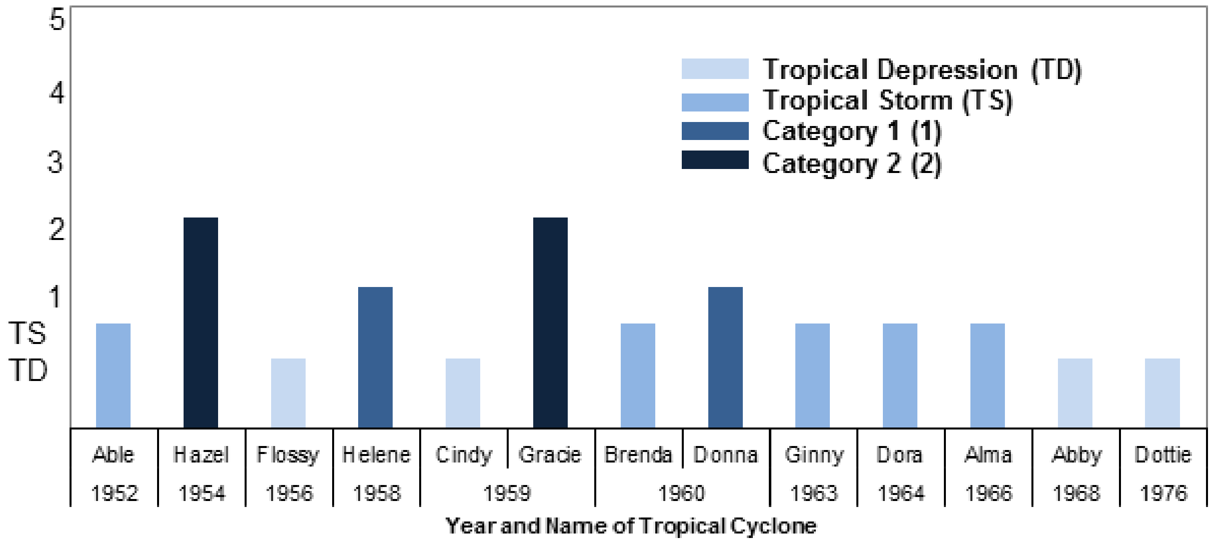


Figure 10. Classification of tropical depressions, storms, and hurricanes that occurred in the North Inlet- Winyah Bay area between 1952 and 1976. Classifications of storms in this figure are based on their category when they hit the North Inlet – Winyah Bay (Georgetown County) area, not on their full core intensity when they were offshore or hit other areas first.

pressure usually less than 980 millibars (mb) (28.94 inches of mercury). Less intense, but more frequent, are tropical storms (winds over 34 knots and under 64 knots: greater than 980 mb central pressure) and tropical depressions (winds under 34 knots). In the period 1901-2009, only 27 tropical cyclones made landfall on the South Carolina coast. Of these, only eight were of Category 2 to Category 4 intensity. Since 1900, no Category 5 hurricanes have hit South Carolina. There have been two Category 4 hurricanes (Hazel, 1954, and Hugo, 1989) and two Category 3 hurricanes (September 17th, 1945, and Gracie, 1959). It is possible that the "Great Storm of 1893" that struck the southern coast on August 20 of that year was at least a Category 4 storm, but there was no way of accurately measuring tropical-cyclone intensity before 1900.

» Lowcounty and NI-WB NERR Tropical Cyclone Impacts

Accounts of major hurricanes are prominent in the history of Georgetown County. According to historical newspaper records, North Inlet was hit by a devastating hurricane in 1822. It made landfall near Charleston and moved up the coast to Virginia before moving out to sea. With the arrival of the hurricane, tides were unable to ebb and then flooded with overwhelming violence, killing more than 300 people who were living on North Island. By 1893, major population centers could be telegraphically alerted to storms moving along the coast, but there were no warnings for the Sea Islands and other isolated areas. The "Great Storm of 1893" struck the south coast at high tide on August 28th, pushing an enormous storm surge ahead of it that swept over and submerged whole islands. Maximum winds in the Beaufort area were estimated to be 125 miles per hour; those in Charleston were estimated near 120 miles per hour. At least 2,000 people lost their lives, and an estimated 20,000-30,000 were left homeless and with no means of subsistence. Notable and historical storms which impacted the NI-WB Reserve from the 1950s to the late 1970s are shown on Figure 10.

In the last 60 years, hurricanes Hazel (October 14th, 1954), Gracie (September 29th, 1959), and Hugo (September 22nd, 1989) have been the most severe storms to impact the northern South Carolina coast. Hazel, a Category 4, made landfall near Little River, S.C., with 106-mph winds and a storm surge of 16.9 feet. Damage was estimated at $27 million. Hurricane Hazel moved parallel to the coast before making landfall; the heaviest damage in South Carolina was from Pawleys Island northward (Pawleys Island is just a few miles north of the North Inlet – Winyah Bay Reserve). Gracie, a Category 3, made landfall between Charleston, SC, and Savannah, Georgia, on St. Helena Island and continued toward the north-northwest, maintaining hurricane strength for more than 100 miles inland. Winds reached 140 mph and tides reached 8 ft. Damage of disaster proportions occurred along the coast from Beaufort to Charleston, and was estimated at $20 million (1959 dollars). These storms did considerable damage to the forests surrounding the North Inlet salt marsh. Heavy rains caused flooding through much of the state and crop damage was severe.

In more recent years, meteorological data have been recorded during the passage of tropical storms and hurricanes by the Baruch Marine Field Laboratory and the North Inlet-Winyah Bay NERR (Table 1). The amounts of rain recorded for the various storms varied and were not related to the classification (category) of the event. Amounts were related to the location of the Reserve relative to the core of the cyclone, the precipitation potential of the storm, and the rate at which it moved across the landscape. The greatest rainfall was recorded during Fran (1996, 12-15 inches) and Floyd (1999, 12-18 inches). Hurricane Floyd (September 1999) did not make landfall in South Carolina but was a very large storm that came ashore near Cape Fear, NC. Heavy rain of more than 15 inches fell in parts of Horry County, SC, causing major flooding along the Waccamaw River (which feeds into Winyah Bay) in and around the city of Conway, SC, for a month. The year 2004 was a particularly active summer for tropical storms with Alex, Bonnie, Charley, Gaston, Frances, and Jeanne affecting the Georgetown area and lowcountry. These six storms occurred within a two-month period (shaded area of Table 1).

Table 1. Tropical systems and their main impacts on the North Inlet – Winyah Bay and Georgetown area between 1981 and 2010. Rainfall amounts recorded at Oyster Landing (OL) Pier are indicated for each named storm; *Hugo rain gauge amount is not correct as the entire pier was uprooted and laid on its side in the marsh. Other noted effects of each storm in nearby counties or along the SC coast are also discussed. The shaded area of the table highlights six storms that occurred within a two-month period.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Dennis	1981	Aug 19-20	Up and along SC Coastline, then into Myrtle Beach, SC	7.62	No data	Heavy rains with significant flooding
Sub-tropical Storm#1	1982	Jun 18-19	Along SC Coast, but Offshore	4.63	No data	No Information
Diana	1984	Sep 9-14	Along SC Coast, but Offshore	4.10	No data	Heavy Rains; gusty winds
Isidore	1984	Sep 29-30	Along SC Coast, but Offshore	2.70	No data	Heavy rains along the SC Coast
Bob	1985	Jul 23-25	Savannah, Ga North and Inland through Columbia, SC	5.00	18mph Jul 25 daily ave	Heavy rains, flooding, gusty winds
Kate	1985	Nov 22	Across SC: Aiken to Myrtle Beach	3.20	15 daily ave	Primarily heavy rain
Charley	1986	Aug 13-15	Along SC Coast, but Offshore	1.60	No data	Heavy rains along the SC Coast
Hugo (see text)	1989	Sep 21	Isle of Palms	*1.70	22 daily ave	Storm surge, tornados, flooding, winds, not much rain (2.5" in Georgetown)
Marco	1990	Oct 10-13	Up through GA then to Columiba, SC	7.00	No data	Rain with significant flooding
Bob	1991	Aug 18-19	Offshore of SC	2.40	9mph daily ave	1 SC storm-related death, rain
Gordon	1994	Nov 21	Up and along the SC coast	0.95	17mph Nov 20 daily ave	Higher than Normal tides, storm surge, flooding
Allison	1995	Jun 4-6	Across SC: Aiken to Florence	1.79	16mph Jun 6 daily ave	Heavy rains with street flooding in Georgetown, minor wind damage
Jerry	1995	Aug 23-27	Huge storm covered entire state; tracked through the upstate from GA	7.90	14mph Aug 26 daily ave	Heavy rains with street flooding in Georgetown
Arthur	1996	Jun 18-19	75 miles offshore of Cape Romain, SC	4.65	No data	Slow Rain event, no flooding
Bertha	1996	Jul 10-12	Offshore of Northern Coastal Counties	2.15	No data	other rain gauges in area: 3.5"; just below 60mph max wind gust in Charleston
Fran	1996	Sep 1-9	Offshore of Northern Coastal Counties	10.83	No data	Heavy rains with flooding
Josephine	1996	Oct 6-8	Up and along SC Coastline, then into Myrtle Beach, SC	3.69	No data	Heavy rain, gusty winds, flooding
Danny	1997	Jul 23-24	Across upstate SC east to around Lumberton, NC	1.23	No data	Weather station up and down in July; rain amount questionable
Bonnie	1998	Aug 26	70 miles offshore of Horry Co., SC	0.45	23 daily ave	More rain than our gauge measured (2 to 4"), at the Myrtle Beach Paviliion highest wind gust was 76mph

Table 1 continued.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Earl	1998	Sep 3-4	Across SC: Aiken to Florence	4.66	14mph Sep 3 daily ave	Tornado in Georgetown, gusts in county were 50-60mph, rain event with flooding
Dennis	1999	Aug 29-30	Offshore of SC: Closest to Horry & Georgetown Counties	2.79	16mph Aug 29 daily ave	Rain and wind event, 6" rain with wind gust of 48mph in Horry County
Floyd	1999	Sep 14-16	Offshore of SC: Closest to Horry & Georgetown Counties	10.29	24mph Sep 15 daily ave; max gust 24.6 on Sep 17	Huge Rain and wind event with flooding of roads & buildings, over 15 inches of rain from other gauges, beach erosion, with 15' waves at Cherry Grove Pier, gusts in Georgetown were 50-60mph
Irene	1999	Oct 16-17	Offshore & Parallel to SC coast	5.66	18mph Oct 17 daily ave	Large rain event with minor street flooding, gust in Charleston was 48 mph with beach erosion
Gordon	2000	Sep 18	Across SC: Savannah, GA to Florence, SC	5.60	11mph Sep 18 daily ave	Large rain event, other gauges > 8" of rain, tornado on Hobcaw Barony (see photograph), wind gust in Charleston 37mph
Helene	2000	Sep 21-23	Across SC: Aiken to Florence	3.83	10mph Sep 23 daily ave	Tornadic event in low country, wind damage, heavy rain in Berkeley County
Allison	2001	Jun 14-15	Across SC: Aiken to Florence	0.16	No data	Tornadic event in low country with wind damage
Kyle	2002	Oct 10-11	Up and along SC Coastline, brushing McClellanville, SC	0.67	12mph Oct 10 daily ave	F-2 Tornado in Georgetown, Beaufort to Goose Creek experienced 3-6 inches of rain with flooding of roads & homes
Alex	2004	Aug 1-2	90 mi SE of Charleston	0.27	13mph Aug 2 daily ave	Heavy rainfall with damaging river flooding occurred primarily upstate
Bonnie	2004	Aug 12-13	Up and along the SC coastline	5.60	7mph Aug 13 daily ave	Tornadic events across the state, including low country with wind damage, severe thunderstorms, heavy rainfall
Charley	2004	Aug 14-15	Offshore of SC: Brushing Horry & Georgetown Counties	4.24	10mph Aug 14 daily ave	Tornados in Georgetown and other nearby lowcounty counties, max wind gust in Georgetown 57mph & 100mph in Surfside, power outages, 5.71" Rain from another gauge, minor coastal erosion
Gaston	2004	Aug 26-31	Northward up through Bulls Bay, SC	4.52	27mph Aug 29 daily ave	Wind Damage in the lowcountry, with tornados and heavy rain, max wind gust at the Isle of Palms was 73mph, flooding and some coastal erosion
Frances	2004	Sep 6-9	Across upstate SC northeast to West Virginia	0.64	19mph Sep 8 daily ave	Tornadic events across the state, including low country with wind damage
Jeanne	2004	Sep 26-28	Upstate mountains	0.79	19mph Sep 26 daily ave	F1 Tornado 27 Sep 2004 in Georgetown, primarily a wind event in the lowcountry, max gust in downtown Charleston 41mph, 1.9" another local rain gauge

Table 1 continued.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Cindy	2005	Jul 7-9	Upstate mountains	3.82	12 & 26 on jul 7	Heavy rain, gusty winds, tornados, flooding statewide, locally wind and rain
Ophelia	2005	Sep 12-14	Offshore; closest to Horry and Georgetown Counties	2.31	17 & 37 on sep 13	In Georgetown and Horry Counties: High surf and severe beach erosion, minor coastal flooding and wind damage, Myrtle Beach Airport max gust 44mph
Tammy	2005	Oct 5-8	South of State: Georgia and Florida; strongest effects north of Center	9.00	19.5 & 44 on oct 6	Major beach erosion along the coast, street & building flooding and damage in Georgetown, 14.88 & 15.14" other local rain gauges, wind damage, max gust at Edisto Beach of 59 mph
Alberto	2006	Jun 13-15	Across SC: Aiken to Florence	1.31	21.5 & 40 on jun 14	Wind Damage in the lowcountry, with tornados and heavy rain, most effects felt south of Charleston
Ernesto	2006	Aug 31 - Sep 1	Offshore of SC: Closest to Horry & Georgetown Counties	4.07	23 & 39 on aug 31	Heavy rain, flood and wind event, especially in Horry and Charleston Counties, North Myrtle Beach Airport 7.20" rain with 44 peak gust
Andrea	2007	May 8-13	Offshore of SC	1.39	17 & 40 on may 8	Primarily wind event with heavy surf
Barry	2007	Jun 2-3	Up and along the SC coastline	1.90	15.5 & 44.5 on jun2	Rain and wind event in lowcountry, minor storm erosion, local gauges in Georgetown 3.81" & 2.07, 51 mph gust at Edisto Beach
Cristobal	2008	Jul 17-20	Offshore & Parallel to SC coast	0.57	13.7 & 28 on jul 17	Very little rain along the coast, no damaging winds
Fay	2008	Aug 20-26	South of SC: East Coast of Florida tracked west through FL panhandle	1.47	20 & 33 on Aug 21 & 22	Heavy rains over SC, tornados upstate, 3.57" Rain in local gauge
Hanna	2008	Sep 4-6	Offshore of SC: Closest to Horry & Georgetown Counties	3.61	17 & 40 on Sep 5	Minor beach erosion, 4.12" & 4.48" other local rain gauges, peak gust in North Myrtle Beach 59mph
Ida	2009	Nov 10-12	South of SC: Alabama east to FL panhandle	3.38	15 & 28 on Nov 12	Heavy rainfall across SC, local gauges 4.08" & 4.2" rain

Tropical storms, tropical depressions and hurricanes affect North Inlet and Winyah Bay in many different ways. Rain, flooding, wind damage, and storm surge can cause severe destruction. Not all tropical storms and hurricanes impart the same type of damage. For example, Hugo had extremely intense winds with a large storm surge, but very little rain. On the other hand, a relatively minor tropical system can cause devastation with its slow movement and heavy rainfall and flooding.

Hurricane Hugo was the most significant storm in recent history to impact the North Inlet – Winyah Bay NERR. Hugo made landfall on September 21st, 1989 as a Category 4 near the Isle of Palms just north of Charleston with winds of 138 miles per hour and gusts over 160 miles per hour and storm surge of 20+ feet. It continued on a northwest track at 25-30 miles per hour and maintained hurricane force winds (gusts up to 109 miles per hour) as far inland as Sumter. Hugo exited the state southwest of Charlotte, N.C., before sunrise on September 22nd. The hurricane caused 35 related deaths, and it injured several hundred people in South Carolina. An estimate of more than 50,000 people were left homeless. Damage in the state was the costliest in history. Damage was estimated to exceed $7 billion, including $2 billion in crop damage. The forests in 36 counties along the path of the storm sustained major damage.

Hugo struck The NI-WB Reserve near high tide and created a storm surge of 12 to 14 ft at the USC Baruch Marine Field Laboratory. Wind-driven waves of up to 5 ft were superimposed on the heighted level of the ocean. Storm surge traversed the barrier islands and salt marshes and caused ocean water to flood over a large area of coastal forest adjacent to the estuary. The surge retreated within a few hours after the storm moved inland. In general, physical impacts on the tidal system were minimal and short-lived. There were no major changes to the saltmarsh creek network or to the size or shape of sand bars in the estuary (Gardner, et al., 1992a). The oyster reefs and lower-lying mud flats were sufficiently buffered by the high tide when the most violent part of the storm and waves arrived, so little evidence of physical disturbance was evident. Wave action and the retreating surge scoured the marsh surface of most of its soft sediments leaving exposed roots on a sandy base. Tidal creek waters remained very turbid for at least 6 weeks. Resuspended sediment was deposited on the vegetated intertidal marsh during the following weeks, but it was months to more than a year before the inner marshes and intertidal creek bottoms and pools were as muddy as they were before the event. Much coarse organic debris remained in the deeper channels for weeks to months. Large volumes of *Spartina* wrack and woody debris from marsh islands were deposited in the forest.


The front of Baruch Marine Field Laboratory the morning after Hurricane Hugo surged through it.

The impact of Hugo's wind and surge was mainly on the uplands. Evidence that saltwater penetrated more than 0.75 km into the Hobcaw forest was found on roads and in forested wetland swales. Many mature pines and hardwoods were blown down or severely damaged. In the months and years following the storm, low-lying forests were killed by saltwater intrusion.

The pier and weather station at Oyster Landing were destroyed and debris was deposited in the forested uplands. The pier and boat shed at Clambank were also destroyed. Hugo flooded and fractured the 14,000 sq ft. USC Baruch Marine Field Laboratory, moving the original building off its foundation, rendering all of the structure too damaged to be repaired. Total losses of buildings, piers, equipment, and contents were about three million dollars. Pre-storm preparation saved all data and all light-weight equipment that could be transported to higher ground at the Kimbel Center, which sustained wind but not flood damage. The loss of the facilities, major analytical instruments, and refrigerated/frozen collections that were awaiting processing were a setback, but post-storm water and biological sampling began within hours of the storm's passing. Results of some of these studies are reported in sections on water chemistry and fauna assemblages.

Coastal Observer
Thursday, September 28, 1989 21

Lab destroyed, research saved

By Zane Wilson

Baruch Marine Lab was destroyed by Hurricane Hugo, but almost all the research was saved, and the facility will be rebuilt, says Dr. Dennis Allen, director at the site.

"There's no question we're out of business down there for the near future," he said.

But the lab was insured, and adjusters visited on Tuesday. The building will cost "better than a million dollars to repair," if it can be fixed, and more than $2 million if it has to be rebuilt farther inland, which is what Allen said he prefers to do.

The lab "took a beating on the back of the building" from the storm surge. The lab is on a creek off North Inlet, and even in locked rooms, he said there was "just short of four feet of standing water" on the floors.

Allen said 95 percent of the research records were saved. Many were on computer disks. Others were hauled out Thursday, when staffers spent the day trying to get the most valuable items to safety.

Of about $1.5

Lab workers are using Kimbel Center off Highway 17, which was undamaged. Bellefield Nature Center was also unscathed, as were the dorms and homes on Hobcaw Barony.

"We really haven't broken stride," Allen said.

Most of the research data can be run on University of South Carolina's mainframes, and much of the lab testing can be done on campus as well.

"It was quite a blow to our operation in terms of being a functional analytical laboratory," he added.

However, there is a bright spot. Allen thinks it's an unprecedented opportunity to study the effect of a major storm on North Inlet's ecosystem.

It will take six months to a year to replace the lab, Allen said, but he added everyone there feels fortunate compared to the losses of some of the community.

Meanwhile, the research continues; workers were out Friday collecting their usual samples, he said.

TIMES Photo / Nicole Parker

Workers at the Belle W. Baruch Institute try to clean the boat maintenance shed, which had parts of the wall facing the marsh knocked out by the force of Hurricane Hugo

Baruch lab lost, but research continues

By Nicole Parker
TIMES REPORTER

Despite the destruction ravaged upon the University of South Carolina marine science laboratory by Hurricane Hugo, researchers at the Belle W. Baruch Institute say the storm also created enormous research opportunities into the effects of hurricanes.

"The hurricane increased the research potential of the the area incredibly," said Dr. Dennis Allen, assistant director of the Belle W. Baruch Institute for Marine Biology and Coastal Research. "It was the biggest natural disaster that could occur in a coastal zone."

Allen said proposals were already being developed for research into the enormity of the storm. He said for the first time, scientists will be able to conduct research on a storm's effect on a particular area and nature's response to it.

Although the storm was a setback in terms of damage, Allen said researchers were expecting it.

"We all anticipated this from the day we started here," he said. "We knew that sooner of later there was going to be a colossal disturbance."

Dr. George Askew, director of the Belle W. Baruch Forest Science Institute of Clemson University, said the opportunities for research into Hobcaw Barony's forest were also numerous.

He said one area that will be closely studied is the long and short-term effects of salt water on the trees in the upland areas. Some of the trees on the 8,000 acres of forest were standing in two-to-four feet of salt water.

Although there was little structural damage to the majority of buildings on the property, the USC marine science lab, located on the edge of the marsh, was completely gutted by the storm surge. Allen said damage estimates to the building and its contents, which included valuable equipment, is estimated at roughly $2 million.

However, only 5 percent of the data collected over the years at the lab was lost due to evacuation measures before the storm and a computer link with the USC campus in Columbia.

Looking to the future, Allen said it will probably be six months to a year before he and the rest of the research staff can get back to normal. But in the meantime, they are able to carry out a vast majority of research they were doing before the storm while working out of three small cottages on the property, packing any specimans collected in dry ice and sending them to Columbia.

Although the property damage to the marine science lab and its surrounding buildings was extensive, Askew said other buildings on the property were not significantly damaged with the exception of an office building near the Bellefield Plantation house, which had roof damage.

Hobcaw House, the office for the Clemson operation, received no significant damage and neither did any of the other historical buildings on the property. However, the boat dock at Hobcaw House on Winyah Bay was destroyed.

The new forest science office currently under construction on the property was practically left untouched with the exception of a few missing shingles.

In the aftermath of the hurricane, forest science researchers are still trying to get a handle on the extent of damages to to the forests. Askew said some stands of pines were bent or broken and some hardwood trees were completely blown over. He said in portions of the upland areas there is no damage but just around a bend in the road there are stands of bent and broken trees.

"It took a week to cut our way into the property," he said."

Allen said there wasn't a great deal of noticeable physical changes in the marsh areas, but both he and Askew agree it will be several years before the full effects of Hurricane Hugo have been realized.

No one is sure at this point how animals fared in the storm. Askew said he has seen no dead animals with the exception of two ferral hogs, but there have been buzzards flying over the property.

Allen said most of the animals living in the marsh came through the storm safely, but he said some of the smaller animals living around the marsh had probably not fared as well. He said he had seen herons and egrets feeding in the marsh and that the shrimp, fish and plant life were all there.

Because of downed trees and the danger of falling limbs, the tours of the property and special programs have been cancelled until at least Friday, October 13. However, the Nature Center, located at the entrance to the property is open.

Hurricane Hugo destroyed the Baruch Marine Field Lab building and weather station in 1989, but pre-storm preparation saved all data and all light-weight equipment that could be transported to higher ground.

» North Inlet Climate and Weather Data Summary

In this section, weather patterns and trends based on long-term data from the NI-WB NERR are provided. The data were collected at Oyster Landing pier starting in 1982. These detailed observations and analyses should be particularly useful to researchers analyzing other long-term time series from the area and to investigators planning new field studies. The frequency, magnitude, and variability associated with physical factors that influence chemical and biological processes provide context for studies that are based on measurements made over short periods.

Aerial view of Oyster Landing pier, the location of the NI-WB NERR weather station.

All summary graphics and findings are based on daily averaged data. The 1983-1996 daily averaged data are derived from hourly averages (n=24) based on one second instantaneous observations (3600 per hour). The 1997-2004 daily means are derived from hourly averages (n=24) based on five second instantaneous readings (720 per hour). The 2005-2010 daily averaged data are derived from 15 minute averages based on five second instantaneous readings (180 readings per 15 minute interval). If there were less than 64-15 minute data (67% of the data per day), then the values were not averaged for the day and the daily average value was listed as missing. If there were less than 20 days of daily averages for the month (less than 67% of the daily values for the month), then the values were not calculated, and the monthly value was listed as missing. Years and variables which had less than 250 days (67% of the year) of daily mean data were not used in annual summary or long-term analysis; years which had less than 310 air temperature, barometric pressure, or wind speed daily values (or less than 85% of the year) are used with caution.

AIR TEMPERATURE

Measurements of air temperature have been made at the North Inlet – Winyah Bay Reserve since June of 1982. Over the 28-year period from 1983 through 2010, mean annual air temperature at North Inlet remained fairly consistent, ranging from a low of 16.7°C (62°F) in 1989 to the hottest yearly average of 19.0°C (66°F) in 1998 (Figure 11). The overall mean based on annual averages from 1985-2010 (excluding 1986, 1987, 1996 & 1997) was 17.8°C (64°F). The five years with the greatest range or variability in daily air temperature during the year were: 1989 (range of 36.6°C (98°F)) and 1994, 1999, 2003, and 2005 (range of about 34°C (93°F)). The five years with the lowest range in daily air temperature were: 1990 (range of 28.5°C (83°F)) and 1987, 1992, 1993, and 1998 (range of about 29°C (84°F)). Fifteen degrees Fahrenheit separated the largest (1989) and the smallest (1990) air temperature ranges; oddly, these were in two consecutive years.

The hottest average daily air temperature of 32.5°C (90.5°F) occurred on August 1st, 1999. The next hottest was 1986 (not graphed) with 31.6°C (88.9°F) on July 10th. July and August 2005 and 2007 also had daily average temperatures of over 31°C (87.8°F). The coldest daily temperature occurred on January 21st, 1985 when the average was -9.3°C (15.3°F). December 25th and 23rd of 1983 and 1989, respectively, averaged below -8.2°C (17.2°F). Figure 11 illustrates that the maximum daily temperatures for each year varied little over the 28 years. However, the minimum daily temperatures warmed by an average of about 5°C (41°F) between the 1980s and the 2000s.

The monthly average air temperatures in North Inlet followed a bell-shaped curve, with the coldest air temperatures averaging between 8°C and 10°C (46°F and 50°F) in the fall & winter months. The hottest average air temperatures of over 25°C (77°F) occurred in summer (July and August), with July having the hottest average temperature of 26.5°C (79.7°F) (Figure 12). Ranges between minimum and maximum daily temperatures were greatest from December through February (26.5 - 31°C or 79.7°-87.8°F), and daily variability was least during June, July, and September (13 - 15°C or 55.4-59.0°F).

The coldest monthly mean with an air temperature of 4.4°C (39.9°F) was recorded in January 1988. January of 1985 and 2010 were the next coldest months/years of the 28 years with an average monthly temperature of 5.8°C (42.4°F). The hottest monthly mean air temperature was 27.9°C (82.3°F) in July 1986. Following very close to this high were July 1993, 1998, 1999, and 2005 which had average air temperatures at or slightly above 27.5°C (81.5°F). 1990, 1991, and 1992 also had average highs of over 27°C (80.6°F) in July.

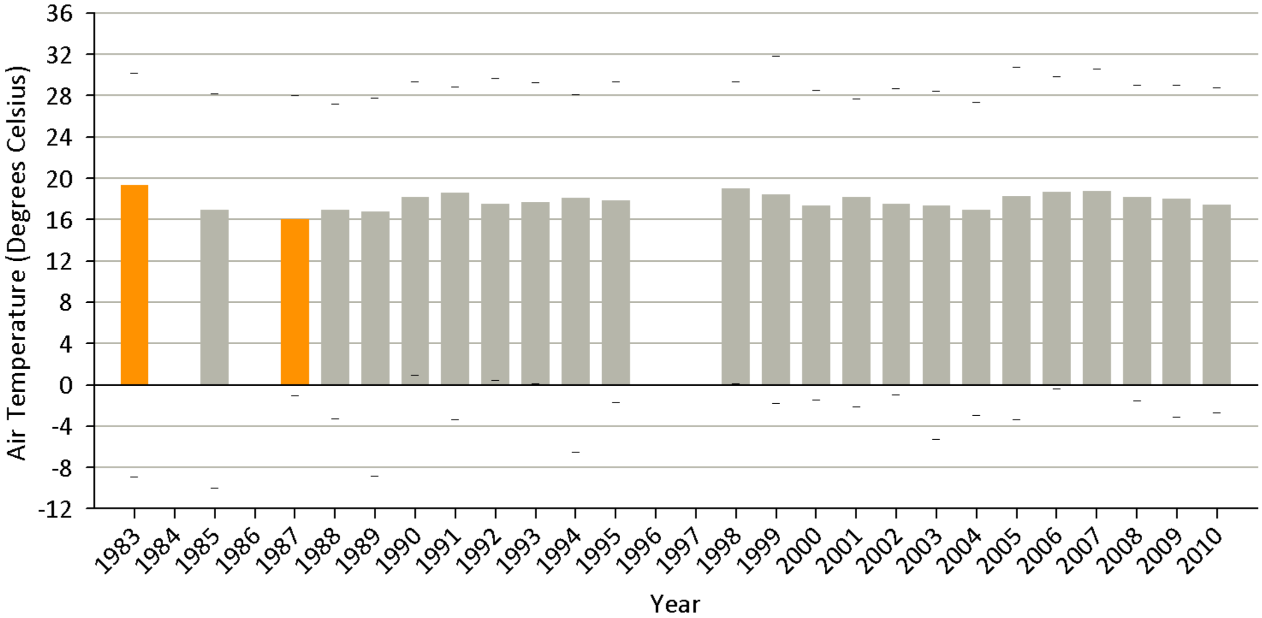


Figure 11. Annual average air temperatures in North Inlet. Minimum and maximum daily temperatures for that year are indicated with a dashed line below and above each bar. Years which did not have enough data for annual temperature summaries were 1982, 1984, 1986, 1996 and 1997. Note: 1983 and 1987 (colored orange) had less than 85% air temperature data for the year, so were graphed here, but not used in annual statistics.

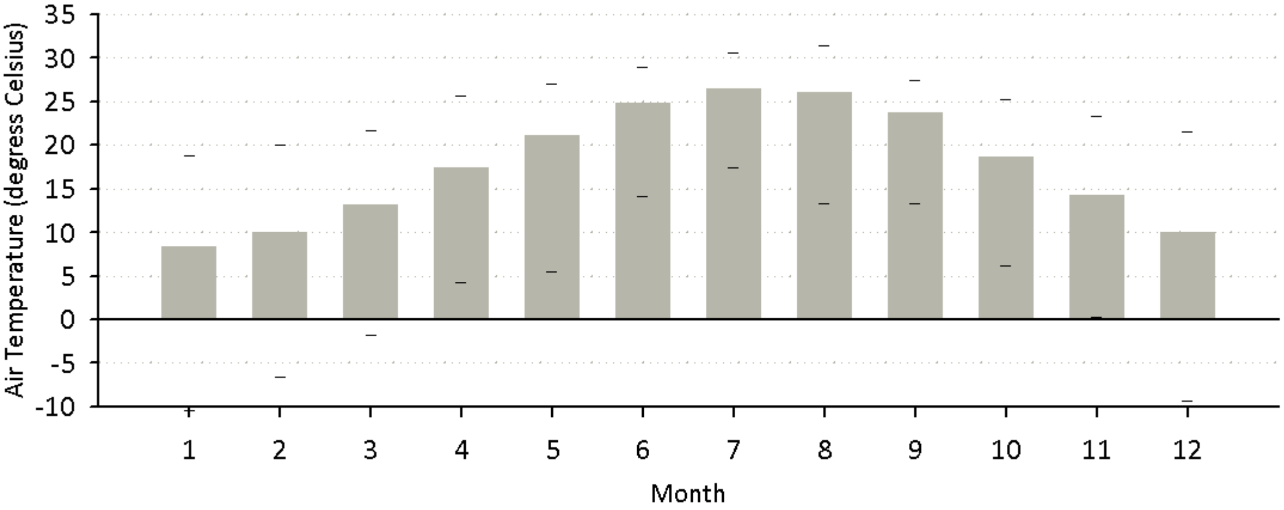


Figure 12. Monthly average air temperatures in North Inlet. Minimum and maximum daily temperatures for the month are indicated with a dashed line below and above each bar. Not all months from all years are included in this graphic, as some years were lacking enough data.

PRECIPITATION

According to 30 years (1981-2010) of rainfall measurements at North Inlet, the overall annual average was 49.14 inches. The seven wettest years were 2003 (66.13 inches), 2005 (62.94 inches), 1992 (59.51 inches), 1998 (59.32 inches), 1994 (59.19 inches), 1982 (58.81 inches), and 1995 (57.87 inches) (Figure 13.). These years coincided with El Niño events that brought unusually high precipitation to the southeastern U.S. from December through April. Two of the strongest El Niño events in 100 years were in 1982 and 1998. Above average precipitation in North Inlet was not always associated with El Niño events. Other wetter than average years (1989, 1996, 1999, and 2008) were due to winter storms (Nor'easters), spring and summer thunderstorms, and/or summer and autumn tropical disturbances. Due to increasing frequency of El Niños and tropical storms during the 1990s, the long-term trend for the North Inlet area was one of increasing precipitation. Severe drought conditions in the 2000s ended this trend (Figure 13).

The six driest years in North Inlet from 1981-2010 were 2007 (31.61 inches), 2001 (33.30 inches), 1993 (33.98 inches), 1990 (34.80 inches), 1988 (38.72 inches), and 1986 (38.99 inches) (Figure 13). A number of these dry years were associated with La Niña events (red bars). Documented severe droughts occurred statewide during the years of 1986, 1990, 1998-2002, and 2007-08. The 1986 and 2001 droughts were two of the most severe droughts in South Carolina. The 1986 drought was accompanied by weeks of record or near-record high temperatures and record high demand for water in July. Less severe droughts were reported in 1988, 1993, and 1995. Adverse impacts on the people and economy were made especially clear during the drought of 1998-2002 which impacted agriculture, forestry, tourism, power generation, public water supplies, and freshwater fisheries. A moderate drought was declared in June 2007 and its status was upgraded to severe from September 2007 through January 2008.

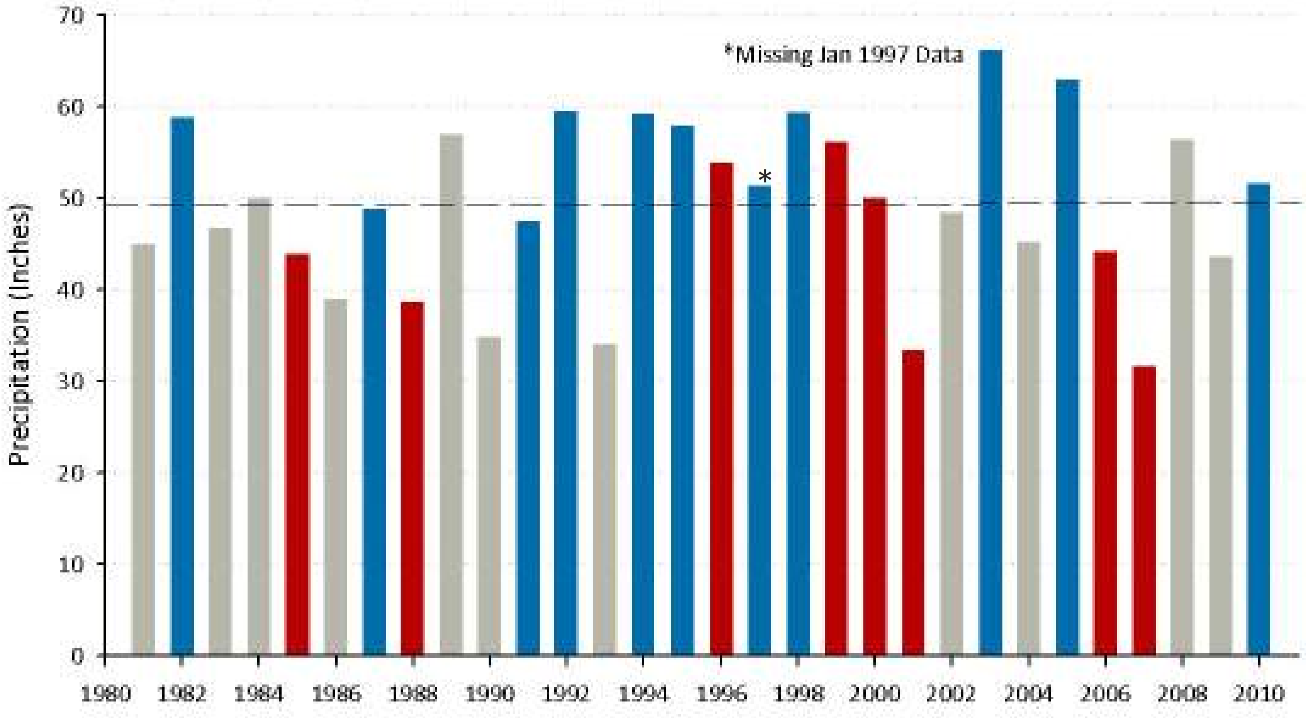


Figure 13. Total annual precipitation measured at Oyster Landing, North Inlet for 1981 through 2010 (30 years). Blue bars indicate years in which El Niño events occurred; red bars denote years when La Niñas were present. El Niño and La Niña events are based on NOAA's monthly NINO 3b Index. The dashed line indicates the 30 year average total rainfall of 49.14 inches.

During the 30 year period, overall monthly average for rainfall in North Inlet was 4.11 inches. Monthly average precipitation was highest in August (6.43 inches), with average rainfall in September and July closely following with 5.91 and 5.81 inches, respectively (Figure 14). The maximum monthly precipitation of 15.33 inches was recorded in August 2004, the greatest monthly rainfall in the 30 years of observations. Other peak monthly values above 14 inches were August 1981, September 1996, 1999 and 2000, and July 2003. The typical high variability observed during the summer and early autumn months (Figure 14) is due to intense thunderstorms and tropical disturbances. Table 1 lists some of the tropical systems that produced large amounts of rain in the Georgetown area. The largest single total daily rainfall of 8.94 inches occurred on September 15th, 1999.

The months with the least amount of rainfall were November, April, and May, with a monthly average of less than 3 inches per month (Figure 14). Some rainfall was recorded for every month during the 30 year period. October 2000 was the driest month with a trace recording of 0.06 inches; the next lowest month/year total rain was November 2007 with 0.10 inches. Other month/years with a monthly total of less than or equal to 0.5 inch of rain were November and December 1984, July 1993, April 1994, August 1997, and April 2001.

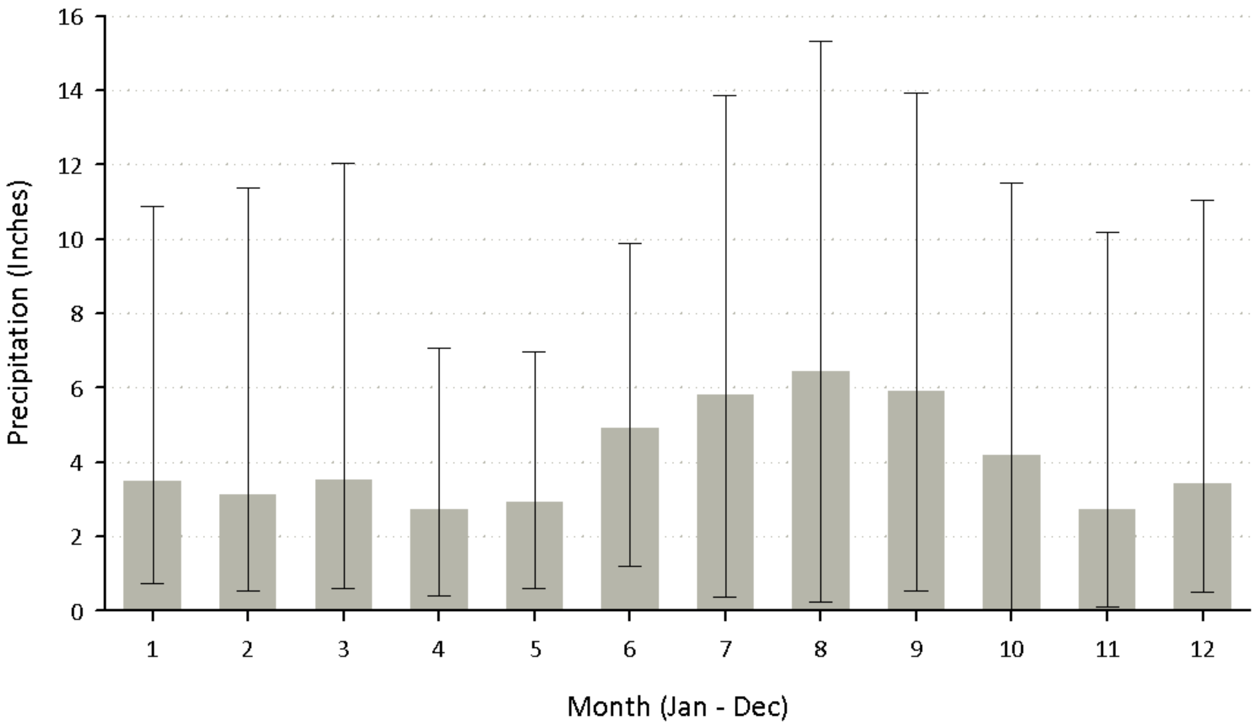


Figure 14. Monthly average precipitation for North Inlet from 1981 through 2010. The minimum and maximum monthly total rainfall recorded over the 30 years are denoted with the vertical range line in each bar.

WIND

The general direction of wind in North Inlet during spring and summer is from the south and west, but wind is more evenly distributed around the compass during autumn and winter. Southwest is the most frequently recorded direction during all seasons. Prevailing wind direction has been consistent from year to year. Data from 1982 through 2004 were analyzed for the following summary and shown in Figure 15.

Spring winds (both low and high velocity) were primarily from the south and west (180 to 270 degrees) direction, but the dominant spring wind pattern was from the southwest. However, both calm and strong episodic wind events from the northeast and southeast directions occurred during spring. Winds from the northwest are uncommon in May and June. In June, the flow from the southwest was more prevalent, although low velocity southeast winds became more common.

During July and August, light winds from the southwest especially dominated, with some from the southeast. In August and September, the pattern changed with an increasing frequency and higher velocities of winds from the northeast. Some southeast winds were recorded but northwest winds were unusual during July and August.

Autumn winds were from all directions, but southwest was still the prevailing direction. Northeast events became more frequent with higher velocities and the frequency and speed of northwest winds increased in December.

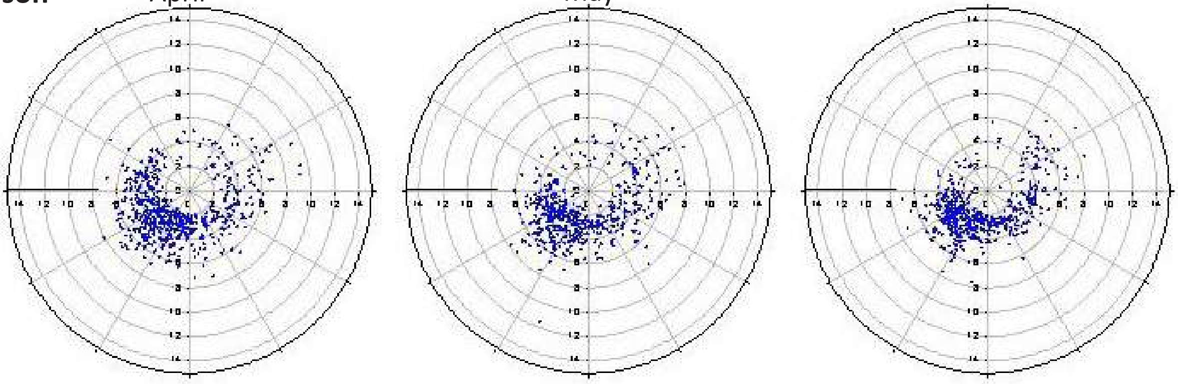
Winter winds were from all directions, but southwest continued to be a dominant direction. In January, northwest winds are also common. The strongest winds were from the northeast during all three winter months, and in March strong winds occurred from the southwest as well. In March, very little wind originated from the north.

Average monthly wind speeds remained fairly constant over the year, with the greatest difference being less than 1 ms^{-1} between the highest and lowest average monthly velocities (Figure 16). Based on daily values for the 28 year period, the mean wind velocity for North Inlet Estuary was 3.6 ms^{-1} or 8.1 miles per hour (mph). The highest average monthly wind velocities of greater than or equal to 4 ms^{-1} or 8.9 mph occurred in March, April and May. March, July, August, and October all had the most variable daily wind velocities of over 12 ms^{-1} (26.8 mph). June and November had the least monthly variation, with less than 8 ms^{-1} (17.9 mph) between the highest and lowest daily wind speed. August through January had the lowest daily wind speeds of less than or equal to 0.5 ms^{-1} (1.1 mph). The highest average daily wind velocity was recorded on August 29th, 1990 of 13.70 ms^{-1} (30.7 mph). Other windy days were March 13th, 1993, October 3rd, 1994, July 18th, 1984, and August 29th, 2004 with average winds over 12 ms^{-1} (27 mph). The March wind event was due to a Nor'easter and the other wind events were due to tropical disturbances. Maximum wind gusts from tropical systems and hurricanes can be found in Table 1. Like the monthly average wind speeds, average yearly wind speeds remain fairly constant over the 28 years; the greatest difference was less than 1 ms^{-1} among the years.

The weather station at Oyster Landing

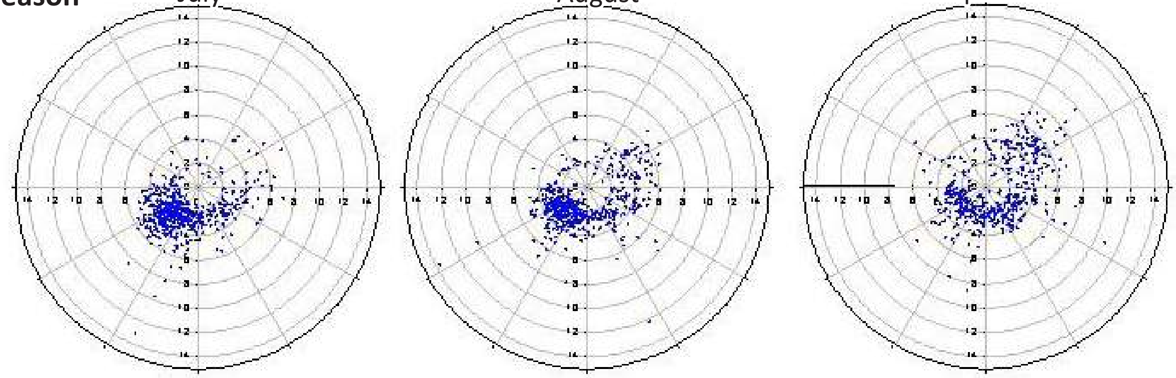
Spring Season

April May June



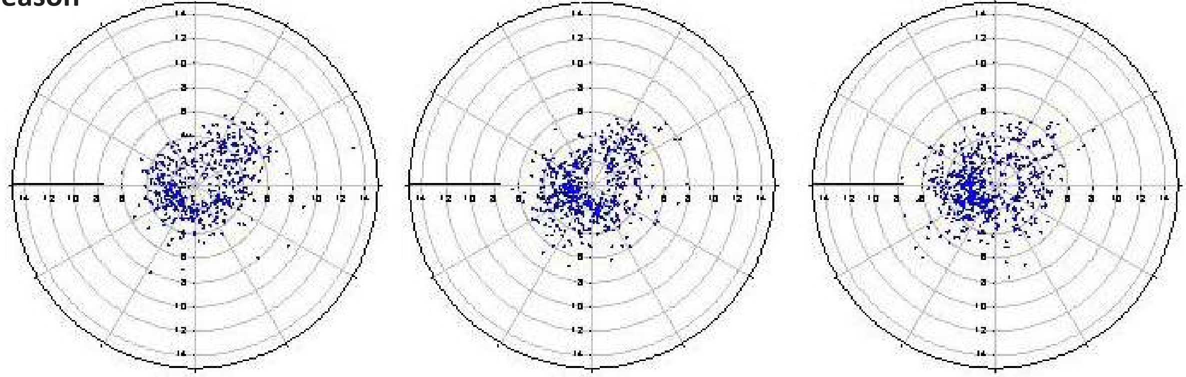
Summer Season

July August September



Autumn Season

October November December



Winter Season

January February March

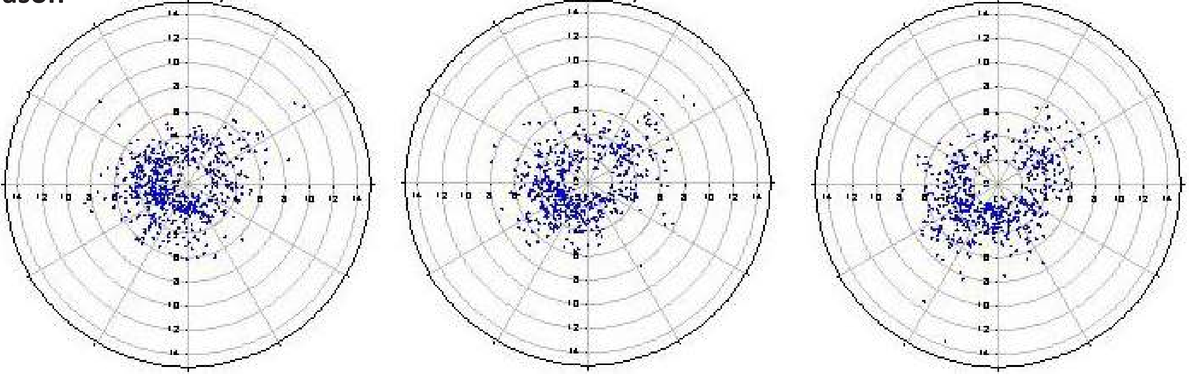


Figure 15. Average daily wind direction and velocity (ms-1) for each month from 1982 through 2004. These data were recorded at the Oyster Landing Pier in North Inlet. Direction of the wind that is coming at you is indicated by the position of the data point (dot) relative to North at the very top edge or 0 degree position of the compass rose. Due east is 90 degrees, south is 180, and west is 270 degrees. Velocity of the wind data point increases with distance from the center and is measured in meters per second.

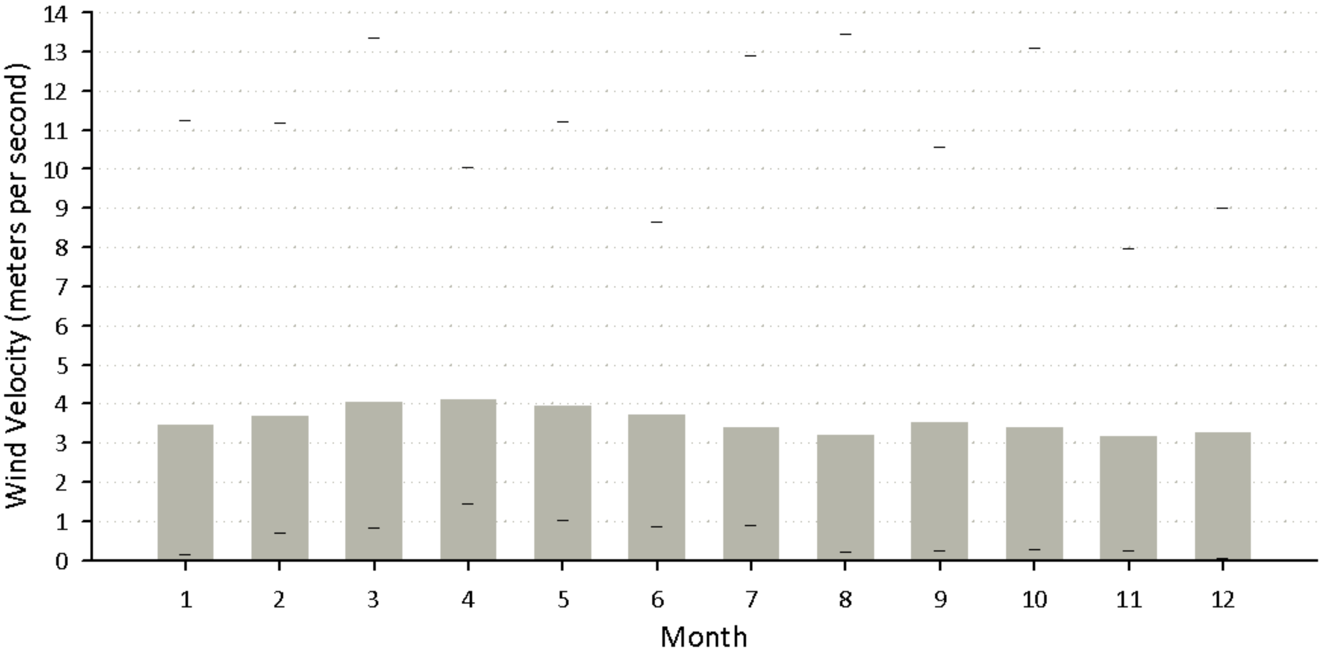


Figure 16. Monthly average wind velocities recorded in North Inlet from mid-1982 through 2010. Minimum and maximum daily wind speeds for the month are indicated with a dash below and above each bar. Values are in meters per second.

BAROMETRIC PRESSURE

The average monthly barometric pressure (BP) in the North Inlet area varied little between January and December (only about 5 millibars (mb)), although the spring and summer months had somewhat lower than average pressures than the winter and autumn months (Figure 17). The overall average barometric pressure for the 28-year period was 1017.3 mb. Day-to-day variation was smallest in July, August, and September. May and June also had the lowest maximum daily pressures (less than or equal to 1029 mb). October through April had the highest monthly average barometric pressures (1033 - 1040 mb) of the year along with the greatest daily variation. These seasonal patterns can be attributed to large weather patterns such as the Bermuda High, continental and oceanic high and low pressures, tropical storms, and large thunderstorm systems.

The highest average daily pressure was recorded on February 26th, 1990 with 1040.00 mb; ten other daily averages of over 1036 mb occurred over the 28 year period; seven of these days were during the month of January in the years of 1998, 2000, 2004, 2005, and 2008. November and December of 2004 and February of 1990 were the other months which had a daily average BP over 1036 (Figure 18).

The lowest average daily pressure of 985.25 mb occurred on May 16th, 1985; six other dates in this month/year also had daily average BPs of 990 mb or less. February 4th, 1998 also had a very low daily average BP value of 988.28 mb; this was the year of the strongest El Niño in 100 years. The weather station instruments at Oyster Landing recorded the lowest daily minimum reading on March 13th, 1993 of 975 mb due to an intense winter cyclone (average daily value was 987.79). The highest daily maximum values of over 1040 mb occurred on February 26th, 1990 and December 1st and 19th, 1991.

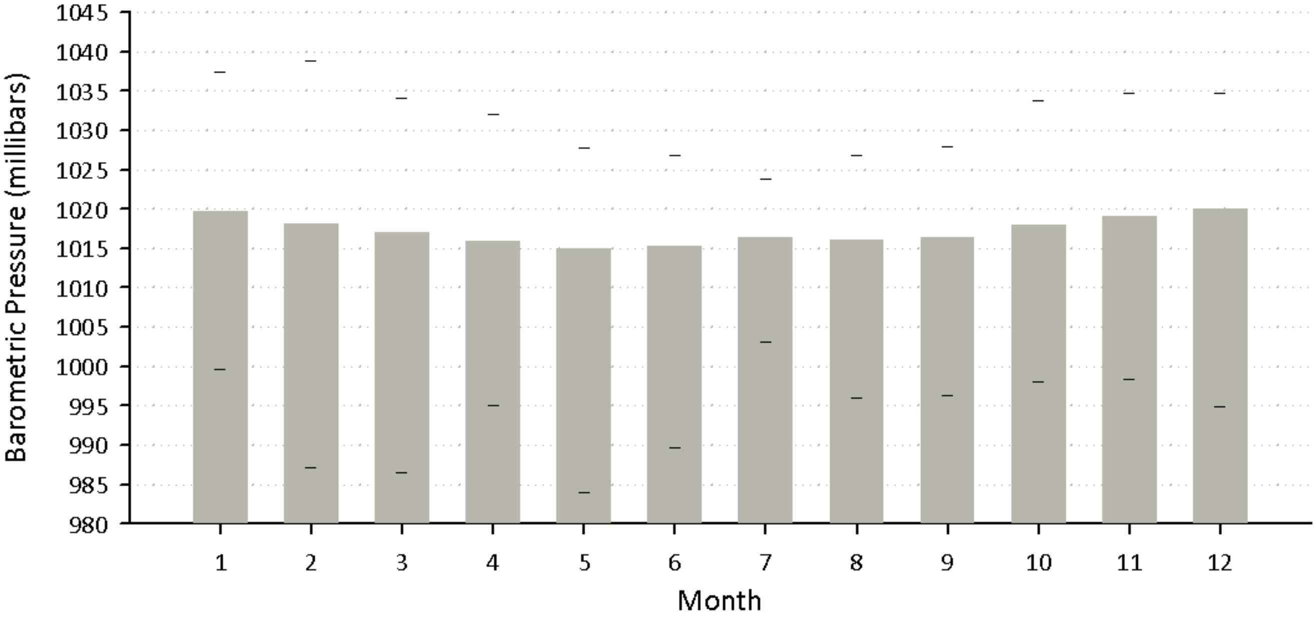


Figure 17. Monthly average barometric pressure recorded in North Inlet. Minimum and maximum daily barometric pressures for the month are indicated with a dash below and above each bar.

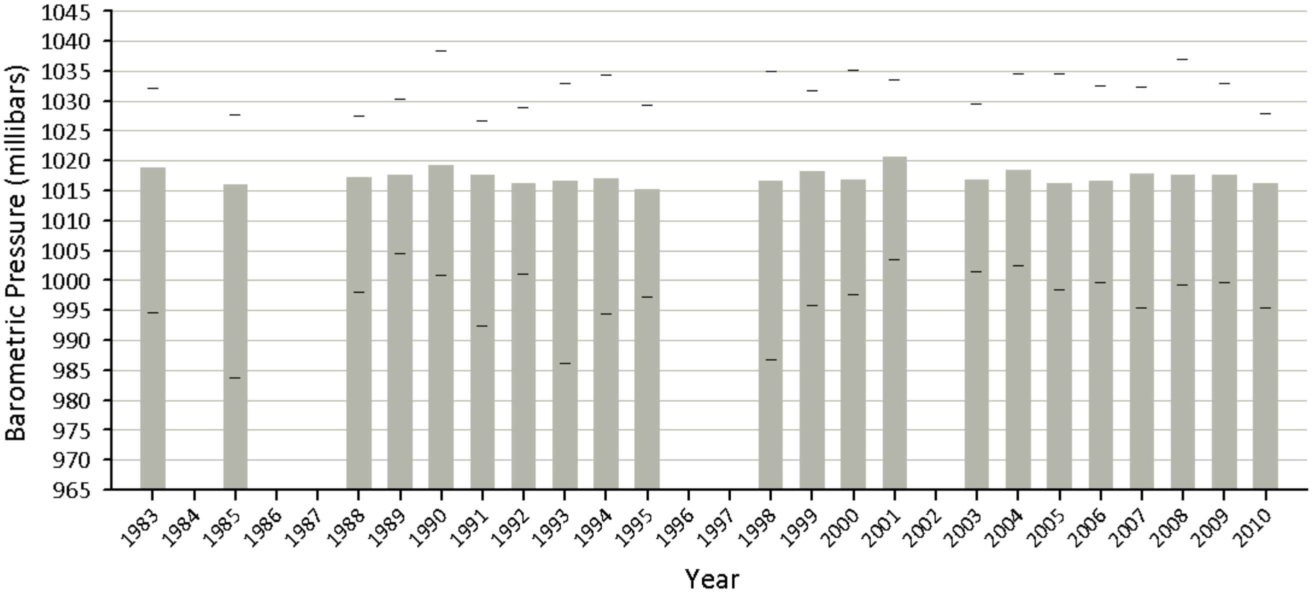


Figure 18. Yearly average barometric pressure recorded in North Inlet. Minimum and maximum daily barometric pressures for the year are indicated with a dash below and above each bar.

General Physical Characteristics and Justification for Treating the Two Estuaries Separately

There are large differences in the physical structure and water properties of the North Inlet and Winyah Bay estuaries, including their water chemistry, ecological functions, and their flora and fauna. These differences are profound enough that we decided to provide separate descriptions of the physical, chemical, and biological characteristics of the two partially-connected estuaries.

Estuaries are broadly defined as coastal areas where freshwater from the land meets the ocean. One extreme type of estuary is so strongly dominated by tidal exchanges from the ocean that the influence of freshwater runoff from the surrounding watershed on the salt content of the major waterways is small. North Inlet is an example of such an ocean- (tidally) dominated estuary. At the other extreme, an estuary may be so strongly dominated by river inflow and drainage from the surrounding watershed that the penetration of seawater with the incoming tides is limited to the area close to the inlet. An example of this kind of estuary is found just south of Winyah Bay where the North and South Santee Rivers flow into the ocean. Because more mixing of freshwater and seawater occurs outside of the inlet than within it, this area has been referred to as the only major delta on the east coast of the US.

Winyah Bay is intermediate between these two extreme types of estuaries. The influence of its rivers is strong but, except under periods of high freshwater outflow, much of the mixing between freshwater and seawater takes place within the estuary, with the area closest to the inlet typically having higher, oceanic salinities. Table 2 highlights many of the gross differences between Winyah Bay and North Inlet that should be kept in mind while reading the subsequent sections of this document. There are also many similarities between portions of both estuaries, but the major functional differences that exist between these two portions of the NERR outweigh their similarities, hence our decision to treat them separately.

In the next two sections, we describe the geology, geography, patterns of water movement, and water quality/chemistry. In the chapter that follows, the habitats common to both estuarine systems are presented. This is followed by a section on the algae, vascular plants, microbes, and animals of North Inlet, then by a section on the same biotic components in Winyah Bay. Figure 19 shows the names and locations of waterways and landmarks mentioned in the many research studies presented in these sections that help characterize the NI-WB NERR.

A final comparative section presents similarities and contrasts differences between the two estuaries. By treating these two estuarine systems independently, the disparity in the extent of our knowledge of the two estuaries becomes even more apparent. Compared to North Inlet and despite its being one of the largest estuaries on the east coast, relatively little research has been conducted in Winyah Bay.

The lighthouse on the southern end of North Island marks the entrance to Winyah Bay.

Table 2. Comparison between the North Inlet and Winyah Bay portions of the North Inlet-Winyah Bay NERR: differences in key features and other characteristics.

Characteristic	North Inlet	Winyah Bay
Watershed size	Small	Very large
Hydrographic regime	Tide-dominated	River-dominated
Circulation shallows	Well-mixed	Stratified channel, mixed
Sources of freshwater	Precipitation	Rivers, precipitation, agricultural runoff, non-point source
Influence of precipitation	Small	Large
Salinity range	High/narrow	Wide/variable
% open water vs. edge	Small	Large
Fetch/current velocity	Short/moderate	Long/strong channel-moderate shallow
Sediment input/turbidity	Small/moderate	Large/high
Depth regime	Shallow	Deep rivers and channels/shallow flanks
Nutrient load	Low	High
Pollutant load	Very low	Moderate-high
Pollutant source	Aerial deposition, creeks connecting Winyah Bay	Aerial, agricultural, municipal, industrial
Dissolved oxygen	High in major waterways	Low-moderate in channels, hypoxia occurs
Dominant marsh plants	*Spartina alterniflora*	*S. alterniflora* near ocean, *S. cynosuroides*, *Juncus* mid-upper bay, *Phragmites* in upper bay
Fauna diversity/structure	High/oyster reefs	Moderate near ocean, low upper bay
Commercial fisheries	Blue crab	Penaeid shrimp, blue crab, shad
Shipping traffic	None	Moderate-high

Figure 19. Waterways and landmarks in the North Inlet-Winyah Bay NERR

NORTH INLET

Sunset over North Inlet viewed from the fire tower at Clambank Landing

» Geology and Geomorphology

The NI-WB NERR lies on the Coastal plain geological province which consists of a tectonically inactive wedge of largely unconsolidated sedimentary strata that began to accumulate about 100 million years ago (Late Cretaceous). More than one half mile (~ 1000 m) of accumulated sediments occur beneath the SC coast. Present topography, bathymetry, and geology reflects changes in climate, sea level, and riverine discharge during the past 15,000 years. Since that time, sea level has increased by about 120 m. The North Inlet and Winyah Bay areas were entirely upland areas located 100 km or more from the ocean. Increasing sea level resulted in the encroachment of the ocean into the present day North Inlet area about 5000 years ago. As the level of the ocean increased, it extended over a series of old shorelines and beach ridges left from when sea level retreated during the Wisconsin Glaciation (>15,000 years ago). Around North Inlet, freshwater marshes and swamps (that had developed between sandy ridges during the time sea level was low) eventually became inundated by tidal water and became salt marshes. Radiocarbon datings of roots of cedar trees collected below the North Inlet salt marsh show that the Crabhaul Creek area was forested about 2600 years ago (Gardner and Porter, 2001).

Tidal creek networks and marshes are the result of spatial and temporal variations in patterns of erosion and deposition over millennia and centuries (Gardner and Bohn, 1980). Rising sea level converted small terrestrial streams to major tidal creeks. Ancient valleys between high sand-ridges were eroded by tidal flow, resulting in the widening and deepening of channels. A net seaward transport of forest sand nourished inlets and barrier islands. At the same time, a net landward transport of clay and mud (probably as suspended material) built new marshes and mudflats within the estuary (Gardner et al., 1992b). Larger, sandier, older, and temporally more stable creek systems occur closest to the ocean whereas more recently formed and more dynamic tidal creeks and marshes occur closer to the forest.

» Tidal Regime/Hydrology

North Inlet is a high-salinity, well-mixed coastal lagoon harboring typical southeastern US salt marsh with an area of 32 km^2 (3,200 ha). It is a bar-built, class C estuary (Pritchard, 1956) and usually has salinities between 30-34 in its main basin. The inlet has an open connection to the sea through which semidiurnal tides flood and ebb twice each tidal day (about 24 h 50 min). Each successive high or low tide occurs about one hour later the following day. Mean tidal range is 1.4 m and average water depth in the basin is about 3.5 m at high tide. Maximum depth is about 8 m. Tidal range is greatest during new and full moons (spring tides, range = 2.1 m) and least during 1st and 3rd quarter moons (neap tides, range = 1.0 m). Maximum tidal range, about 2.5 m, occurs when the moon, sun, and Earth are aligned. Approximately half the water in the North Inlet basin flows to the Atlantic Ocean during ebb tides. The mouth of the inlet is part of an active subtidal sediment transport system driven by net southerly alongshore currents. As water moves in and out of the inlet, depositional deltas form both outside (seaward) and inside (landward) the mouth, constricting flow into deeper channels that change location when storms reconfigure the bottom contours (Blood and Vernberg, 1992).

Flooding tides enter North Inlet with velocities that are slightly slower than the velocity of ebbing tides. Flood duration can last up to 1.5 h longer than ebb duration. This asymmetry in the tidal regime results in seaward transport of suspended sediments, but hurricanes in the summer and fall and other fall storm events can shift huge amounts of sand along the coastal beaches, greatly altering the configuration of the inlet's mouth. Depending on season, much of the water that leaves North Inlet re-enters on the next flooding tide. The net result is that enough sediment is retained within the basin for the marsh surface to maintain its position relative to the local rate of sea level rise, 1.5 – 3.0 mm per year. Water levels within the basin are greatly influenced by the wind. With prevailing and persistent easterly and northeasterly winds, water can be pushed into or held within North Inlet to such an extent that, for instance, the next predicted low tide is higher and later than predicted. It is rare that southwesterly winds are so strong as to affect entry of a flooding tide, but the predicted arrival times of flood tides can be delayed by such winds. Strong westerly winds can result in lower tide levels than those predicted. The combination of spring tides and strong westerly winds on April 15-16th, 2007 resulted in some of the lowest tides in a decade, with low tides being about 0.7 m (about 2 ft.) below mean low tide. Persistent southwesterly winds often result in increased penetration of Winyah Bay water into North Inlet, especially when river discharge is high during winter and spring.

Freshwater input to North Inlet comes primarily from the surrounding forested watershed and is on the order of 10 m^3s^{-1}(Dame et al., 1991). Following heavy precipitation events; however, salinities can temporarily decrease to nearly freshwater values in the shallowest tidal creeks. With prolonged periods (days) of runoff from the surrounding forest, salinities can remain depressed for several days at a time, with salinities on the order of 10 in surface waters of the inlet, but these are rare events.

Tidally-driven currents in the main channels of North Inlet (e.g., Town Creek) can reach 2.3 ms^{-1} and have been known to move heavy equipment moored or anchored to the bottom. Ebbing flows are substantially faster than floods, so the ebb-dominance must be taken into account whenever time-integrated volume flux measurements are made in North Inlet. Current velocities are typically slower in creeks near the forest border than near the inlet, and velocities are also lower near the bottom than at the surface of creeks. Throughout North Inlet, water flow into smaller creeks is, of course, tidally-driven, but when water level exceeds the height of the creek banks, sheet flow from adjacent creeks will enter the marsh. Compared to creek flow, however, sheet flow is minor, accounting for only about 1% of the tidal prism (Eiser and Kjerfve, 1986). Sheet flow may be very significant as a conduit for movement of organisms between the marsh surface and the creeks within North Inlet, especially during spring tides when 50% of the volume of water that enters smaller basins inside North Inlet can be a result of sheet flow over the grassy flats of the marsh (Miller and Gardner, 1981).

Besides the Atlantic Ocean entrance, there are three other outlets/inlets for water in the North Inlet basin. No Man's Friend and Haulover creeks are minor in this regard compared with Jones Creek, a well-defined channel that also opens into the Mud Bay portion of Winyah Bay to the south of North Inlet. Jones Creek accounts for about 80% of the exchange of water between North Inlet and Winyah Bay. Jones Creek meanders 8 km in a N-S direction from just inside the mouth of North Inlet to the eastern side of Mud Bay. It averages <3 m deep and 50-80 m wide. Flow in the creek is unidirectional at all depths. The creek has a 2 km long stretch at its northern end where water is warmer and higher in salinity than the southernmost 3 km stretch with fresher and cooler water. Between these two water masses lies a transition zone having sharp longitudinal gradients of temperature and salinity. In the transition zone is a region where a nodal point exists such that tidally-driven water simultaneously floods Jones Creek from North Inlet and from Winyah Bay. Likewise, water north of the nodal point leaves Jones Creek via North Inlet and water to the south of the nodal point travels toward Winyah Bay (Traynum and Styles, 2008). Tidal flows within Jones Creek can be half a tidal cycle out of phase (Schwing and Kjerfve, 1980).

» Water Quality in North Inlet

Good water quality is essential for the health of our nation's estuaries. Reduced water quality can result from elevated nutrient levels (harmful algal blooms), low levels of dissolved oxygen (anoxia, fish kills), chemical contaminants (toxins, oil spills, heavy metals), and elevated fecal coliform bacteria or viruses (shellfish harvesting closures, skin infections, diarrhea). Any of these problems may be a sign of poor estuarine ecosystem health because they subvert and disrupt natural biogeochemical cycles that normally insure high water quality. Conflicts often arise between economic concerns and resource use that can be deleterious to water quality, e.g., dredging, industrial discharges, resource harvesting methods, and accidental spills. Monitoring water quality therefore has important implications far beyond local concerns and thus remains a critical element guiding and informing regulatory services imposed by local, state, and federal levels of government.

The NERR system was designed in part to monitor many of these measures of coastal ecosystem health (Wenner and Geist, 2001; Kennish, 2004). The NI-WB NERR conducts a water monitoring program – System Wide Monitoring Program (SWMP) - to provide high-quality data to researchers and coastal decision makers. The same instruments and methods are used at all NERR sites and hence the water quality data from all locations are directly comparable. Data from all 28 Reserves nationwide are compiled and certified at the Baruch Marine Field Laboratory by personnel in the NERRS Centralized Data Management Office (CDMO). Porter et al. (1994, 2004) describe how the estuarine data management process is organized, and Fletcher et al. (2006) describe data collection and management for the system of offshore sensors in the South Atlantic Bight. These water quality data are used to examine tidal, seasonal, and annual changes and trends in water quality parameters.

Until such time as additional sampling stations for broader spatial coverage and more reliable offshore monitoring capabilities can be established, the NERR's System Wide Monitoring Program will remain at the forefront for monitoring estuarine health in the U.S. Local scale, individual NERR site monitoring becomes regional and/or national when the SWMP database is considered *in toto*. In addition to the non-regulatory SWMP programs in South Carolina are other state level, regulatory, water quality monitoring efforts under the Department of Health and Environmental Control (DHEC) and the Department of Natural Resources that are beyond the scope of this overview (e.g., Van Dolah et al., 2008).

Monitoring of water characteristics has occurred at least somewhere in North Inlet for several decades, and at Oyster Landing since 1981 under aegis of the National Science Foundation's Long Term Ecological Research (LTER) program (Wolaver et al., 1984). These long-term data provide an infrastructural capacity that is uncommon in most other U.S. estuarine waters. They are exceedingly valuable for researchers making predictions about climate change or for understanding the impacts of sea level rise, drought, weather events (tropical storms and hurricanes), or human-caused alterations to drainage basins under the constant pressures of coastal development.

At the NI-WB NERR, one SWMP station exists at Oyster Landing, a location that has also served as the original water quality and meteorological station for North Inlet since the LTER program started in 1980. Two additional SWMP stations are located in Debidue Creek (Lohrer and Wetz, 2003) and at Clambank Landing. Another SWMP station is located in a small creek in central Winyah Bay. This is Thousand Acre marsh, an old rice field that undergoes regular tidal flooding. Details about the overall SWMP sampling program can be found in Wenner and Geist (2001), Sanger et al. (2002), and Kennish (2004). Details about the sampling protocol here are found in the Baruch database metadata descriptors (**www.baruch.sc.edu**) or more briefly in Buzzelli et al. (2004).

Research on water quality in the NI-WB NERR has been conducted at a variety of spatial and temporal scales, but most studies have sampled only a very few stations and have been directed at questions related to sources and sinks, variability of concentrations over tidal, seasonal, and interannual periods of time, exchanges between subsystems within the estuary, and fluxes of dissolved materials to and from the adjacent coastal ocean or fluxes between subsystems within the marsh. Calculations of material and chemical fluxes require knowledge of an entities' instantaneous concentration and the volume and flow rate (discharge) of the water carrying those concentrations, whether in natural creeks and channels or in experimental flumes (Wolaver et al., 1985). Overviews of physical and chemical factors in North Inlet and Winyah Bay can be found in the earlier synthesis works by Blood and Vernberg (1992) and Vernberg (1993), while overviews of inter-estuary comparisons between many of these same factors can be found in Vernberg (1981, 1996) and Blood and Smith (1996).

The four strategically located SWMP stations are adequate to characterize water quality to the degree that is currently needed in the NI-WB NERR. The long-term data that exist are generally continuous but occasionally interrupted by a variety of short-term equipment malfunctions and/or faulty instrument calibrations. Regular long-term sampling in tidal systems can be problematic in the face of a stochastically or periodically changing landscape. Sampling water at a single fixed time of day can result in data aliasing with a semidiurnal tide regime, but Hutchinson and Sklar (1993), by grouping data into lunar periods, found an efficient way to remove short-term cycles in a long-term data set for analysis of longer-term trends, spatial patterns, and unusual events. Considerable effort has been put into solving many of the logistical and statistical sampling problems that have arisen in this regard (Kjerfve et al., 1981, 1991; Childers et al., 1994). Wilde et al. (2007) have used data from five different NERR sites in the southeastern US region and a variety of statistical methods to separate signal from noise in the long-term water quality monitoring data sets.

In the following sections, water quality studies are compartmentalized according to their physically- and analytically-measured foci. Additional information on each topic (e.g., salinity) can be found in other sections of this document that address hydrology, phytoplankton, animal communities, and water chemistry.

SALINITY

Salinity used to be expressed as parts per thousand (ppt or ‰). The correct expression in use today is the Practical Salinity Scale which has no units – salinity is a ratio between the measured salt concentration and that of a standard salt solution (UNESCO, 1985). Because both numerator and denominator have the same units, they cancel each other mathematically and the resultant measure has no units. Some investigators have reported salinity using the term "psu" (practical salinity unit), but this unit has lost favor in the literature and is only used when the term 'salinity' does not precede it in a sentence (Millero, 1993). The values of the newer, dimensionless measures are very close to the old parts per thousand values.

North Inlet is a high-salinity estuary with little freshwater input. The concentration of dissolved salts in the water is altered by precipitation, surface and underground runoff, evaporation, riverine inputs during flood events, drought, freezing (extremely rare here), and tidal fluxes. Most of the time salinity of the water column in North Inlet falls between about 29 and 34, but occasionally up to 37 or down to about 20, but after rain, it can get down to about 4 in the tidal creeks closest to the forest.

Salinity varies spatially and can change rapidly but has some regular temporal variations. Creeks close to land drainage or to exchanges with Winyah Bay have lower salinities than those closer to the mouth of the inlet. Generally speaking, however, salinities are spatially homogeneous in North Inlet because so much of its volume is exchanged with each change of the tide (approximately 40%) and because the water is well-mixed from top to bottom and has a hydrodynamic residence time of only about 15 hours (Kjerfve, 1986). Tropical storms and hurricanes can lower the entire estuary's salinity dramatically. The resultant freshwater discharges and prolonged runoff from watersheds surrounding the North Inlet salt marsh can keep surface salinities low for periods of days if rainfall persists. Waters closest to the uplands have much higher variability in salinity than those near the inlet. Groundwater in the uppermost several meters of upland soils moves very slowly under gravity toward the tidal system and discharges at various points in the marsh surface and especially from the banks and bottoms of creeks. On the salt marsh, sediment pore water (= interstitial water in marsh soils) salinities are generally invariant with depth in the sediment down to 30 cm but salinities in the uppermost 1 cm can reach nearly 60 in the high marsh in summer during times of intense insolation and high evaporation at low tide (Morris, 1995).

Short-term patterns for salinity are similar at the two North Inlet stations located in creeks near the uplands borders. The dataset from Oyster Landing is useful for describing the salinity record for North Inlet as a whole, and a general description of the results based on the monitoring there is presented below.

Figure 20 shows the salinity track during a typical 48 hour summer period during which there was no dilution of the water from rain. Salinities over multiple tidal cycles were near the 35 levels found in the coastal ocean. Even though this site is near the forest border, high tidal flushing in the North Inlet estuary maintains high salinity throughout the system most of the time. After a runoff event, salinity at Oyster Landing is depressed especially during the ebbing tide and especially at low tide before saltier water from the ocean pushes the introduced freshwater back up the creek toward the forest. During both longer (days, weeks) and major (high amounts) periods of rain, salinities can drop to very low levels, even depressing salinities in the flood tide waters until the input ceases and the tides re-establish high salinity conditions. The runoff signal is much dampened closer to the ocean origin of salty water.

The pattern seen in Figure 21 compresses 15 minute data for a full year of measurements. Although salinities remained above 32 for most of 2010, periods of lowered salinity were evident in all seasons. Summer low salinity events reflected short rain events (e.g., thunderstorms) of various intensities; salinities returned to high levels within days. During the fall, and especially in winter, low salinity persisted for longer periods due to extended periods of runoff and recovery following the last rain events.

Mean salinity values based on all measurements made during the fall season for each year from 1994 -2010 show that salinity remained at high levels, dipping below 30 on only a few years (Figure 22). The short-lived periods of major salinity fluctuations seen in fall 2010 (Figure 21) had a relatively small overall impact on the salinity regime at Oyster Landing. The year 2010 was part of an extended period of drought on the SC coast. Even though 1997 and 2005 had wetter falls, the mean salinity for the innermost area of the North Inlet estuary was still high.

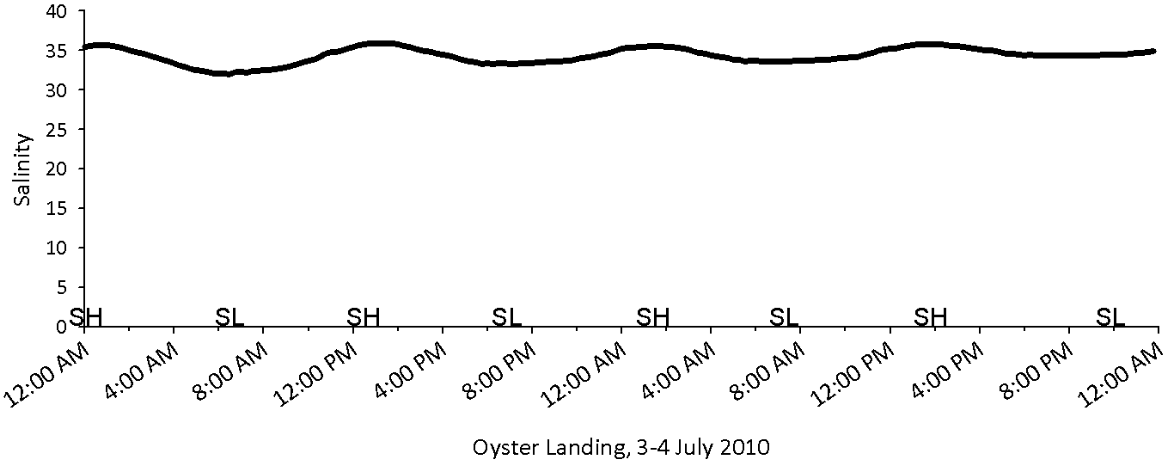


Figure 20. Salinity values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

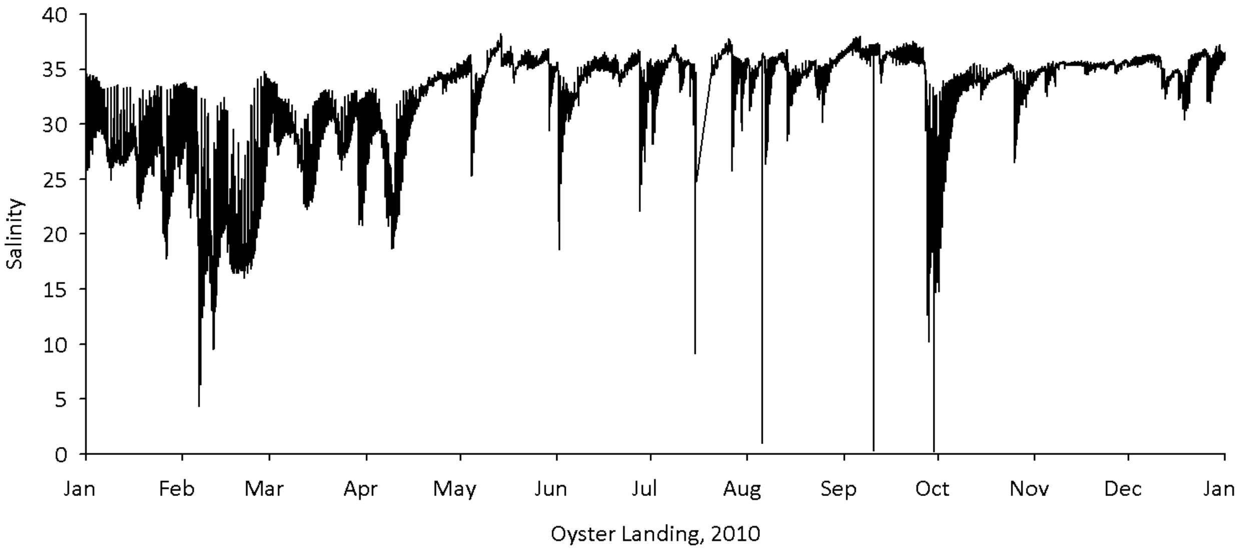


Figure 21. Salinity values recorded every 15 minutes over a 12 month period at the NI-WB NERR SWMP station at Oyster Landing January 1 – December 31, 2010.

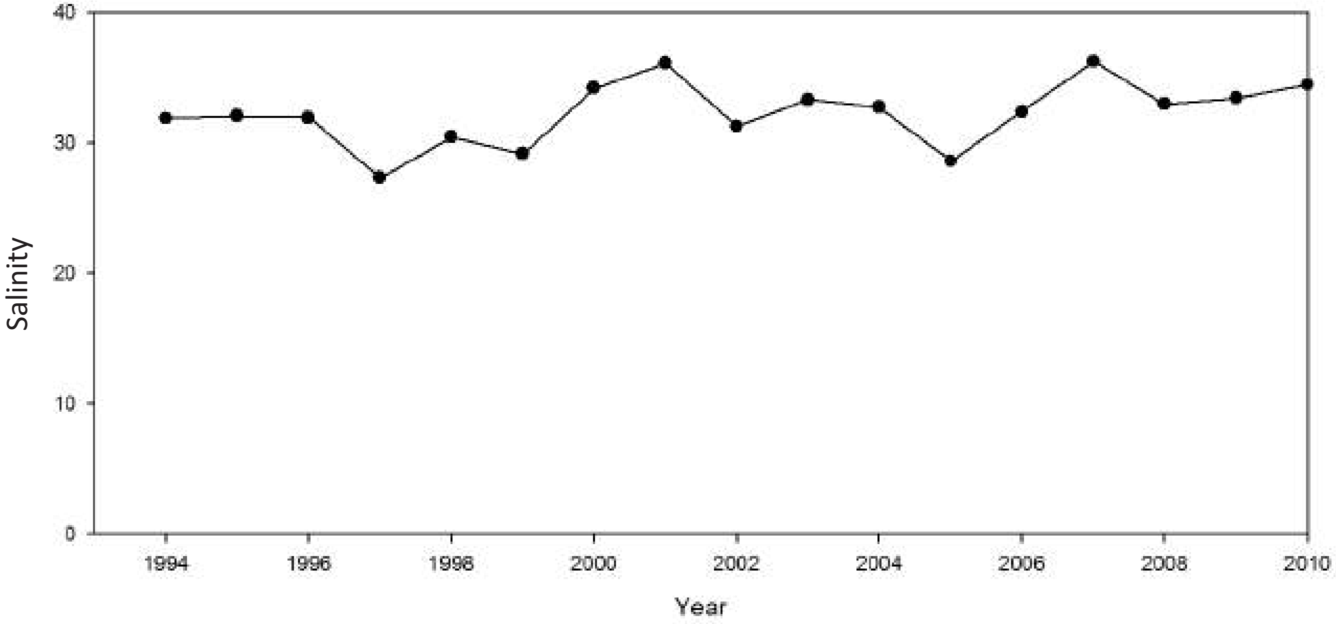


Figure 22. Mean salinities for measurements made during the fall season from 1994-2010 at the Oyster Landing NI-WB NERR SWMP site.

An independent time series of measurements at Oyster Landing from 1984 (pre-SWMP) - 2011 shows a significant long-term increase in the surface salinity (Figure 23). The biweekly measurements used to generate these seasonal means were made at low tide in an intertidal creek pool adjacent to the SWMP measurement site at the pier in the intertidal channel. Measurements made at low tide reflect the lowest salinities that occur in the intertidal basin, because runoff from the watershed is not affected by the flooding tide. Unlike the high mean salinities based on data from all tide stages in the nearby subtidal channel (shown in the preceding graphs), the average low tide salinity is close to 20. Salinities below 10, which are the result of particularly rainy seasons, occurred periodically throughout the

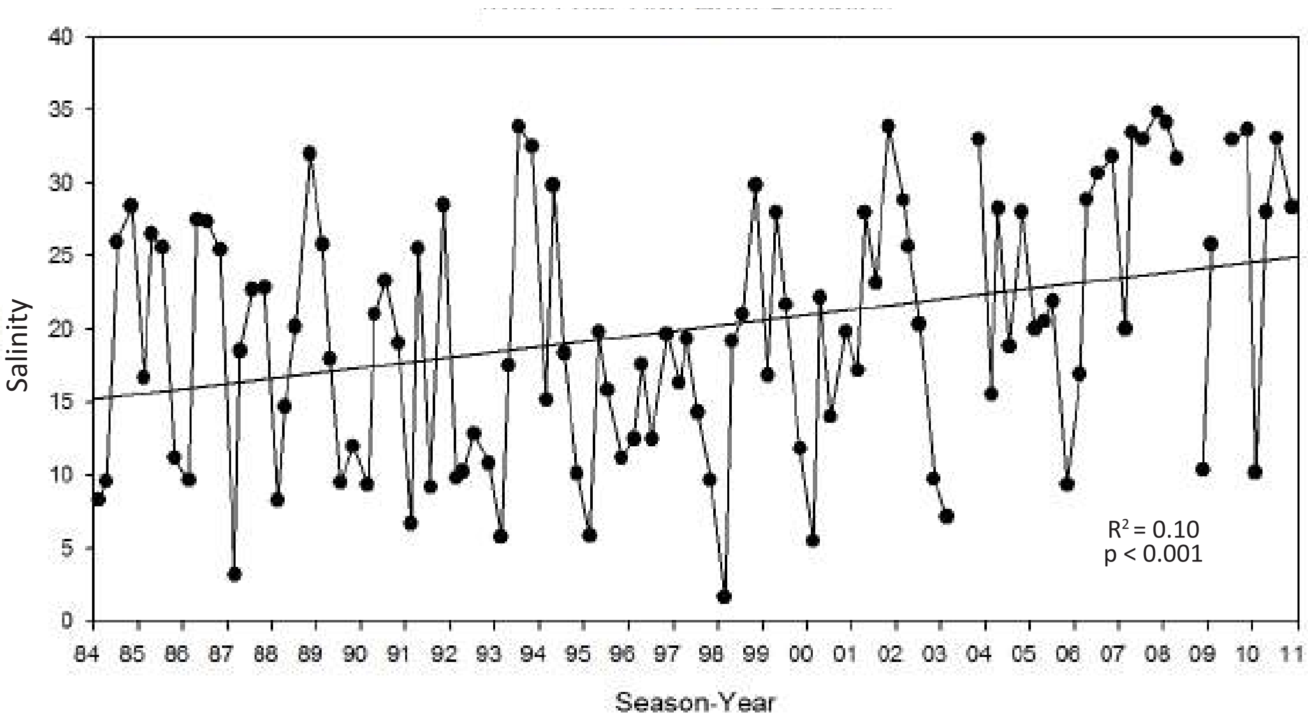


Figure 23. Mean seasonal salinities for measurements made from 1984-2010 at the Oyster Landing Creek intertidal pool near NI-WB NERR SWMP site. Note that although the SWMP series did not start until 1994, historic data from the same location are available for the previous ten years, providing an opportunity to determine whether a long-term trend could be detected with linear regression (shown here as a diagonal line).

27-year period. Despite seasonal variations, the frequent occurrence of El Niño-driven wet years in the 1990s is evident in Figure 23 and so is the much drier period through the 2000s. A long-term trend with significant increase in salinity was determined for the time series with salinities in recent years being higher than at the beginning of the period of measurement.

SUMMARY OF SALINITY STUDIES IN NORTH INLET

While measuring microbial biomass in two intertidal creeks in North Inlet, Erkenbrecher and Stevenson (1975) took water samples over five tidal cycles. These data were reported separately by Erkenbrecher and Stevenson (1977). The salinity in one of the two creeks sampled, near Clambank Landing, varied between 15 and 34, while at Crab Haul Creek much nearer the forest, it varied between 2 and 34. This illustrated how dramatically physical conditions in tidal creeks can change over relatively short periods of time.

Weiland et al. (1979) examined the effects of freshwater intrusion in five different tidal creeks, including one in Mud Bay, on microbial biomass. They encountered a gradient of salinity that ranged from 11.5 to 32.7 over an 8 month period. Salinity and other variables explained different percentages of the variability in microbial biomass, depending on which creek was sampled. They cautioned that no two creeks were similar enough that extrapolations of their conditions could be applied to other unsampled creeks.

Gardner and Gorman (1984) measured specific conductance every 30 minutes over 65 tidal cycles in spring and summer during 1976 and 1977. Automated measurements were taken from the Oyster Landing walkway over the creek. The net salt transport was an amount of 57,000 kg over a tidal cycle, but this is only about 2% of the mean amount of salt held in the Oyster Landing basin at high tide.

An examination of groundwater salinity (conductivity) was conducted by Powell (1985) in summer 1984. On transects across Goat Island, piezometers were used (14 on one, 11 on the other transect) and water samples were collected to measure transmittance to test for the presence of discoloring from dissolved organic constituents in the groundwater. They found salinities ranging from zero to 83, with the highest values always associated with the presence of *Salicornia* plants. They found that the water table was often exposed at the ground surface in the *Salicornia* zone and that groundwater was actively discharged upward in this zone.

Kjerfve (1986) characterized the complex hydrodynamics of tidal flow in North Inlet as part of the Outwelling Study mentioned earlier. His estimates of salt flux suggested that water velocity and hence volume transport had a greater impact on the salt balance of the estuary than did slight changes in its concentration, and that the net salt balance in the system results from advective ebb transport and flood-directed transport due to tidal sloshing, the dominant dispersive flux mechanism. Because North Inlet is so well-mixed and lacks a pycnocline, shear fluxes are negligible. Kjerfve suggested that measurements of export of materials to the adjacent coastal ocean should be made at the coastal boundary front outside the estuary rather than at its entrance.

Childers et al. (1994) measured chlorophyll and salinity with transect data taken at North Inlet during ebbing and flooding tides in winter, spring, and summer 1991. They found total dissimilarity in the magnitude of salinity data from one season to the next, but inter-seasonal similarity in spatial patterns over both hourly and monthly scales.

Blood et al. (1991) and Gardner et al. (1992a) studied the effects of the tidal surge that came ashore with Hurricane Hugo in September, 1989. Soil salinities increased dramatically, causing extensive tree defoliation, with the most salt-induced mortality at the forest's edge next to the saltmarsh. Soil chemistry changed dramatically as well. Conner (1995) and Conner and Inabinette (2003) followed what happened in the forest over time after the hurricane.

Morris (1995) used measures of salt concentrations as a conservative tracer of porewater turnover. He had measured the salinity of porewater to depths of 30 cm at Goat Island and at Oyster Landing since 1987 and then modeled the mass balance of salt and water in a representative portion of the marsh. The model found that of the three ways salt is moved in the marsh (drainage, diffusion across the marsh surface, uptake and excretion by plants), only drainage accounted for a significant flux.

Gardner and Reeves (2002) examined the fluxes of water at the forest-marsh edge, an input to the system that measurably dilutes salinity of soil porewater, especially during winter. They suggest that this dilution is good for *Spartina* growth in the following spring. Deeper examination of the juncture between the flow of fresh groundwater into North Inlet was performed by Carter et al. (2008) who used resistivity probes to measure salinity at sediment depths of up to 4 m monthly during 2005 in Crabhaul Creek. The interface between the fresh and saline water belowground in this margin moves on a time scale of months but is not well correlated with either rainfall or tidal cycles as one might expect.

Although their main focus was on some other aspect of North Inlet, the following papers also included salinity measurements or measured the effects of salinity: Agosta (1985) – runoff and groundwater dilution of nutrient-rich pore water; Apple et al. (2008) – salinity effects on auto- and heterotrophy; Gardner et al. (1992a) – seawater intrusion into shallow groundwater after a hurricane; Nelson et al. (2005) – comparison of long-term data in North Inlet and Murrells Inlet; Weiland et al. (1979) – effects of salinity on microbial biomass (ATP) in North Inlet tidal creeks; and White et al. (2004) – comparative aspects of nutrients in Murrells and North Inlets.

The most important aspects of salinity in North Inlet are that it is generally much higher than in Winyah Bay and that it exhibits modest fluctuations with the tide. Greater variations in salinity occur as weather-driven events, and the long-term trend is towards higher average salinities over time.

WATER TEMPERATURE

In North Inlet, water temperature follows a regular seasonal pattern, coolest in winter (January) and hottest in mid-to-late summer (July-August). Because of vigorous semi-diurnal tidal mixing even into the shallowest reaches of the estuary, neither thermoclines nor pycnoclines form on a regular basis in North Inlet. When they do form, they are weak and not persistent. The average low is about 8 °C and the average high is about 27 °C, although at times greater extremes are reached, especially in the shallow creeks of the inlet. Those who work in the intertidal portions of the marsh have encountered temperature extremes in standing pools of water that reach into the mid 40 °C range, and ice formation has been observed on the exposed marsh surface on rare occasions. Temperature has not been a focus for research activity in the NI-WB NERR, but it has been monitored almost daily since the start of the Long Term Ecological Research program in 1980. Water and air temperatures are included as part of the SWMP protocol. For modeling purposes, the annual change of water temperatures in North Inlet is typically represented as a sinusoidal function over time.

Short-term fluctuations in water temperature are shown in Figure 24. Even during the summer, water temperatures tend to rise in the afternoon and drop overnight; however, diel fluctuations are much lower in summer than during fall and spring, times when exposed intertidal areas warm or cool faster than the water column before they are inundated on the next flooding tide.

Diel and diurnal variations in water temperature can be seen on the curve showing the annual pattern in 2010 (Figure 25). Temperatures are typically lowest from December to February, increase sharply from March to June, and remain fairly stable from June to September before decreasing sharply in the fall.

When seasonal mean values from Oyster Landing are plotted for the entire 27-year time series, a very symmetric pattern is evident; mean seasonal water temperatures appear to be very similar from year to year (Figure 26). However, when the annual mean temperatures are plotted, an increasing trend becomes apparent. Linear regression indicates a significant long-term increase (Figure 27). The increase predicted by linear regression over the period 1982-2010 was about 1.4°C. Trend analyses for each month also revealed significant increases during winter (January, Figure 27 B) and summer (August, Figure 27 C); the increase estimated for January was about 1.8°C and for August was about 2.3°C. Note that measured values and estimated amounts of change vary between monitoring stations in North Inlet, but all indicate increasing trends for temperature.

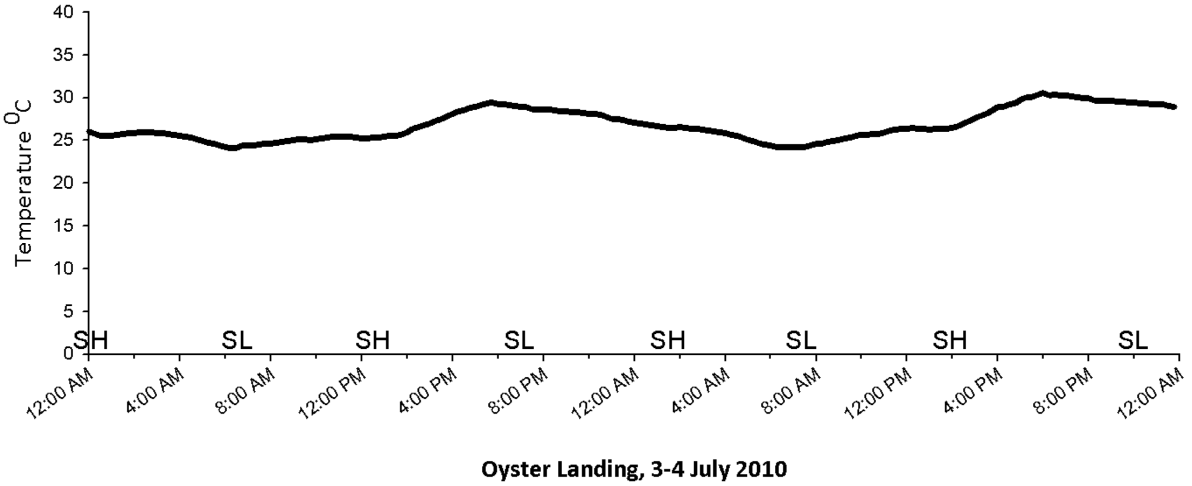


Figure 24. Water temperature values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

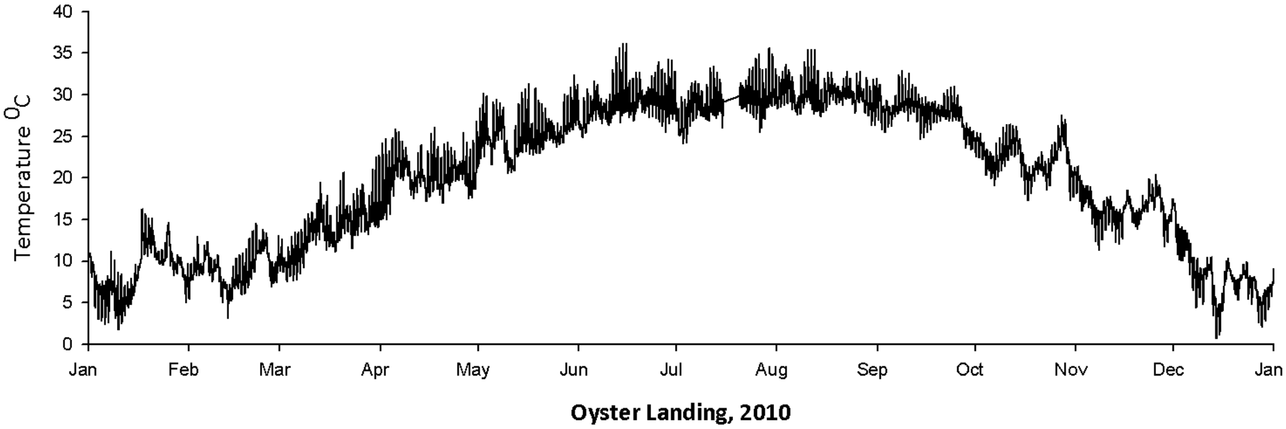


Figure 25. Water temperature values recorded every 15 minutes over a 12 month period at the NI-WB NERR SWMP station at Oyster Landing January 1 – December 31, 2010.

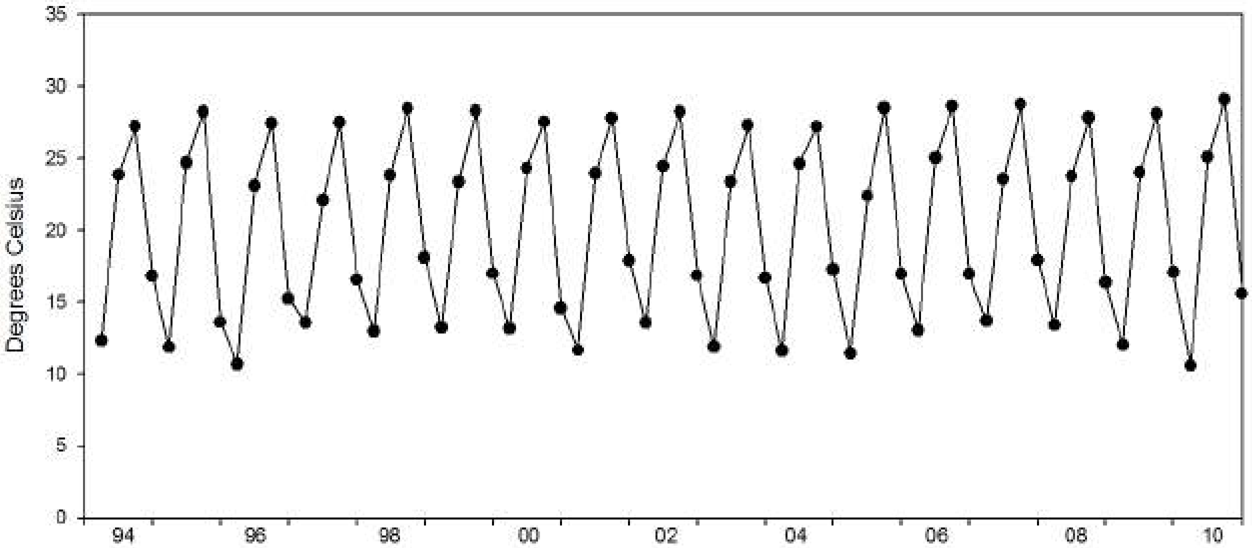


Figure 26. Mean seasonal water temperatures at the NI-WB NERR SWMP station at Oyster Landing from January 1994 – December 2010.

SUMMARY OF STUDIES ON WATER TEMPERATURE IN NORTH INLET

Wilde et al. (2007) analyzed a multi-year record of temperature from Debidue Creek (see their Figure 8). Gardner and Gorman (1984) measured temperature and calculated the net transport of heat (as kilocalories) over 65 tidal cycles in late spring and summer in Oyster Landing creek. A slightly greater amount of heat is exported in the volume of water leaving the Oyster Landing basin during ebb tides, with a little less imported during flood tides, yielding a net discharge of heat of about 129 kcal per square meter of basin area per day. This heat amounted to less than 2% of the heat added to the basin daily by the sun.

Kratz et al. (1991) addressed temperature patterns and its variability at different LTER sites, including North Inlet, and Apple et al. (2008) compared a variety of water quality parameters collected at 21 different NERR sites. Using principal components analysis, they found that temperature and salinity were the primary variables that differentiated the reserves. Both of these properties were also identified as most important in generating a balance between heterotrophic and autotrophic processes in the water. They suggested using site-specific temperature and salinity regimes to classify the different NERR sites for comparative purposes in the future.

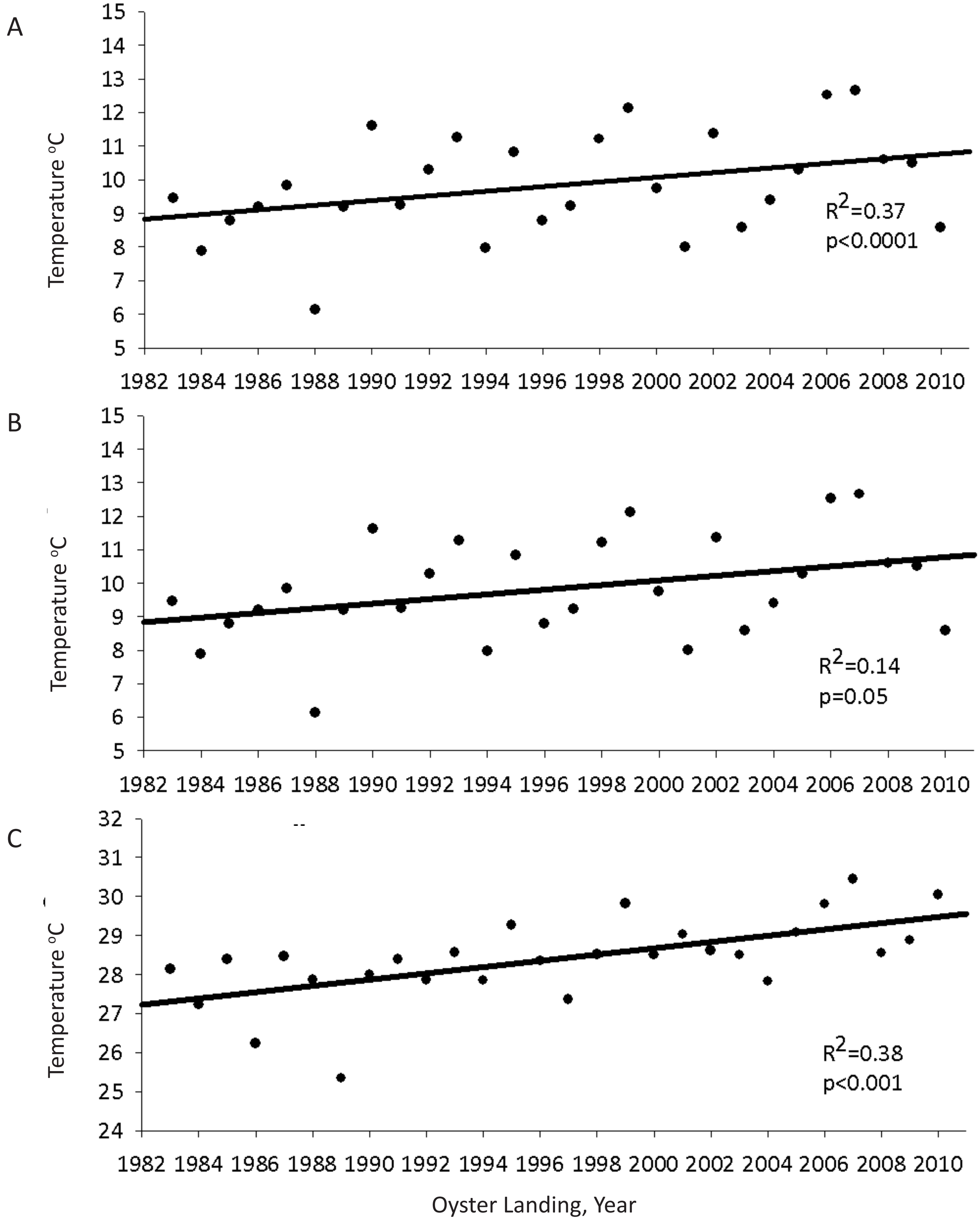


Figure 27. Yearly, winter and summer water temperature trends. A) Mean annual water temperatures at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. B) Mean water temperatures for the month of January at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. A significant increasing trend was determined by linear regression. C) Mean water temperatures for the month of August at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. A significant increasing trend was determined by linear regression.

In summary, water temperatures in North Inlet are rising slowly over the long term. They fluctuate on a variety of temporal and spatial scales, but the most obvious differences in temperature occur as seasonal changes. North Inlet is so well mixed that thermoclines do not usually develop. As a fundamental driver of many ecological and physiological processes, water temperature has great importance in long-term monitoring efforts.

pH AND REDOX POTENTIAL

Having a high buffering capacity, the pH of seawater in the open ocean typically changes very little in response to additions of acids or bases and thus stays within a narrow range of values. In estuaries, however, the close proximity of chemical-laden discharges from land and biogeochemical reactions within the marshes and shallow waterways makes changes in pH considerably greater and more frequent than in the open sea. In estuaries, pH and redox potential (Eh) are usually measured by investigators who study sediment chemistry, diagenesis of organic matter and sediments, and the vertical distribution of living organisms in the sediment (e.g., *Spartina* roots, bacteria, meiobenthos, macrobenthos).

The NI-WB NERR SWMP water quality instruments measure pH in the water column at the same location and frequency as the other variables. Tidal variations of up to one pH unit are common, but the long-term average is between 7 and 8. Although a characterization of the SWMP data is not included in this section, these data (and all SWMP data) are available at the NERR CDMO web site.

SUMMARY OF STUDIES ON pH AND REDOX POTENTIAL IN NORTH INLET

Gardner (1973a, 1975) found that North Inlet interstitial waters had pH values in the range of 6.4 to 7.8, with an average of 6.8. He found that surface waters were usually around 8.0. Erkenbrecher and Stevenson (1977) found that tidal creek surface water pH averaged 7.5 over the range 7.1 to 7.9 during five tidal cycles. Gardner et al. (1988) measured pH in sediment porewater along three transects in North Inlet and found decreasing values from the creek banks (7.3) to the high marsh (6.5). Eh showed similar trends, being slightly oxidizing (+100 mv) at the creek bank and reducing (-200 mv) in the high marsh.

Duncan and Shaw (2003) measured concentrations of rare earth and redox sensitive elements from groundwater wells along a transect across the forest-marsh interface in North Inlet. They found concentrations of iron, manganese and uranium that were consistent with the reducing conditions belowground along the entire transect and calculated a net export of dissolved rare earth elements to the tidal creek system and ultimately to the coastal ocean. This export results from diagenetic mobilization of organic rich carbon phases where the saline wells were located, and they suggested that degradation of relic organic carbon and rare earth elements that are exported is on a scale equal to or even exceeding those from river inputs in this region.

A few other studies in which pH and/or redox measurements were reported as key variables include Agosta (1985), Aller and Aller (1998), Aller and Yingst (1985), Aller et al. (1983) and Gardner (1973a, 1975).

The pH of water within North Inlet varies mostly with changes in the tide, but porewater pH and Eh variations have rather well-defined spatial characteristics. Changes in water chemistry are also temperature-dependent and affect the distributions of both chemical and biological species, particularly within sediments.

SEDIMENTS AND TURBIDITY

Measurements of turbidity with the SWMP water quality data loggers have revealed patterns on various time scales. A repeatable tidal pattern occurs at Oyster Landing with highest levels of suspended sediments occurring when currents are strongest near the middle of the ebbing tides (Figure 28). Resuspension of sediments is typically lower during the mid-flood tide and lowest around slack high tides. Peak and low levels were separated by a factor of about three during July 2010.

The background level of turbidity is highest from

April to November, but large short-lived spikes can occur at any time of year (Figure 29). The higher levels seen during the warmest months are attributed to the increased numbers and activity of benthic invertebrates and nekton, particularly those associated with the bottom. Bioturbation results from feeding, burrowing, and other activities that suspend sediment in both the intertidal zone and subtidal channels. Changes in other physical properties and chemical processes during the warmest period of the year factor into the elevated levels of turbidity in the creeks. Superimposed on this source of resuspension are major spikes caused by strong rain/runoff and wind events that result in large amounts of sediment being resuspended. Recovery usually occurs within a tide cycle or two after the rain or wind stops. The higher incidence of these events during summer and fall is probably related to thunderstorms and the resulting runoff from the marshes and exposed lower intertidal flats. For this reason, summer or fall are consistently the highest points on a plot of seasonal mean turbidity over a 15 year period (Figure 30). The long-term pattern is irregular, but winter lows were higher during the 1990s, the decade of frequent El Niño events and associated wet winters and springs. A very high, weather-related, spike was observed during the spring of 2000.

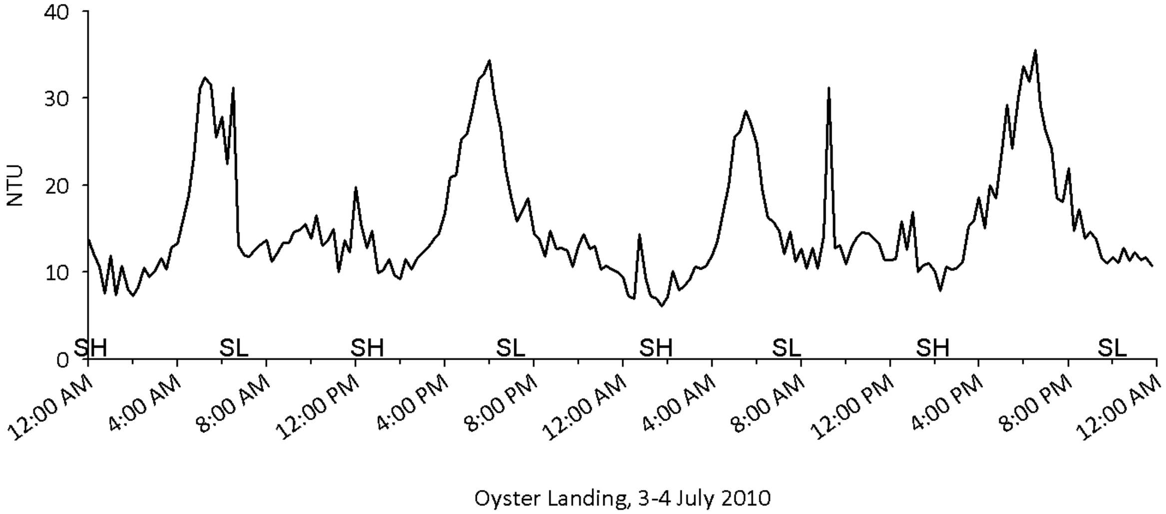


Figure 28. Turbidity values (Nephelometric turbidity units) recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

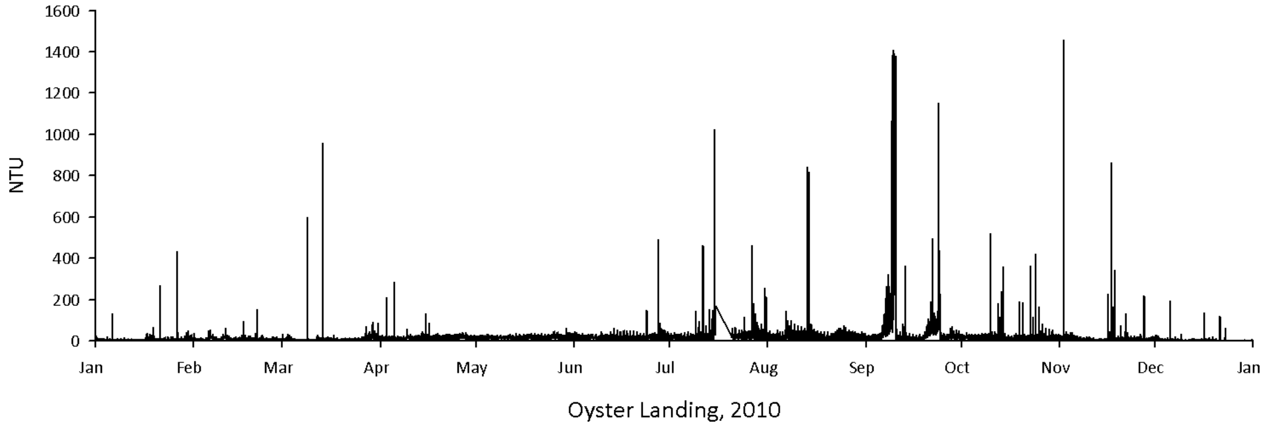


Figure 29. Turbidity values (Nephelometric turbidity units) recorded every 15 minutes over a 12 month period (2010) at the NI-WB NERR SWMP station at Oyster Landing.

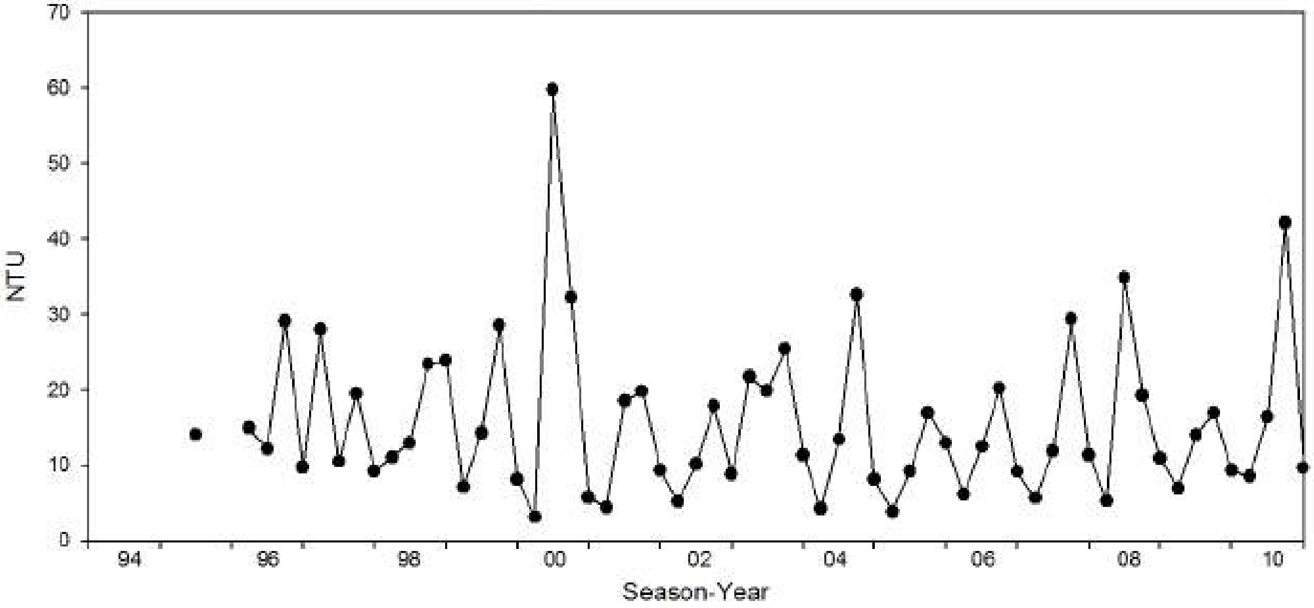


Figure 30. Mean seasonal turbidity (Nephelometric turbidity units) values from January 1995 to December 2010 at the NI-WB NERR SWMP station at Oyster Landing.

SUMMARY OF STUDIES OF SUSPENDED SEDIMENTS IN NORTH INLET

The earliest mention of sediment dynamics in North Inlet is a result of quarterly studies of beach and inlet morphology by Finley (1976). Wave observations, wind measurements, storms, and a series of beach profiles at 11 locations showed that erosion is primarily due to northeastern storm events directed to the south. A 7 m (22 ft) foredune retreat was measured in 1972-73 that contributed sediments to the ebb tidal delta in the inlet. The beach on the south side of the inlet was not eroding because the ebb tide delta afforded it some protection from wave energy.

Gayes (1991) used side scan sonar to show what happened to sediments in the nearshore zone just outside coastal SC inlets after Hurricane Hugo passed. Stauble et al. (1991) provide an additional overview of the storm's effects on shore protection structures and dunes such as exist near the mouth of North Inlet. Kjerfve et al. (2002) provided a macroscale comparison between the Atlantic coastlines of North and South America and highlight how muddy sediments dominate the coastal landscapes of both.

The first systematic examination of suspended sediment concentrations took place as part of the Outwelling Study that measured fluxes of material across the mouth of North Inlet (Dame et al., 1986). Fluxes were calculated based on the volumes of water transported and the concentrations of materials the water carried. Over the year, there was a net export of suspended sediments from North Inlet. Sediments were imported during spring tides and exported on neap tides. Imports occurred mostly during fall and winter, while exports took place in spring and summer. Suspended sediments were comprised of 20% organic and 80% inorganic particles by weight. In winter the concentration of suspended particulates declines, leaving the clearest water of the year and the deepest Secchi depth readings. In the spring, turbidity increases along with the activities of bioturbating organsisms (e.g., by fiddler crabs - McCraith et al., 2003; by benthic fishes and invertebrates – Grant, 1983). Total suspended sediments comprised the greatest flux of particulate material in the Outwelling Study. Dame et al. (1986) suggested that the salt marsh is a sink for inorganic sediment particles but that organic sediment flux varied with every change of the tide.

Gardner et al. (1989) analyzed suspended sediment data, both organic and inorganic. High turbidity was associated with high water temperature more so than with tide height or salinity. They proposed that sediment enters the marsh through the ocean inlet rather than from freshwater river intrusions and that sediment reworking by organisms, bioturbation, is the main source of suspended sediments in North Inlet. Wolaver et al. (1988a) looked at net organic and inorganic suspended sediment data collected for 34 tidal cycles at a flume constructed in Bly Creek. They measured net sediment exchange during tidal inundation and during marsh runoff through the flume at low tide exposure (including during storms). Highest concentrations occurred in summer, and they found that the marsh is a net sediment sink, exporting only about 35% of what comes in with the tide, sufficient for the marsh surface level to keep pace with the rise of sea level. In the Wolaver et al. (1988b) Bly Creek Study, inorganic suspended sediment concentrations varied seasonally and ranged between 6.5 in winter and 85.1 mg L^{-1} in summer. Freshwater input of inorganic suspended sediments was negligible, and sediment accumulation in the marsh was, again, found to be keeping up with sea level rise.

As for marsh elevations relative to sea level rise, Childers et al. (1993a) measured them seasonally in North Inlet at six locations using a clever, mechanical leveling-arm device. They found elevations increasing at the greatest rates, two to three times the rate of apparent sea level rise, at the sites closest to freshwater influence. However, marsh elevations at the dead ends of tidal creeks without freshwater input increased only at the same rate as apparent sea level rise.

Pillay et al. (1992) compared three different methods for calculating suspended sediment transport rates in Town Creek. These investigators found high correlation coefficients between the three methods, suggesting that the LTER daily water sample data can be used confidently to estimate instantaneous discharge from continuous tide data, provided an accurate hypsographic model of basin volume change can be developed.

Sediment traps were used by Hutchinson et al. (1995) in two areas (Mud Bank (MB) and Sixty Bass (SB)) where there is a close connection to the oceanic inlet (SB) and where the influence of input of brackish water from Winyah Bay is significant. They also measured sediment concentrations (both organic and inorganic), salinity, carbon and nitrogen in adjacent creeks. Because the Mud Bank site was 27 cm (about 1 ft) higher than the Sixty Bass site, it was inundated only about half as long per day, yet sediment deposition rates were higher at this higher site (MB) than at Sixty Bass (5.3 mg/d/cm^2 vs 4.2 at SB). They found essentially no correlation between water sediment concentrations or tidal inundation duration and the sedimentation rates measured, suggesting that bioturbation activities are important to sediment dynamics.

Mobilization and redistribution of sediments by rain drops falling on the exposed intertidal marsh surface was studied by Mwamba and Torres (2002). They also simulated tidal flow with a flood irrigation experiment. Sediment concentrations were up to 1000 times higher in the sprinkler runoff plots than in the flood irrigation water. Most of the sediment mobilization took place within the first 5 minutes following raindrop impact detachment of sediments from the marsh surface and subsequent transfer via sheetflow. Even though rainfall volume is very small compared to the tidal prism, rainfall effects can be disproportionately large in moving and redistributing sediments. Additional data analysis from these experiments measured how much organic matter was entrained by the rainfall effect (Torres et al., 2003). Compared to their abundances in the surrounding substratum, the rainfall carried considerably higher amounts of organic matter, organic carbon and nitrogen, suggesting that rainfall events can deplete the marsh surface of these constituents. Most of the organic matter mobilized was a mixture of algae and vascular plant detritus.

In response to an application to dredge the Debordieu Channel and Debidue Creek for boat access to homes at the northern edge of the NI-WB NERR boundary, a long-term monitoring station was established there in spring 1998. Its purpose was to provide a record of pre-dredging water quality conditions, because this disturbance to the creek bottom was expected to release nutrients that normally leach slowly from sediments into the overlying water, with concerns that turbidity and DO would also be impacted. The long canal was dredged in fall/winter 2001-2002, and the creek leading into the canal was dredged in October 2001. In addition to the long-term water quality station, a set of synoptic samples was taken in Debidue Creek during the dredging operation. This study reports the results found for total suspended solids (TSS) and nutrient concentrations. TSS was highest in summer and highest at slack tides and lowest when tidal currents were swiftest, on both ebb and flood. Samples taken within the cloud of sediments during dredging operations revealed higher concentrations of TSS than occurred about 700 m downstream. TSS declined rapidly when dredging ceased for the day. Samples taken along the creek transect while it was being dredged failed to find any significant temporal or spatial gradient in TSS that could be ascribed to the downstream effects of dredging. TSS impacts were tightly localized to an area within 10 m of the dredge and water cleared to background levels within 10 min after dredge cessation. The coarse sandy sediments from the creek bottom settled rapidly. Lohrer and Wetz (2003) concluded that there was essentially no impact to water quality realized from the dredging activity but cautioned that the timing, duration and spatial scale of such activities in the future might have greater consequences for the environment. Monitoring of dredging activity in the future should include measures of water flux so that nutrient fluxes can be estimated rather than just the instantaneous concentration measurements made in this study. Caine and Hull (1981) summarized many of the expected effects of dredging salt marsh creeks.

Buzzelli et al. (2004) compared SWMP data from 1994-2001 for suspended solids at the Oyster Landing (OL) and Thousand Acre (TA) marsh long-term sampling sites. Mean concentrations were twice as high at TA, as was turbidity during all seasons. Turbidity was, in fact, the most variable of all the parameters measured during that time, especially at Oyster Landing. Inorganic particles comprised between 66 and 80% of the total suspended solids, with organic particles the rest.

Sedimentation was also investigated by Voulgaris and Meyers (2004a) using a laser diffraction system, acoustic Doppler velocimeters and optical backscatter sensors in a tidal creek. They found that sediments suspended in tidal creeks exist primarily as flocs with a mean particle size between 25 and 75 micrometers and with settling velocities of between 0.02 and 0.2 mm per second. During spring tides, the flocs were larger and had larger average grain sizes. Their time series of measurements revealed that erosion occurred only during the ebb stage of spring tides, with essentially no bed erosion during flood tides. They also found that sedimentation onto the marsh surface occurs mostly in the form of flocs that settle to the bottom at the same rates (0.24 mm/s) during both neap and spring tides. They suggest that marsh sedimentation is controlled by availability of sediment flocs for deposition and inundation time, both of which are higher during spring tides.

In their evaluative overview of the three past outwelling-related studies conducted in the North Inlet basin (entire basin: Dame et al., 1986; Bly Creek sub-basin and Bly Creek flume study: Dame et al., 1991), Gardner and Kjerfve (2006) examined whether the water chemistry data collected with the SWMP protocol at Oyster Landing can be used to estimate fluxes of nutrients and sediments. Their study was prompted by the lack of precision with which these three earlier studies estimated fluxes of materials on a diurnal, seasonal, or long-term basis. By examining the SWMP's half-hour data collection protocol, they hoped to make recommendations for protocol changes that might improve measurements that could provide a better understanding of outwelling processes.

Using instantaneous concentrations of various water constituents measured at Oyster Landing and flow discharges from Crab Haul Creek, Gardner and Kjerfve (2006) were able to estimate instantaneous fluxes of nutrients, sediments and salt. Everything measured, except salt, had mean long-term advective fluxes significantly less than zero, i.e., they are exported. None of the particulate materials, including inorganic and organic sediments, had statistically significant dispersive fluxes, while all of the dissolved constituents did. Movements and redistribution (dispersive flux) of materials that exist in the basin were balanced by their import and export due to changes in the tidal height.

Sediment resuspension in a tidal channel in North Inlet was examined by Traynum and Styles (2007). The deployed an acoustic Doppler current profiler onto the bottom of a mid-marsh shallow channel of Town Creek for measurements during a spring tide cycle when river discharge into Winyah Bay was great. Suspended sediment concentrations were highest during the late stages of the ebbing tide, indicating net particulate transport from Winyah Bay to North Inlet through this creek despite the fact that the creek channel is flood-dominated. Flow asymmetries along the bottom caused higher concentrations of suspended sediments during ebb when bottom friction created the highest stresses near the time of low water, even though stronger currents existed during flood tide. A rigorous description of the current variations that exist in the creek study area around its nodal point from data collected with an acoustic Doppler current profiler over a 35 day set suggests that winds are heavily involved in tidal asymmetries in the area (Traynum and Styles, 2008).

Another view of short-term sediment dynamics under flow conditions was constructed by Wargo and Styles (2007) along the deep channels just inside the mouth of North Inlet. They measured currents, bed sediment, salinity, and suspended sediment concentrations plus particle size distributions over a complete tidal cycle. Bed elevation and channel width variability, i.e., changing bathymetry, caused many changes in tidal current velocity, shear stress, with highest values observed in the narrowest section of the inlet throat. At stations closer to the marsh, channel "geometry" and branching results in a reduction of flow energies. They found higher currents and associated sediment transport during ebb tide. Interestingly on this particular tide cycle in 2005, they found that depth-integrated transport of sediments is directed towards the marsh on the landward side of the intersection between Town and Debidue Creeks. Seaward of this intersection, transport was out of the inlet. Examination of changes in the size spectrum of particles as it changed during the tide cycle suggested that there was a net transport of fine-grained sediments landward.

Styles and Teague (2007) made current velocity measurements in tidal creeks and over the marsh surface using an ultrahigh-frequency radar system that transmits from an antenna set up next to the marsh. The return signal's Doppler shift is calibrated to be proportional to surface current velocity. The ability to make current measurements in the marsh at high tide was complicated by the radar reflections from *Spartina* grass.

Summarizing sediment dynamics in North Inlet is difficult because studies have been conducted at various locations and at different spatial and temporal scales. Suspended inorganic sediments enter North Inlet from offshore and once inside they settle out and get redistributed with wave action and changes in the tide. Summertime bioturbation resuspends large amounts of sediment. Water turbidity is thus highest in summer but is minimal in winter when waters are clearer than at any other time of year. The rate of sediment supply to the system has been sufficiently high to keep pace elevationally with the rate of sea level rise. Whether this will continue in the future, especially with predicted accelerated rates of sea level rise, remains to be determined.

DISSOLVED OXYGEN

Dissolved oxygen (DO) is measured at the SWMP datalogger sites in North Inlet. DO exhibits high short-term variability with typically higher levels during the day when photosynthetic phytoplankton and microbenthic algae produce oxygen. The cessation of photosynthesis at night results in reductions in DO levels in the water column especially before daybreak; this may be due to continuing activity of microbes which consume DO while decomposing organic material. This pattern can be seen in Figure 31 where DO was about twice as high on daytime low than on night low tides on July 3rd-4th, 2010. Little difference was observed between the nighttime high and low tides.

These diel and tidal patterns of DO variation are evident in the 12-month track of DO shown in Figure 32. More short-term variability is evident during the warmest months when overall DO is at the lowest levels of the year. In summer DO can vary from 2 to 7 mg/L within a week or even a few days. DO is least variable during winter when values of 7-11 are typical.

Interannual variations in DO are shown in Figure 33 where the seasonal mean values are plotted. Summer DOs are lower than winter's, and spring values are usually higher than fall's. No long-term trend was evident for the 16 year period.

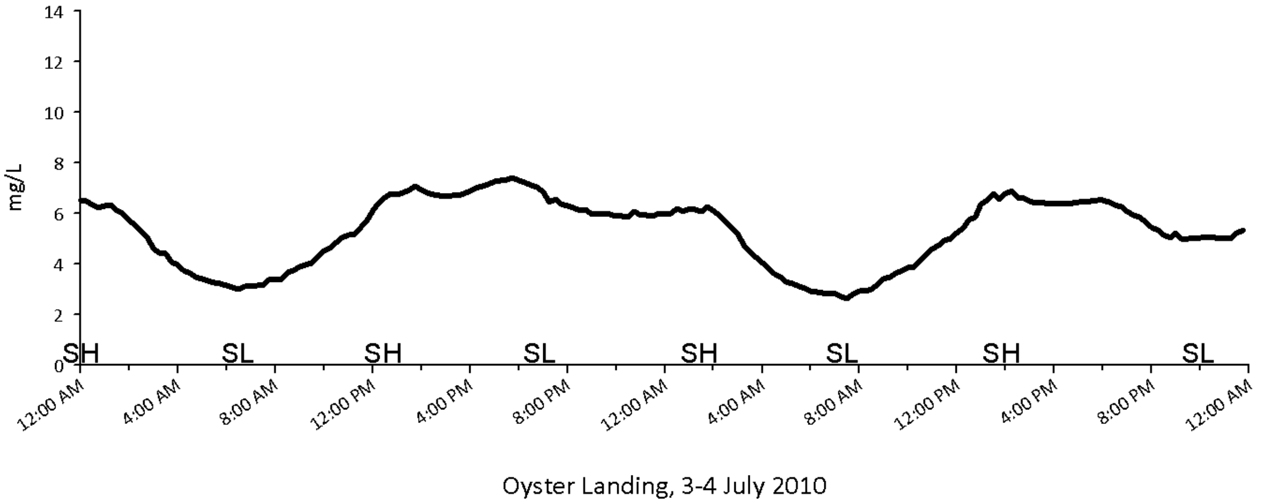


Figure 31. Dissolved oxygen values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

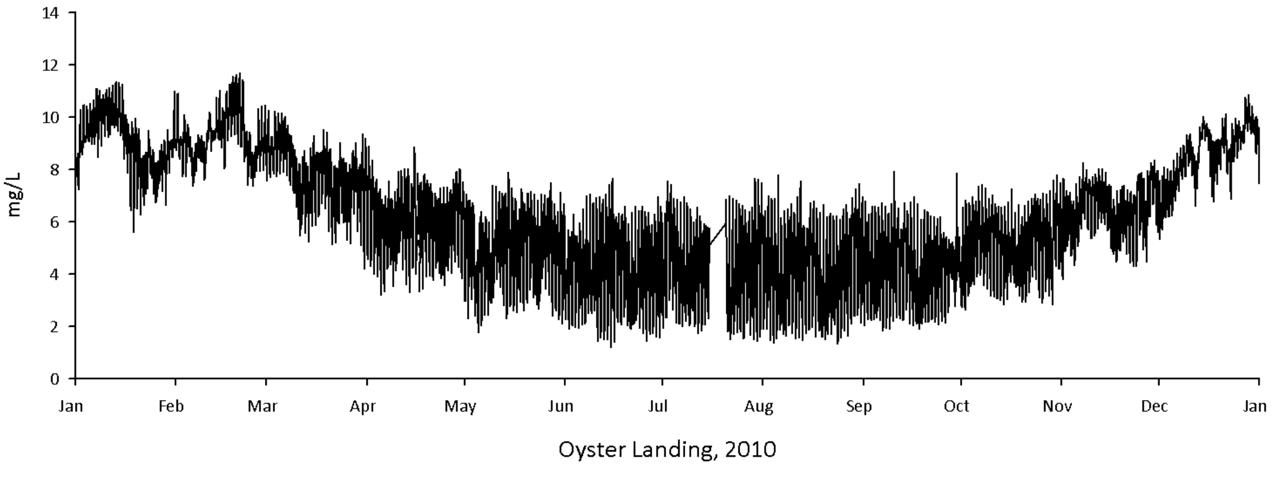


Figure 32. Dissolved oxygen values recorded every 15 minutes over a 12 month period (2010) at the NI-WB NERR SWMP station at Oyster Landing.

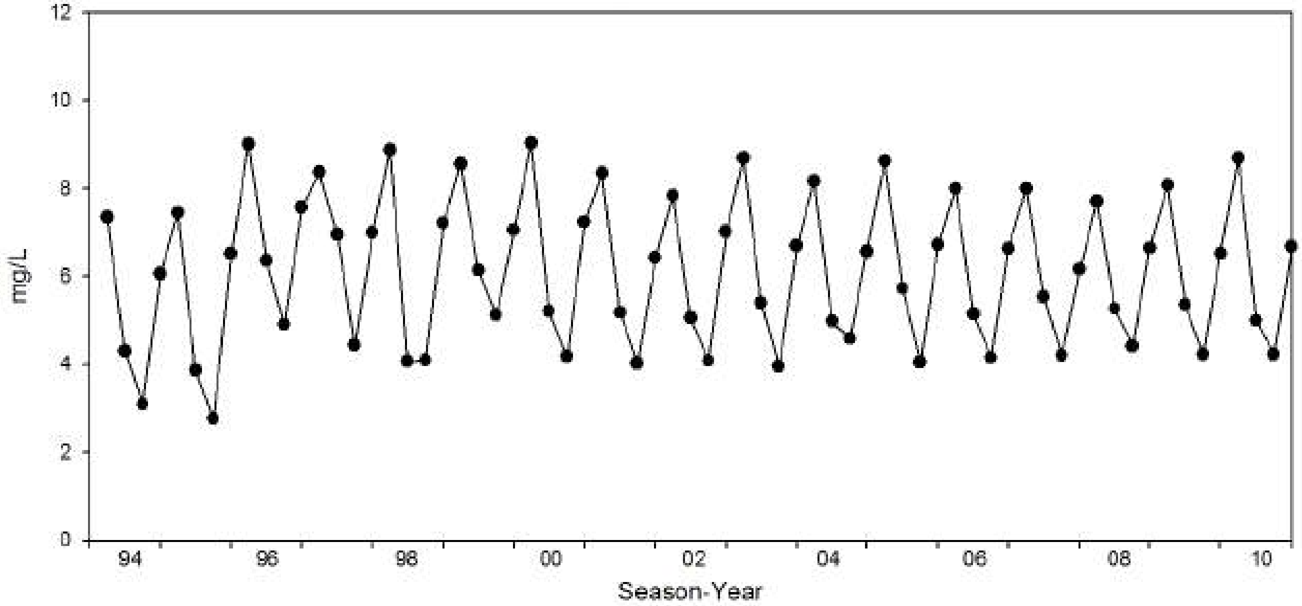


Figure 33. Mean seasonal dissolved oxygen values from January 1994 to December 2010 at the NI-WB NERR SWMP station at Oyster Landing.

SUMMARY OF OTHER STUDIES ON DISSOLVED OXYGEN IN NORTH INLET.

Wenner et al. (2004) examined the incidence of hypoxia at 55 sampling locations within 22 different NERR sites based on SWMP data collected up to that point in time. Their study illustrated the value of high frequency sampling in the SWMP protocol because it allowed detection of many hypoxia situations that would otherwise have gone undetected. Wenner and Geist (2001) also examined hypoxic events and found that natural processes affecting dissolved oxygen concentrations differ among NERR sites depending on tidal amplitude, a measure of the difference between high and low tide water levels. Both of these studies involved analysis of other water quality parameters as well.

Because DO was not measured during the Outwelling Study, it was measured every 30 min during spring and summer over 65 tidal cycles at the Oyster Landing boardwalk in a separate study by Gardner and Gorman (1984) to see if DO was exported or imported in this portion of North Inlet. They also measured biological oxygen demand (BOD) over 14 tidal cycles as part of their study. They found that the principal determinants of the DO flux over a tidal cycle were the amount of sunlight received and the volume of water flowing in and out of the Oyster Landing basin. There was a direct correlation between net heat transport and net DO transport as a consequence. Interestingly, the times when DO was exported from the basin occurred only when high tide happened within 2 hours of local noon, i.e., between 10 am and 2 pm. Maximum exports of DO from photosynthesis took place during spring tides that started at sunrise. The BOD study was inconclusive, but the investigators felt that most of the BOD, either imported or exported, was a water column phenomenon that happened on a much faster time scale than the export of particulate organic carbon that may impose the oxygen demand. They suggested that excess loads of oxygen demanding materials (e.g. bacteria-laden detritus) could produce anoxia in the headwaters of marsh tidal creeks.

Aelion et al. (1997) measured the concentration of dissolved oxygen in groundwater collected from deep wells in the edge of the forest near Oyster Creek in North Inlet. This was a study examining the rate of denitrification in coastal aquifers, so the DO measurements were made in that context. They found between 0.4 and 1.0 mg/L concentrations and described this DO level as “microaerophilic”.

Using SWMP data collected at Oyster Landing from November 1993 and April 1996, Gardner et al. (2006) examined DO to see whether Crab Haul Creek exported or imported oxygen, a further test of the outwelling hypothesis. Their Figure 1 provides a concise overview of "DO dynamics in aquatic ecosystems". Up to 40% of total oxygen uptake can be due to sediment oxygen demand where organisms and biogeochemical reactions utilize DO from the water column while plankton and nekton consume the rest. Tidal fluxes of water to and from the creek were estimated using current velocity and depth measurements, so that the volume of water in the basin could be calculated based on tidal height. Some error is inherent in this method due to sheet flow across the entire marsh at high tide, i.e., basins are isolated only when water is confined within the creek's banks during lower tides (Miller and Gardner, 1981). Their methods assumed that the concentrations of DO measured at the Oyster Landing pier were the same as those occurring in the channel cross section of Crab Haul Creek. A separate study confirmed that it was, i.e., DO is spatially uniform there. Concentrations of DO were described as having a "sawtooth pattern", with January peaks at about 10 mg L^{-1} and July troughs at about 3 mg L^{-1}. Tide cycle-to-tide cycle fluctuations averaged about 2.0 mg L^{-1}. For the entire study period of 30 months, there was a small net export of DO from the creek, indicating that there was, on average, slightly more oxygen produced by photosynthesis and diffusion from the air than was consumed by biological and chemical processes.

Buzzelli et al. (2004) synthesized SWMP data from Oyster Landing and Thousand Acre marsh from 1994-2001. DO concentrations varied seasonally at both sites but were higher at the TA site in winter and spring. Concentrations ranged from zero to 17.6 mg L^{-1} at TA and from 0.9 to 23.7 at OL. Comparing average monthly values for the water quality parameters measured, DO had a highly significant negative correlation with water temperature (r2 = 0.91) over the range of 9 to 29 ºC. DO was also negatively correlated with dissolved organic nitrogen and chlorophyll-*a*.

Caffrey (2004) analyzed dissolved oxygen records from 42 sites within 22 NERRs from 1995 to 2000. DO concentrations, taken every 30 min, were mathematically converted to production gains and respiratory losses while accounting for air-sea exchanges. Caffrey's goal was to determine whether the types of environments represented by NERR sites were sources or sinks for carbon. All but three sites were net heterotrophic over a year's time. Trends in production and respiration were consistent at all sites, with rates higher in summer and lower in winter. Both the Thousand Acre and Oyster Landing sites were net heterotrophic, i.e., oxygen consumption exceeded production on average.

The results of the study by Gardner et al. (2006) conflicts with the results found above by Caffrey (2004) who estimated that the same basin imported oxygen because respiration exceeded gross primary production. Neither study found great differences between the basin's being in DO balance (import flux = export flux), and both methodologies had enough error that they were probably not that different. Thus outwelling of DO, if it exists at all, is not great enough to affect the trophic status of continental shelf communities. In contrast, outwelling of carbon contributes significantly to the net heterotrophy of shelf waters.

These DO budgeting studies demonstrate the types of analyses that are afforded by the existence of long-term SWMP data, their power for making it easier to detect changes in these shallow coastal ecosystems and, through careful statistical comparisons, their utility for making rigorous generalizations about how these ecosystems are regulated. Differences in nutrient inputs explained most of the variability that existed in DO concentrations between sites.

Dissolved oxygen is one of the more dynamic chemical species in North Inlet. DO concentration varies considerably at all temporal scales that have been measured. North Inlet is usually so well mixed that DO levels remain high except during periods of stagnation in summer in shallow portions of the estuary. DO is negatively correlated with water temperatures and responds quickly to changes in organic matter loadings.

» Water Chemistry in North Inlet

The term 'water chemistry' is used here to refer to dissolved and particulate inorganic and organic materials in the water. These include the various forms of nitrogen and phosphorous as well as many other important building blocks for synthesizing organic compounds such as carbohydrates, lipids, and proteins. Microbial decomposers remineralize organic materials in complex biogeochemical cycles.

NITROGEN AND PHOSPHORUS

The most comprehensive studies of nutrient cycles in North Inlet were conducted as part of the Long-Term Ecological Research (LTER) project's daily water sampling program starting in 1978 at Oyster Landing, Clambank Creek, and Town Creek. To better understand the contributions and fluxes of materials and nutrients to and from Winyah Bay, many water samples have been taken at No Man's Friend and in Jones Creek (at both its north and south ends), the two major connections between the two estuaries. Movement of nutrients within the marsh via exports to creeks and from creeks to the coastal ocean (the Outwelling Study) dominated most of the early research on chemical species. More recently there have been a number of studies using the quality of North Inlet waters as the natural, undisturbed, baseline against which nearby anthropogenically-impacted coastal bodies of water have been compared. Nutrient budgets have been proposed and several models constructed to explain how the complex biogeochemical nutrient cycles work and change under various stressors in both North Inlet and Winyah Bay.


Water samples were collected at the same time daily, 1979-1993, prior to the NERR becoming established.

The NI-WB NERR 20-day water chemistry monitoring database, initiated in June 1993 and continued to the present (2014), is a continuation of the (LTER) Daily Water Sample 1978-1993 database. Because the LTER daily water sampling collections were taken every day at 10:00 am EST, it was determined that those nutrient data are biased for spring high tides; therefore, not all tide levels would be represented. The NI-WB NERR water chemistry collection protocols sample all tidal stages (day and night) over the years. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours). Samples are collected from 0.5 m below the water's surface into one-Liter sampling bottles by an automated water sampler. Samples are collected at each of the four water-quality/chemistry monitoring stations: Oyster Landing (OL), Debidue Creek (DC), Clambank Creek (CB), and Thousand Acre Marsh (TA). Sampling events always begin and end on predicted slack low tide (SL) and cover two tide cycles, one in the day and one at night. The timing of SL for the North Inlet sites (DC, CB, OL) is different than the timing of SL for the Winyah Bay site (TA), due to differences in runoff, river flow, and distance from the ocean. Therefore, sample times for each site do not match exactly within a sample event, but tide stages or levels do match.

The Oyster Landing monitoring site is used in this document to represent nutrient levels which have been recorded and analyzed in short- and long-term time frames in North Inlet. A 20-day sampling event in July 2010 showed that nitrate+nitrite (NN), ammonium (NH_4^+), and orthophosphate (PO_4^-) concentrations are influenced by tide and time of day (Figure 34). For this particular sampling event, nutrient levels were typically higher from about midnight to 8:00 am and then dropped off sharply during the noon-time slack high tide. Values remained low until the nighttime hours when they began to increase again.

A 2010 yearly plot of these nutrients at the OL site puts the July 3-4 values in context with the rest of the 20-day data for that year (Figure 35). Lower July 2010 NN concentrations, which range from 0.0 to about 0.6 micromoles per liter, are similar to the

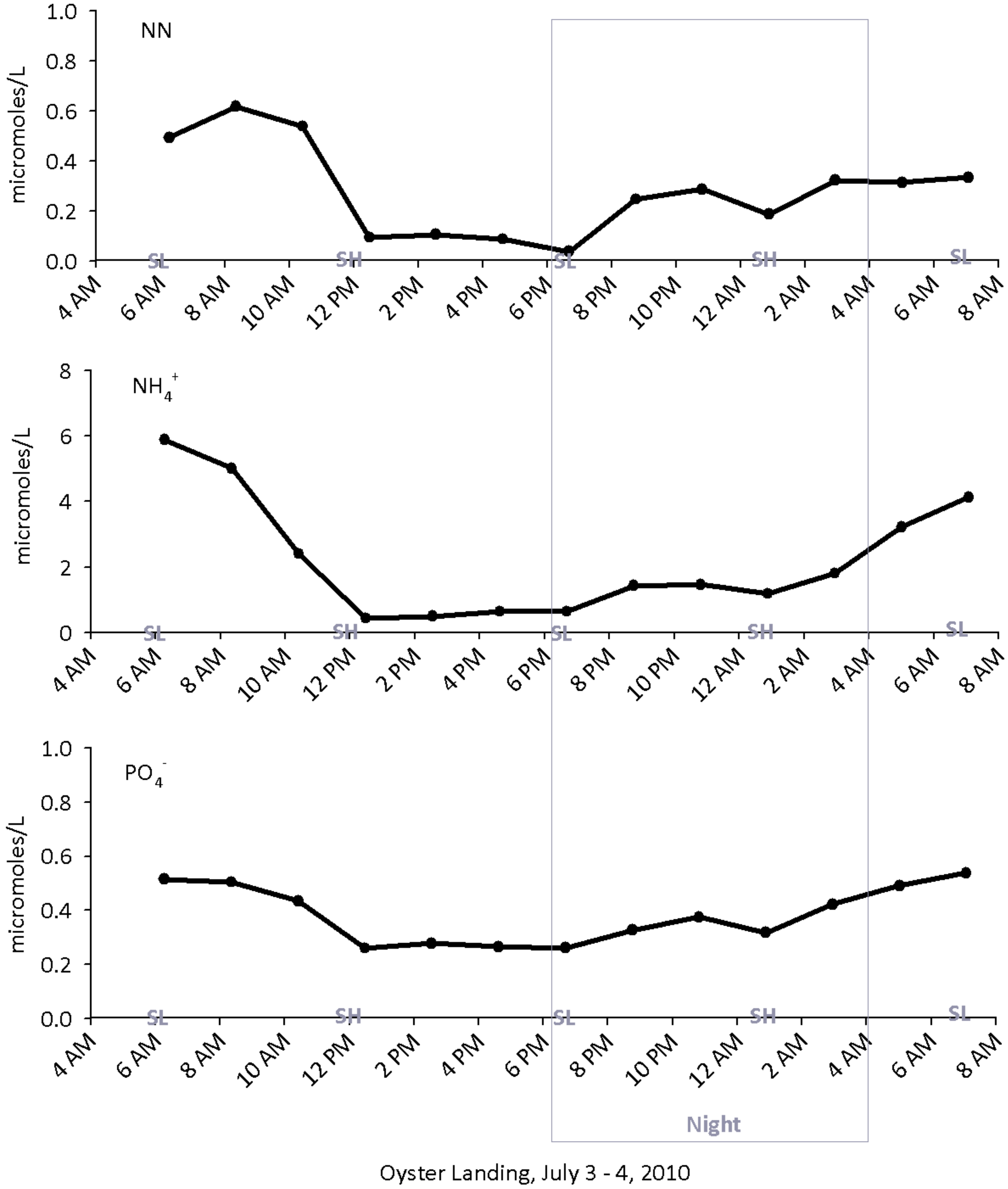


Figure 34. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

rest of the summer and early fall values. Winter, spring, and late fall have comparable low levels of NN, but the variation within each 20-day event is much greater (up to 3.0 micromoles per liter – see February's data in Figure 35). Figure 35 demonstrates that NH_4^+ and PO_4^- have the highest values (NH_4^+ with 16 and PO_4^- with 1.1 micromoles per liter) and variability from about April/May through December. Winter NH_4^+ and PO_4^- levels are much less variable and lower in concentration during these months. Seasonally averaging the nutrient data illustrates differences within and among years, and long-term trends are also elucidated. Figure 36 demonstrates seasonal differences within years with most winter NN values being the lowest of each year (about 0.2 or less micromoles per liter), and with spring and summer concentrations typically the largest. The rainy El Niño years 1998 and 2003 have the highest NN values. The drought years' (latter part of 1999 through the summer of 2001 and about 2007-2010) values are lower and less variable. If the drought trend continues over the next decade, it could be expected that the long-term trend of NN concentrations in North Inlet may decline and continue to have less variation. NH_4^+ seasonal averages from 1994 through 2010 show similar characteristics to NN, although the latter three seasons in 2010 are increasing in concentration (Figure 36). There is no apparent long-term trend for NH_4^+ in North Inlet. In all the above-mentioned graphs, NH_4^+ is about an order of magnitude greater in concentration than either NN or PO_4^-, both of which have very low levels (usually <1.0 micromoles per liter). The most obvious feature in Figure 36 is the increasing trend for PO_4^- values, and, like NN and NH_4^+, PO_4^- has seasonal low values in the winter and highs in the spring and summer.

SUMMARY OF OTHER STUDIES ON NITROGEN AND PHOSPHOROUS IN NORTH INLET

Gardner (1975) collected drainage from small tidal rivulets at Goat Island at low tide to examine the contribution of diffusion to the release and discharge of nutrients from interstitial waters in the marsh. Diffusion from the sediments was the most important process in this translocation of nutrients into tidal waters. An earlier preliminary study found that, compared to the receiving creek water, this water was enriched in silica, phosphate, alkalinity, calcium and possibly ammonium as well as having a reduced pH (Gardner 1973a). Because salinities did not change appreciably over time in the interstitial water samples, it was concluded that there was no freshwater input from subsurface groundwater or terrestrial sources. Compared to freshwater runoff along the coast of SC, marsh drainage as detected here supplied less than 10% (by volume) of total runoff from the land. But because the concentrations of SiO_2 and PO_4^- are so much higher in marsh runoff, this mechanism supplies a disproportionate amount of nutrient runoff. Gardner (1975) concluded that "the impact of marshlands on silica and phosphate concentrations in coastal waters may equal or perhaps even exceed that of freshwater runoff."

Water samples are anaylzed at the Baruch Marine Field Lab.

Wolaver et al. (1984) reported data collected during the first 15 months of the LTER daily water sampling program at the Town Creek transect. Ammonium, orthophosphate, and nitrate+nitrite concentrations (the labile fraction) all had a tidal signature: highest at low tide and lowest at high tide. This tidal signature was less evident in winter. Orthophosphate and nitrate + nitrite were highest in fall and low in winter and spring. Because all the dissolved inorganic species had high concentrations at low tide, this suggested their source must lie within the inlet. Possible sources included the vegetated marsh surface during tidal inundation, runoff and seepage from the marsh surface during low tide exposure, diffusion from the sediments within the

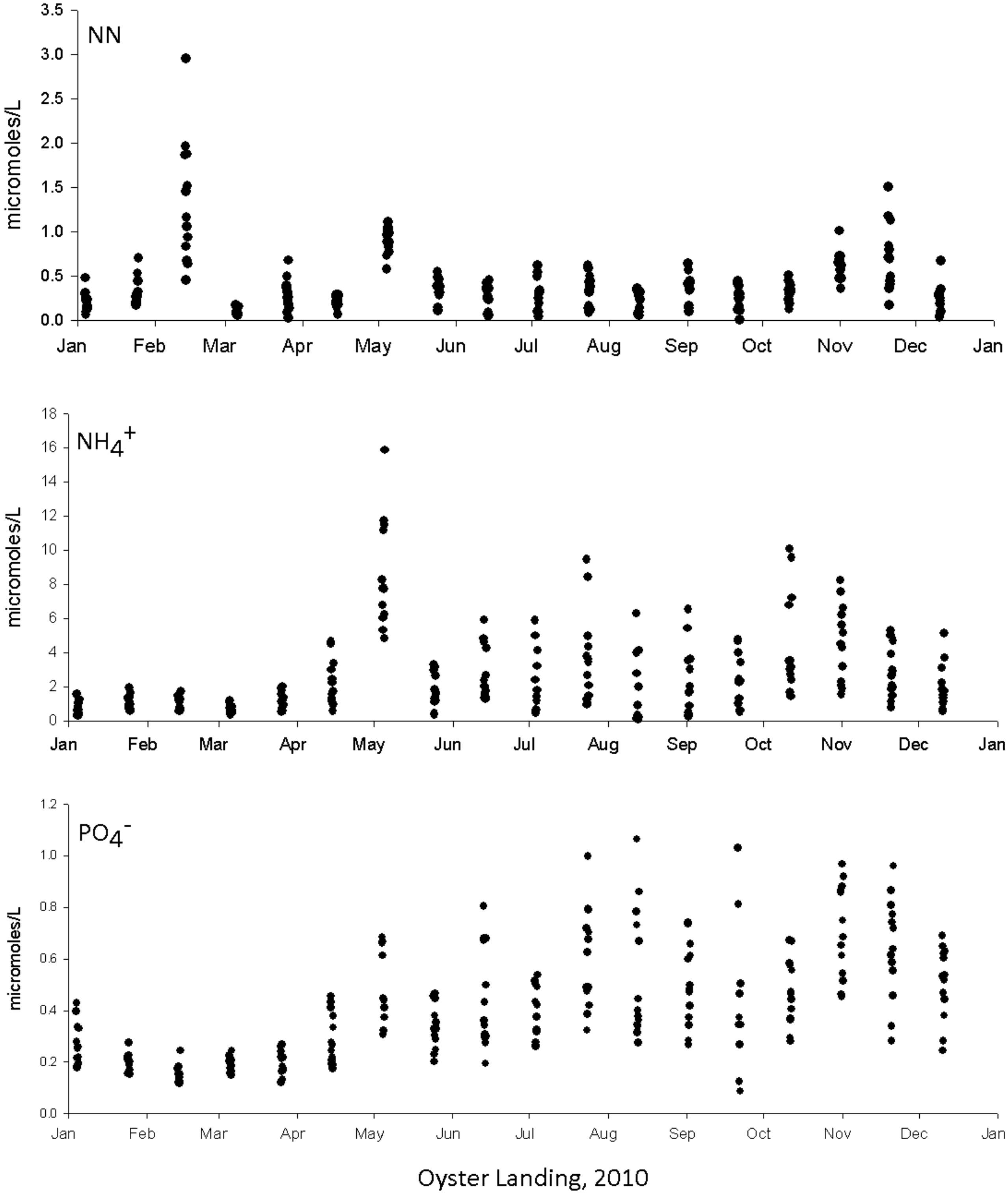


Figure 35. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour event.

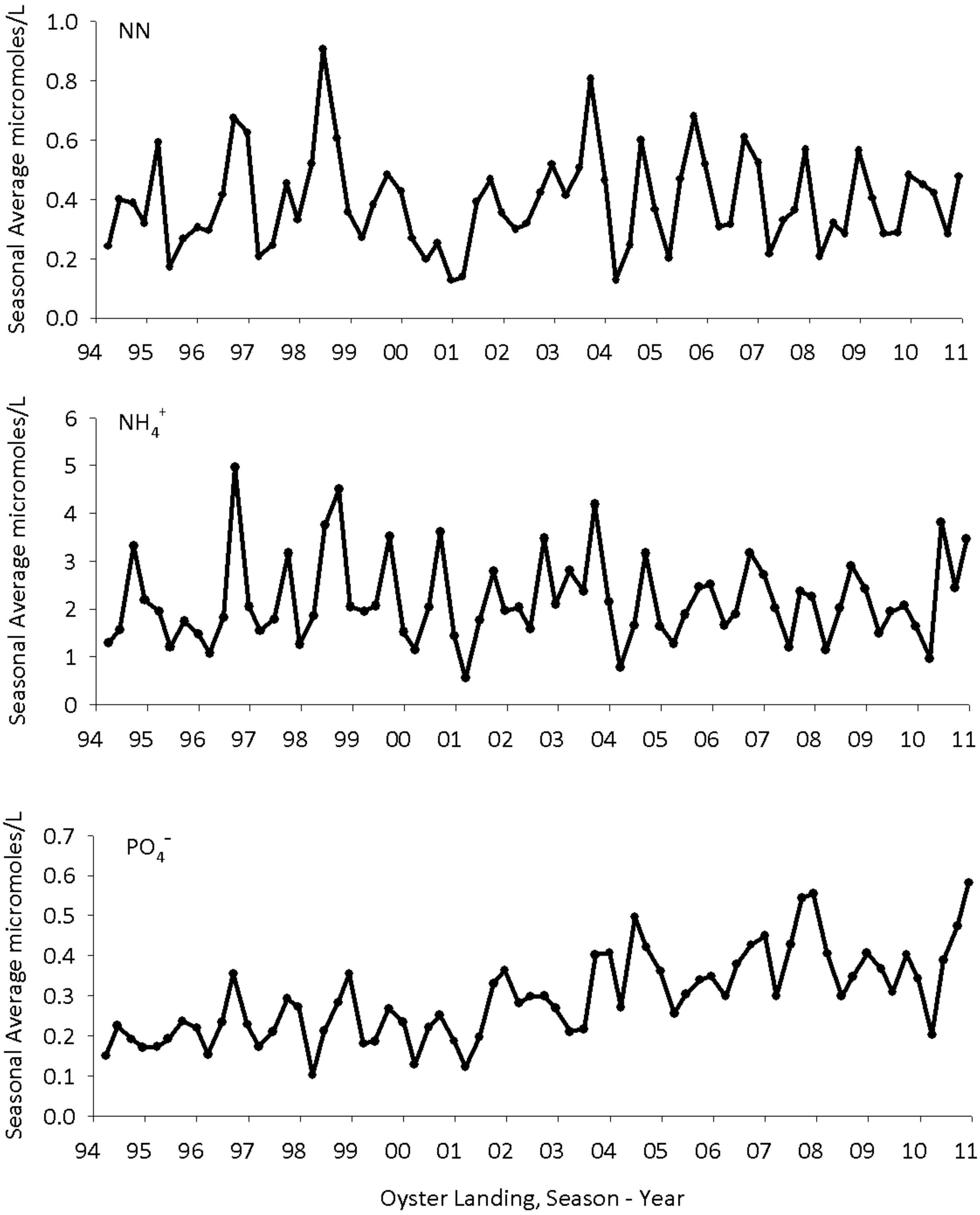


Figure 36. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

tidal creeks, possibly coupled with groundwater flow, and excretion from organisms. Sources and sinks for the dissolved organic phases of N and P were unclear, but on a seasonal basis DON and DOP had different sources. DOP is generated within the system, whereas DON enters via freshwater inputs. Neither particulate P nor particulate N had a tidal signature. Both were low during the winter. Tidal scour of creekbanks, rainfall-driven erosion, and tidal scour of creek bottoms when flow velocities are high (resuspension) pointed to sources for these particulate phases of N and P. These refractory constituents (DON, DOP, PN, and PP) get moved rapidly through the system, while the labile species had dynamic behavior within the system.

The focus of nutrient cycling research in the 1980s in North Inlet was the question of whether coastal marshes act as sources or sinks for nutrients and whether nutrients and materials are exported to coastal oceans by outwelling. Major funding was obtained in the late 1970s to examine the outwelling hypothesis and a coordinated series of studies was performed across the major outlets from North Inlet to the ocean and Winyah Bay. The basic sampling design for the North Inlet Outwelling Study was to measure various waterborne constituents at stations along a transect across the narrowest connection between the inlet and the ocean. Kjerfve and McKellar (1980) provided a scheme for calculating flows and fluxes across the transect. Transects were established that also took into account cross-sectional variability in tidal flow patterns and asymmetrical flow velocities (Whiting et al., 1985; Kjerfve and Medeiros, 1989). Water samples were taken at intervals over several tide cycles at near-surface, mid- and near-bottom depths for measurements of nutrient concentrations. Other constituents were measured as well, including macrodetritus, chlorophyll-*a*, zooplankton, sediments, ATP, and physical properties of the water like temperature and salinity. Many of these details have been mentioned above and the overview of the Outwelling Study was reported by Dame et al. (1986). Water input as runoff from the surrounding forest, precipitation, and input from Winyah Bay was exported to the coastal ocean. This water exported everything measured except for total sediments (imported in fall and winter) and chl-*a* and zooplankton that were imported in summer and fall. Carbon, nitrogen and phosphorus export was high compared to other places where similar outwelling has been measured. It was suggested that some of the nutrients (ammonium and orthophosphate) exported fuel phytoplankton production offshore that is later imported back into the marsh where it is consumed, decomposes and gets remineralized. Many of the questions raised by the Outwelling Study gave impetus for examination of nutrient cycling processes within various portions of the salt marsh itself, and chief among these efforts was the Bly Creek Study.

Bly Creek runs between Goat Island and is an intermediate-aged intertidal system that connects to the mouth of North Inlet via Town Creek. Once again, the task of estimating nutrient fluxes within the creek required a sophisticated modeling technique and experimental sampling design (Spurrier and Kjerfve, 1988). Once this was established, 34 tidal cycles were sampled between 1983 and 1984 and nutrient inputs from rainwater, stream flow and groundwater were balanced against those resulting from changes of the tide as well as the flux of materials transported via the marsh, oyster reefs, and the tidal creek (Wolaver et al., 1988c; Dame et al., 1990). Spurrier and Kjerfve (1988) found that nitrate+nitrite was exported to the ocean out of Town Creek, but there was an increased concentration of these constituents in the water flowing into South Jones Creek on flooding tides. Despite the higher concentrations,

Flumes were used in Bly Creek to examine the transport of nutrients in the marsh.

the flux of water out to Winyah Bay on ebb tides negated the existence of any flux into North Inlet. Orthophosphate data suggested a source of this species inside the marsh, consistent with what Gardner (1975) found in marsh runoff. Spurrier and Kjerfve (1988) also cautioned that variations in concentrations and water flux imbalances can complicate the calculations of nutrient fluxes.

Groundwater flow and nutrient concentrations were measured from a grid of 108 piezometers arrayed around the site (Wolaver et al., 1988c). Rainfall N was measured nearby. There was a net tidal flux of NH_4^+ into the basin during late summer and early fall, with export the rest of the time. The total N exported from the basin was statistically insignificant. That is, the Bly Creek basin was neither source nor sink, but ammonium nitrogen was actively recycled within the basin during the year. Nitrate and nitrite dynamics suggested that these species were produced during periods of maximum tidal flow and turbulence, perhaps from nitrification in the sediments. Streamwater from the forest (as blackwater) carried DON to the creek from March to July. This source combined with other sources in the marsh resulted in a net export of DON throughout the year. PN loads increased during storms and from marsh runoff at low tide, but the basin was neither a source nor a sink for PN. The data on N suggested a net balance between production and utilization of the various species measured such that N is retained in the system via recycling.

As for phosphorus in the Bly Creek Study (Dame et al., 1990), the area was a sink for particulate P and for orthophosphate. The annual net flux of water from the creek was less than 2.4% of the basin capacity at high tide, but this estimate was fraught with measurement error from sheetflow (Eiser and Kjerfve, 1986). PO_4^- concentrations were highest in summer and lowest in fall and winter. Particulate P was highest in summer and lowest in winter, suggesting that bioturbation released PP to the system. Net flux of PP and TP was zero across the Bly Creek transect. Concurrent with the Bly Creek basin transect measurements, a flume study was conducted near the head of the creek (Wolaver and Spurrier, 1988), and an Oyster Reef Study in the lower reach of the creek seaward of the transect across the creek (Dame et al., 1989).

Wolaver and Spurrier (1988) conducted a flume study to measure phosphorus exchange between the vegetated marsh and the upper reaches of Bly Creek. They also collected runoff from the marsh surface using a weir system. The flume, 140 m long, was two parallel walls set 2 m apart that crossed from the short *Spartina* zone to the edge of the tidal creek. It channeled water on a rising tide into the marsh and from it on an ebbing tide. The walls were removable to prevent any longer term effects of its presence (see Wolaver et al., 1985 for specifics about the flume design). Between April 1983 and June 1984, 40 tidal cycles were sampled every 11.8 days on average to capture lunar and diel cycles within each season. Orthophosphate was removed from the water as it flooded the marsh surface. The marsh surface was also a sink for particulate P, especially in summer, and most of it was removed from flooding tidal water in the low marsh. Total P followed the same trends as particulate P. Some of these constituents left the marsh at low tide, but overall their uptake exceeded loss, hence the marsh surface was a net sink for P.


A 10 m long portable tunnel was used by Dame et al. to study nutrient flows over an oyster reef in Bly Creek.

Dame et al. (1989) also participated in the Bly Creek Study with a separate study of nutrient flows over an oyster reef downstream from the main transect. They deployed a 10 m long portable tunnel that was placed over an oyster reef. Materials were either taken up by organisms in the tunnel or released by them. Net annual fluxes of constituents were estimated using a regression model (Spurrier and Kjerfve, 1988). Over the

33 observed tidal cycles that included neaps and springs, total and particulate nitrogen were taken up on flooding tides and released on the ebb. Only ammonium showed both uptake and release during all changes of the tide (ebbs and floods). Other dissolved N constituents were also taken up and released by the reef. The measured net uptake of N (189 g N m^{-2} yr^{-1}) was not statistically different from zero. Total and particulate P were taken up by the reef during about 90% of the flooding tides and released on the ebb. Overall annual uptake was 98 g P m^{-2} yr^{-1}. The reef serves as a nutrient retention mechanism that processes them rapidly, converting particulate forms to dissolved forms, consistently releasing ammonium. Thus oyster reefs, depending on their size and distribution within the marsh and on how much water flows over them, can have a significant role in nutrient cycling. As presaged by Dame et al. (1980), it is clear that benthic filter feeders affect many aspects of biogeochemical cycles in North Inlet. Childers (1994) provides an overview of the Bly Creek Study in the context of other similar flume-based studies.

Dame and Gardner (1993) reviewed multiple lines of evidence that parts of North Inlet's marsh are much older geologically (Pleistocene versus Holocene) and suggested that this age difference is reflected in the manner in which nutrients are processed in the different-aged marsh. They constructed a map (their Figure 1) identifying sites at different stages of evolutionary maturity. Immature marsh to the west of Bly Creek exports N and imports P and C. Intermediate stage marsh like Bly Creek imports particulates and exports dissolved phases of most nutrients. The Town Creek opening to the Atlantic Ocean is the most mature part of North Inlet. The Dame and Gardner paper is a "must read" for potential marsh investigators who may be perplexed by the high spatial variability documented in so many published studies about nutrient cycles in North Inlet. It provides context for the hypotheses of Odum (1969) about coastal ecosystem development and Vitousek and Reiners (1975) about ecosystem succession and nutrient retention. In a young developing ecosystem, nutrients are stored to support a growing biomass, whereas in a mature one with lower growth, fewer nutrients are needed. Much the same is seen across the marsh age spectrum in North Inlet, though sampling variability at all spatial and temporal scales often clouds some of these gradations.

It was not until 30 years after his 1975 work above that Gardner (2005) published a model describing pore water seepage from salt marsh sediments into tidal channels. This interesting numerical boundary integral equation model showed water movement dynamics that clustered within only a few meters from the creek bank into the marsh, with much less flushing out from the creek bottom. Water moves from this bank area rather quickly and thus has a relatively short residence time (1-2 years) there. He suggested that this flushing action between draining at low tide and recharging during flood tides might enhance *Spartina* productivity in creek bank areas of the marsh.

Because nitrogen is generally regarded as a major limiting nutrient for coastal marshes, and because so little work had been done on N transport in southeastern salt marshes, Whiting et al. (1987) conducted a detailed study of net fluxes and tidal concentration patterns for total N, ammonium, and nitrate+nitrite in North Inlet. They sampled four consecutive tidal cycles at three locations: Town Creek, North Jones Creek, South Jones Creek. These locations are the major passages through which North Inlet water is exchanged with the coastal ocean and Winyah Bay. The calculated fluxes showed consistent export of dissolved inorganic N (DIN) to the coastal ocean. Ammonium and nitrate+nitrite showed increasing values during ebbing tides as marsh processes released these forms to the water. Ammonium export was greatest during the summer. Interestingly, these forms increased in concentration during the flood tide at South Jones Creek as lower salinity enriched bay water entered this gateway into North Inlet. Their measures of water export and changes in salinity suggested that neither freshwater inputs from the forest nor imports of Winyah Bay water were a factor in the export fluxes. Ammonium export was significant during all seasons, being greatest through Town Creek during summer. Nitrate+nitrite export was also significant during all seasons, but greatest out

Town Creek in winter. Trying to balance exports with utilization (uptake) of N in the marsh suggested that much of the N uptake was from N-fixation in the marsh itself. They also suggested that the ratio of marsh surface to tidal creek surface (3:1 for North Inlet) could play a role in explaining differences in N dynamics seen by researchers in other marshes.

To optimize future sampling efforts and information return at Bly Creek, Kjerfve and Wolaver (1988) undertook a calibration study of water flow, particulate organic carbon, and nitrate+nitrite at the 53-m wide Bly Creek transect over two tidal cycles in October 1982. The concentrations of POC and nitrate+nitrite did not change appreciably, and water discharge explained over 90% of their variability. Thus their recommendation for future flux measurements was to measure water flow most carefully.

Whiting et al. (1989) examined several aspects of nitrogen exchange between the vegetated marsh and an adjacent tidal creek using the Bly Creek flume (Dame et al., 1990). A regression model correlated with relevant measures of tidal, weather, and plant biomass predictor variables was used to estimate a net annual N flux. During inundation by the tide, the marsh surface imported ammonium, nitrate + nitrite, and particulate N and exported dissolved organic nitrogen (DON) on an annual basis. The low marsh had higher exchange rates than the high marsh. During the time between late ebb and early flood when marsh surface drainage occurred, both particulate and dissolved organic N were lost in substantial amounts to the tidal creek , but drainage loss of dissolved inorganic nitrogen (DIN) was small. Rainfall increased runoff drainage from the marsh surface when it was exposed, and particulate N export to the tidal creek increased by a factor of 40. They estimated that the vegetated marsh exported about 4.5 g N m^{-2} yr^{-1}, mostly as DON. Their findings also suggested that when seasonal imports of N occurred to the marsh, they were dependent on the concentration of nitrogenous compounds in the flood waters.

Other locations of nutrient enrichment sources were studied by Whiting and Childers (1989) who examined the advection of water from creek sediments, a process that is also known as seepage (Agosta, 1985). Seepage from Bly Creek (14 L m^{-2} tide $cycle^{-1}$) was three times greater than at Clambank. Nutrient concentrations in the advected water were 5 times higher than in the overlying creek water, but there was great spatial variation depending on which transect site was measured. NH_4^+ concentrations in seepage from the creek bottom exceeded overlying creek water by an order of magnitude, while interstitial water contained 4X that in seepage. Orthophosphate concentration in seepage was 4X that of overlying waters and about equivalent to interstitial porewater concentrations. Drainage water collected in the weir had inorganic nutrient concentrations at least 5X higher than in overlying creek water. This so-called "tidal pumping" of interstitial porewater and subsurface water through the creek bottom contributes very significant amounts of dissolved nutrients to tidal creek waters and occurs via three mechanisms: 1) remineralization and diffusion from creek sediments; 2) direct advection (seepage) of interstitial water from the marsh sediments out through the creek bottom; and 3) diffusion of nutrients from the marsh surface into water draining off the marsh at low tide. Of the three, direct advection through the creek bottom was most important for exporting ammonium, NH_4^+ , but about the same as marsh runoff for phosphate export to creek waters. Low tide drainage delivered more oxidized inorganic nitrogen (NO_3^- and NO_2^-) to creek waters than benthic advection. Because nutrient concentrations in the tidal creek water column are enriched at low tide compared to high tide, it is clear that these advective and diffusive processes are the source of this enrichment. Once again, their data indicated that discharge of groundwater into these processes did not occur.

Krest et al. (2000) had difficulty accounting for the amounts of nutrients outwelled by North Inlet (Dame et al., 1986) and proposed a different source for the surplus nutrients. They suggested that the amounts outwelled simply could not be accounted for from remineralization of detritus in the estuary or of phytoplankton imported to the estuary. Nutrient inputs from Winyah Bay were also deemed insufficient to account for the excess. Marsh mud serves as an impermeable cap on top of a subsurface porous sandy layer (found with vibracores) within which the coastal groundwater aquifer exists. As tidal creeks cut across the marsh, their deepest parts intersect the aquifer. Previous work by Rama and Moore (1996) used radium isotope data during the summer to estimate groundwater discharge in the inlet, but the amounts calculated were deemed to overestimate the actual discharge. Ammonium and dissolved reactive phosphorus were measured in the samples along with radium. Groundwater contained up to two orders of magnitude greater concentrations of radium and both nutrients than was found in the inlet water.

Moore (1999) had found winter nutrient concentration in North Inlet to be twice that in summer, and winter radium concentrations were likewise double those of summer. This suggested a linkage between radium and nutrients. Based on previous estimates of nutrient export, Krest et al. (2000) eliminated all possibilities other than groundwater discharge as being too small, i.e., surficial freshwater input, diffusion from sediments on the marsh surface, and import of sediments were insufficient to account for the magnitude of the export. They determined that there was more than enough groundwater input to account for the shortfall from nutrients that are converted to biomass during the growing season.

Moore (1999) proposed that this groundwater input derives from seawater intrusion much like seawater, because of its greater density, moves under fresher water into estuaries on a rising tide. He coined the term “subterranean estuary” to describe this long-neglected zone of mixing in the aquifer that drives a major input of dissolved nutrients to coastal marshes and the nearshore coastal ocean itself. Because empirical measurements of seepage and drainage and all the other ways that nutrients reach the inlet are considerably out of balance with this groundwater input, Gardner (2005) suggested that there is really no conclusive evidence for existence of a subterranean estuary beneath the North Inlet basin. Research on this issue will continue, of course.

Building on the earlier modeling efforts of Wilson and Gardner (2006) and the model of Gardner and Wilson (2006) that showed the importance of incorporating sediment compressibility as a relevant variable that affects seepage from the marsh, Wilson and Morris (2012) provide a summary overview of the role of groundwater in the nutrient cycles of North Inlet. They used a new numerical model to demonstrate how changes in water level due to both the tide and to relative sea level affects porewater and groundwater flux into tidal creeks. Based on empirical nutrient concentration data collected over many years at Goat Island and Oyster Landing, the model accurately depicted the magnitude of nitrogen and phosphorus exchanges between the salt marsh and tidal creeks as water level changes. Because nutrient concentrations in porewater are basically always higher than in the water brought to the marsh by the tide, it is clear that biogeochemical processes in the upper meter or two below the marsh surface generate nutrients that are then flushed into tidal creeks by deeper groundwater moving upward in response to hydraulic pressure from the overlying water. Compared to the amounts of nutrients from tidal exchanges, runoff, precipitation, and other sources, this porewater-fluxed source is biologically significant, is much greater, and is perhaps the dominant fuel for what eventually gets exported to the coastal ocean from North Inlet. What remains to be determined is how this belowground nutrient-generating system will respond biologically and elevationally to future changes in sea level.

Blood and Smith (1996) compared Murrells Inlet and North Inlet with respect to the impacts of urbanization. North Inlet has less than 6% urbanization, while Murrells Inlet is over 50% urbanized. Water samples at 30 stations throughout each inlet were analyzed for salinity, oxygen, inorganic nitrogen, and inorganic phosphorus and examined for both spatial and temporal distribution patterns. When averaged over seasons and tides, nutrients (ammonium, nitrate, orthophosphate) showed no significant differences between estuaries. Ammonium concentrations were highest near land in both estuaries, but the highest concentration found (> 60 microgram-atoms per liter) was in the upland drainage area of North Inlet. Nitrate concentrations did not differ between near-land and near-ocean stations in either inlet, but there were several times when concentrations were quite different. Orthophosphate concentrations had no regional differences within either estuary overall, but were different for certain tidal stages and seasons. Only ammonium concentrations varied significantly with tidal stage, being higher at low tide in both estuaries. Water exchanges with Winyah Bay provided higher concentrations of nitrate in North Inlet at high tides. Highest nutrient concentrations occurred in both estuaries during the summer. Surface water drainage impoundments were successful in retaining nutrients in Murrells Inlet. In both inlets the amount of tidal flushing is great, and this contributes to the minimization of runoff effects and lack of eutrophication problems in each. However, continued nutrient loading could become a problem in the future.

Tufford et al. (2003) compared nitrogen and phosphorus concentrations in nonpoint source runoff in Murrells and North Inlets. Surface water samples were collected at low tide monthly during 1999. Total, dissolved inorganic, and dissolved organic forms were analyzed from 8 small drainage basins in Murrells Inlet and two in North Inlet. The landscape was partitioned into forested creeks, urban creeks, and urban ponds. DON and ammonia were highest in forested streams, while nitrate and total phosphorus were highest in urban streams. Their major finding was that land use was not a reliable indicator or predictor of nutrient concentrations.

White et al. (2004) compared concentrations of nutrients in North Inlet with those in the developed Murrells Inlet estuary. They hypothesized that greater non-point source runoff in Murrells Inlet would cause elevated nutrient levels and more chlorophyll-*a* as a result. When salinity declined (from runoff after rain storms), inorganic nutrients increased more in Murrells Inlet than in North Inlet. Lowest nutrient concentrations occurred in November 1998 and July 1999 in both estuaries. Two hurricanes (Floyd and Irene) brought high precipitation with subsequent increases in nitrate concentrations in both inlets, but more so in Murrells Inlet. Ammonium concentrations were negatively correlated with salinity in Murrells Inlet, but there was no correlation between these variables in North Inlet. Dissolved organic nitrogen concentrations were highly variable in both inlets with no distinct seasonal trends. DON was highest in North Inlet after passage of hurricane Irene. Orthophosphate was positively correlated with temperature in both study areas. Reactive silicate followed a similar trend, higher in summer, lower in winter. There were indications of eutrophication in Murrells Inlet, but overall the system there seemed able to respond quickly to stochastic runoff events. Both North Inlet and Murrells Inlet have high rates of water turnover as the tide changes, hence their response to nutrient inputs is not as dramatic compared to estuaries with much greater freshwater inputs of nutrients and less tidally-driven exchanges with the coastal ocean.

Nelson et al. (2005) screened historical (1967-1995) records of rainfall and fecal coliform bacteria concentrations measured in the waters of North Inlet and at Murrells Inlet. They focused on major interventions – jetty construction and sewage diversion from septic tanks to municipal treatment at Murrells Inlet, construction of the Baruch Marine Field Laboratory and development of homes at Debordieu Colony for North Inlet – to see what effect they had on water quality in the two areas. The interventions at Murrells Inlet resulted in decreased fecal coliform counts, especially from elimination of septic tanks, but the jetty completion probably kept the decreases from being even greater because the jetty restricted the flow of clean coastal water into the inlet there. At North Inlet, neither intervention was detectable, most probably because they were such small scale, but also because of the greater contribution of fecal coliforms from wildlife there masked any small increase that might have been due to human activities. More data will be needed to measure impacts of future changes in land use at the coast.

Aelion et al. (1997) examined water quality in groundwater wells dug in North Inlet in the forested headwaters of the Oyster Landing basin and another in nearby urbanized Murrells Inlet for comparison. Rates of denitrification were also measured on 1 m deep sediment samples collected from adjacent creeks at both sites. Nitrate concentrations were higher in the urbanized site, but ammonium concentrations were considerably higher in the forested site where leaf litter is abundant. Nitrate additions to the sediments altered the rates of denitrification and its efficiency.

In another comparative study between denitrification rates at North Inlet and at Kiawah Island, SC, a developed barrier island with golf courses and residential areas adjacent to the marsh there, Aelion and Engle (2010) found significant differences in the two study areas. Both core sampling sites had typical dark, sulphidic marsh sediments. The impacted site had more active denitrification and faster NO_3^- removal than the unimpacted site, North Inlet. Based on ^{15}N measurements, the impacted site had more active participation of ammonium in its nitrogen cycling than North Inlet. This suggested that the impacted site had responded better to episodic N inputs.

BIOTIC ELEMENTS IN NUTRIENT CYCLES

Bildstein et al. (1992) calculated nutrient transport of the white ibis, a colonial nesting bird that had established springtime breeding colonies on Pumpkinseed Island in Mud Bay for many years. Annual fluxes of N, P, K, and Ca to North Inlet due to white ibis activities were compared to those from tidal input of nutrients from Winyah Bay for two years, 1984-85. Their calculations included many assumptions about bird ingestion, caloric content of food, assimilation efficiencies of adults and nestlings, etc. Bird census counts differed greatly each year, with about 85% fewer nesting pairs on the island in 1985 compared to 1984; i.e., 12,973 in 1984 to 1,976 in 1985. Despite the large year-to-year difference in the census, compared to nutrient inputs from a nearby watershed, precipitation, and flow from Winyah Bay, the ibis population contributed at most (in 1984), 33% as much P, 9% as much N, and <1% as much K and Ca. Thus these and possibly other birds that take up residence in the area for any appreciable amount of time can translocate significant amounts of nutrients, especially to localized areas like their nesting grounds where excreta are differentially and perhaps preferentially deposited.

Haertel-Borer et al. (2004) examined the role that excretions from motile species of fishes and shrimps play in the biogeochemical cycling of nitrogenous materials (urea and ammonium) and phosphorus as orthophosphate in tidal creeks of North Inlet. There are over 700 such intertidal creeks in the estuary that feed into the marsh from 15 larger subtidal creeks. Collections of fauna from 8 intertidal creeks were made over all seasons for this study. Animals were collected and placed in bags of filtered creek water and suspended for 2 hr in the creek to maintain ambient temperatures. DO and nutrient concentrations were measured before and after incubations, with controls. In spring the fauna were representative of the community that utilizes the creeks (e.g., silversides, mullet, spot, grass shrimp, mummichogs) and in summer the fauna included a few additional species. Mass-specific excretion rates were calculated based on faunal biomass and container volumes. Other experiments were done in tanks containing natural creek sediments to separate the effects of bioturbation from excretion on changes in nutrient concentrations in both spring and summer trials of 6-hr duration during which animals were fed *ad libitum*. Data from these and many other studies done in North Inlet were used to calculate nutrient input to the system expressed as hourly rates per square meter of intertidal channel surface at high tide. In the bag experiments, ammonium excretion rates were higher in summer than in spring as temperatures were higher then. Urea excretion rate was always much lower than for ammonia, depending on species, as were orthophosphorus excretion rates, but these were higher in spring than in summer. Summer N:P ratios for excretory products were higher than in spring. Nutrient production rates in the tank experiments followed the same patterns as in the bag experiments, and bioturbation inputs were about 40% of excretory inputs alone. Using nekton biomass and other faunal component data from other studies, nutrient inputs to the creek were spread equally across nekton, oyster reefs, and sediment, with the zooplankton and atmospheric contributions much smaller. The effect of nekton was mostly translocation of nutrients among subsystems of the marsh, but the amounts of ammonium released were significant enough to have an important impact on water column primary production. This and the Allen et al. (2013) studies evaluated the magnitude of the nektonic, biotic component of nutrient cycles in saltmarsh-dominated coastal ecosystems.

Oyster reefs in North Inlet also participate in nutrient cycles. Dame et al. (1985) constructed a plastic tunnel for emplacement over a reef to measure input/output concentrations and flow velocities over several tidal cycles in summer. They found elevated concentrations of ammonia, with its release greater on the ebb than on flood tides. N uptake through oyster feeding was the source of this ammonia return to the water. Dame (1984) and Dame et al. (1989) also pertain to the role of oysters in nutrient cycles in North Inlet. Dame and Libes (1993) used oyster removal manipulations in tidal creeks to deduce that oyster reefs act as nutrient retention reservoirs. Dame et al. (2000a) reviewed the impacts of benthic-pelagic coupling, both passive and active, on nutrient cycling and other processes within marsh ecosystems as well as within coastal oceans.

In summary, the essential nutrients N and P in North Inlet have been investigated in several different modes. First, their short-term concentrations in the water are higher during low than during high tides. Second, quantitative estimates of their source and sink dynamics within the estuary were evaluated as part of the Outwelling Study which showed export of these constituents to the coastal ocean. Third, the Bly Creek Study found how nutrient concentrations change as water flows over the marsh. Nutrients, particularly N, are basically retained and recycled within the marsh while P is taken up by the marsh sink. Fourth, oyster reefs both take up and release significant amounts of N and P as the tide changes. Fifth, marsh porewaters serve as a source for nutrients by leaking N into the tidal creeks. Sixth, groundwater flux also contributes dissolved nutrients to the system. Seventh, rainfall redistributes nutrients when the marsh surface is exposed at low tide. Eighth, long-term monitoring has shown that nitrate N increases during years with higher precipitation and declines during droughts. Seasonal changes were also apparent. Orthophosphate is trending to higher concentrations over time. How nutrients will respond to future changes in sea level and marsh elevation and how continued coastal development in the NI-WB NERR watershed will impact water quality remains to be seen.

SULFUR

Wolaver and Gardner (1983) used interstitial water samplers along transects at three sites in North Inlet to measure a variety of water quality parameters, including total dissolved iron, total dissolved sulfide and sulfate. Out in the old marsh at Bread and Butter Creek, porewater sulfides were negligible in the mud flat and on the creek berm by the tall *Spartina*. In the high marsh transect, iron and sulphide profiles increased in concentration during late summer and fall and underwent dissolution in winter. Along the Goat Island and Town Creek transects, no such seasonality was found. Regardless of site, however, sulphides increased from lows in winter to higher values in late summer and fall.

King (1988) took sediment cores at Goat Island and Oyster Landing, injected them with radio-labeled sulfate, incubated the cores for 72 hr, and then froze them to stop metabolic processes. Sulfate reduction rates (micromoles per cubic cm per day) varied seasonally and spatially over the 30-mo study, with lowest rates in January and highest in August. Rates were proportional to temperature as expected and were about twice as high in short *Spartina* as in the tall form zones. Rates were about 5-10 times greater in the uppermost 2 cm of the cores than in the 8-10 cm sections, correlating with carbon content. The labeled sulfate was also traced to its end products, pyrites and acid-volatile pools, for instance. Sulfate reduction was inversely proportional to *Spartina* productivity.

The only other major study of sulfur chemistry in North Inlet was conducted by Gardner et al. (1988). This study emphasized spatial differences by the examination of samples along three different transects: Goat Island, Bread and Butter, and Town

Creek. This study produced too much data for presentation here, but they found that downward movement of iron oxide via fiddler crab burrowing activities played a large role in the mechanism by which pyrite was moved to the surface and oxidized there. Most of the sulfur compounds increased in concentration, as did carbon, with distance from tidal creeks, although acid volatile sulfur (FeS) decreased with distance. Interactions between reactive iron oxide and sulfur compounds dictated much of the spatial variability found.

Remaining questions about how decomposition of organic matter is related to the process of sulfate reduction and sulfide oxidation led Gardner (1990) to construct a model of how carbon, sulfur, and dissolved oxygen contribute to generating the observed vertical profiles at different locations in the salt marsh. He hoped to achieve a greater understanding of how the oxygen, sulfur, and carbon cycles intersect within saltmarsh sediments. The numerical model has many compartments and non-linear differential equations, but conclusions from many experimental simulations revealed the following conclusions: 1) oxygen supply to the sediments prevents the buildup of excessive amounts of reduced sulfur, with plant root exudates playing a greater role than simple diffusion of oxygen into the sediments: 2) in the mid-marsh areas, root oxidation is much more important than fiddler crab bioturbation and pore water movement in preventing reduced sulfur buildup; 3) the stable carbon isotope signature of sediments is influenced more by fiddler crab burrowing in the creek bank sediments than in the back marsh; and 4) future work is required on the mechanisms involved in root oxidation of sediments and processes making *Spartina* decomposition products. The genesis of this 1990 model began with some of the earliest studies of nutrient chemistry and sulfate reduction in North Inlet (Gardner 1973b, 1975).

Though little research has focused directly on sulfur and sulfurous compounds in North Inlet, their role in moderating marsh productivity suggests that process studies of the role of microbes in the sulfur cycle will be a future focus. Sediments and sulfur are inextricably linked in the diagenesis of organic matter and its decompositional fate.

CARBON

The NI-WB NERR 20-day water chemistry monitoring database, described earlier in the section on nitrogen and phosphorous also collects and measures dissolved organic carbon (DOC). These collections and results are not formally required in the NERR System-Wide Monitoring Program (SWMP), but are a part of USC Baruch Institute's long-term monitoring program. The NI-WB NERR water chemistry collection protocol is to sample all tidal stages (day and night) over the years. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Oyster Landing monitoring site is used in this document to represent DOC levels which have been examined in both short- and long-term time frames in North Inlet. A 20-day sampling event in July 2010 shows that DOC concentrations are influenced primarily by tide (Figure 37). DOC levels during slack low tides were about twice as high as those at slack high tide. The tidal water ebbing out to sea carries higher concentrations of DOC than the ocean waters entering North Inlet. Time of day appears to have no influence on DOC values.

Figure 38 illustrates that the winter months had the highest levels and variation of DOC; spring months had the next highest. Summer and Fall had similar concentrations, ranging from about 2 to 4 milligrams per liter.

Figure 39 demonstrates seasonal differences within and among years. The El Niño years 1998 and 2003, which had large amounts of rain, had the highest DOC values. The drought years' (latter part of 1999 through the summer of 2001 and about 2007-2010) values were lower and less variable. DOC concentrations in North Inlet have declined since 2004.

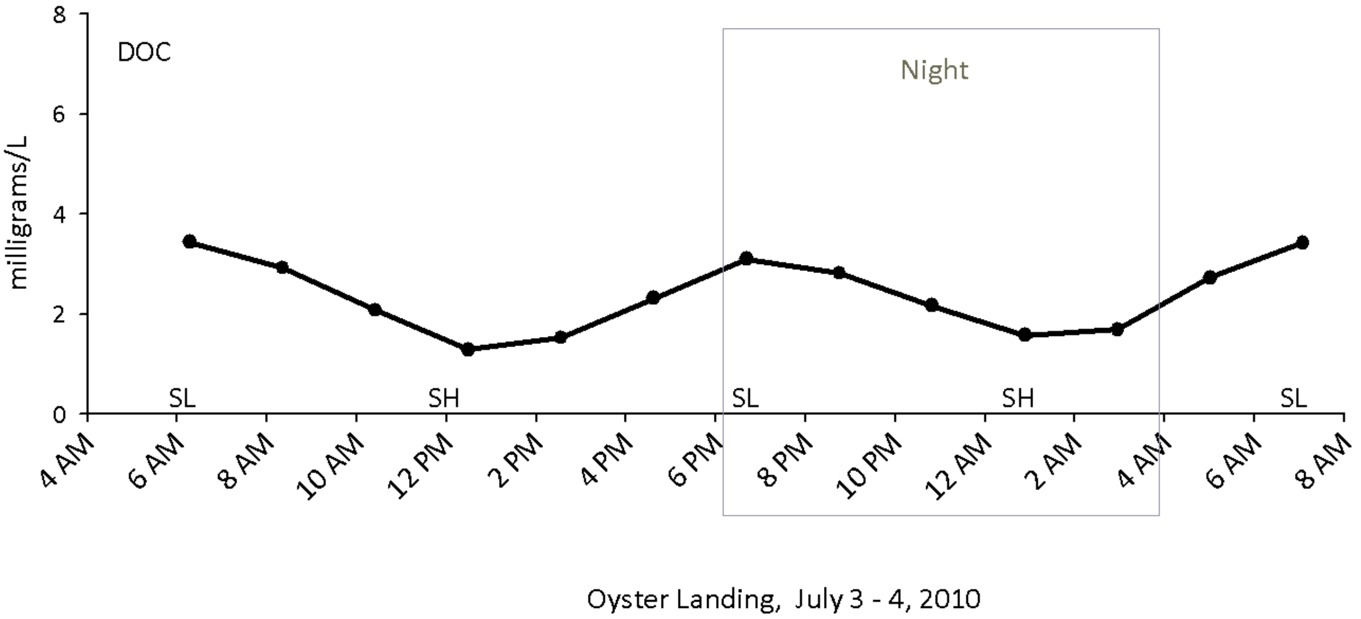


Figure 37. 25hr. Oyster Landing dissolved organic carbon (DOC) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

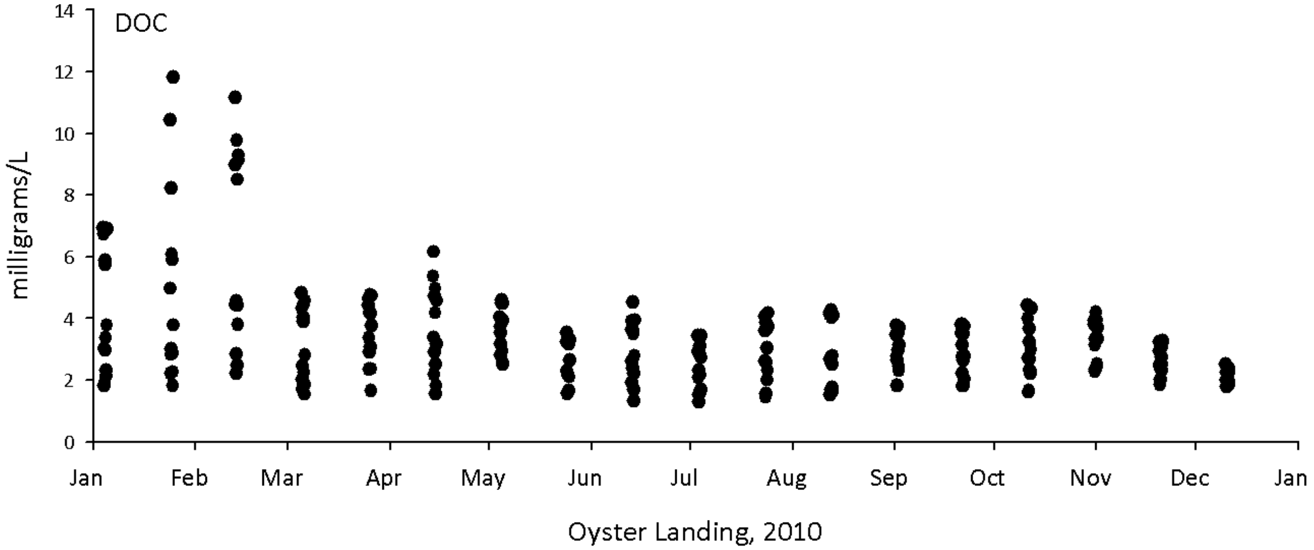


Figure 38. Oyster Landing dissolved organic carbon (DOC) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour event.

SUMMARY OF OTHER STUDIES ON CARBON IN NORTH INLET

Early studies related to carbon fluxes were done by Erkenbrecher and Stevenson (1975) who sampled water for particulate organic carbon (POC) over a 12-hr tidal cycle in a small creek near Clambank Landing and in Crab Haul Creek during May 1973. Throughout the sampling period, about 2-5% of the total POC was living carbon, presumably mostly microbial. POC at low tide was twice the concentration found at high tide at the Clambank station and three times higher (low vs high tide) in Crab Haul Creek. An additional sampling at Crab Haul Creek in August 1973 again found POC highest at low tide and lowest at high tide but, averaged over the 12-hr tidal cycle, POC was 2.5 times higher than in May. Another interesting finding was that

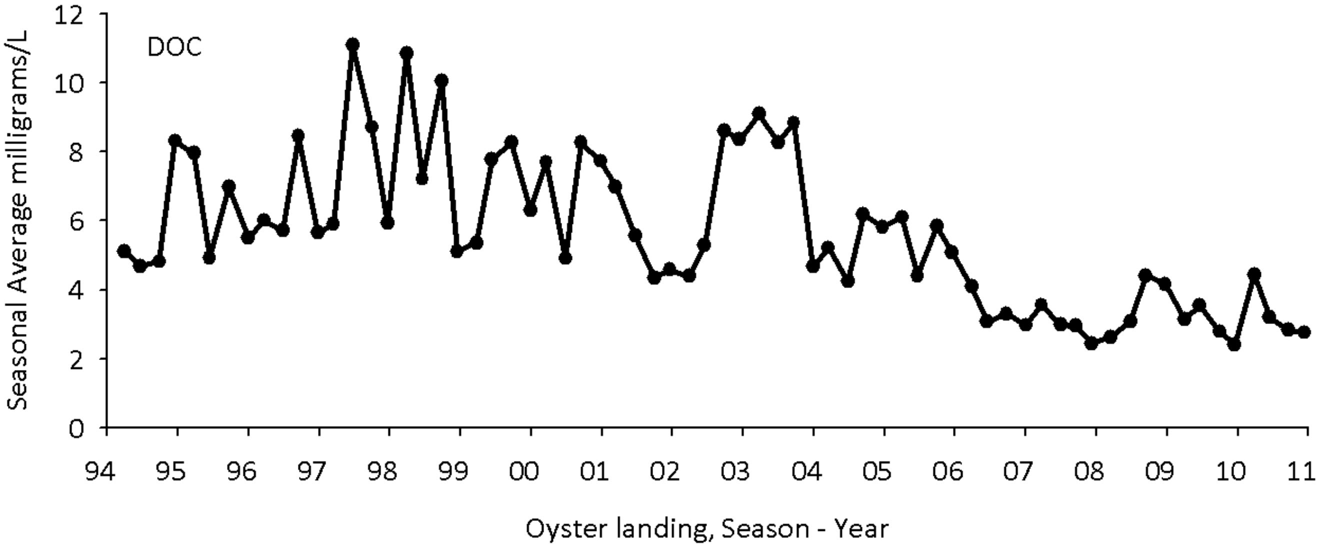


Figure 39. Oyster Landing dissolved organic carbon seasonal average concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

the low marsh station near Clambank Landing had a considerably higher proportion of non-living detrital carbon than in Crab Haul Creek. The lessons learned here were that organic carbon in marsh creeks is neither static nor homogeneous over a tidal cycle, making extrapolations to other areas tenuous at best.

Sampling 5 tidal cycles at the same two tidal creeks (Clambank and Crab Haul) as in their 1975 study, Erkenbrecher and Stevenson (1977) measured POC as one of many variables used to correlate with their measures of microbial biomass. POC varied over two orders of magnitude during the study, as the creeks experience wide temperature fluctuations (10-34ºC). POC correlated positively with bacteria numbers. POC had an inverse relationship with water depth and positive correlations with water temperature, pH, and dissolved oxygen concentrations. POC variations accounted for 55% of the variation in microbial biomass (ATP) during ebb tides but only 1% during floods. Several regression techniques were used to examine relationships between all 10 variables measured, but POC seemed to always be most important during ebbing tides. Single variable regressions (e.g., A vs B) were commonly low, but multiple variable regressions (e.g., A, B, C, and D vs F) explained more of the variation measured in any given variable.

Erkenbrecher and Stevenson (1978) took water samples and measured the fluxes/transport of materials (bacterial biomass, total microbial biomass, ATP, POC, chl-*a*, and suspended matter that was categorized as total suspended material, TSM, fixed, FSM, and volatile, VSM) in Crab Haul Creek, the same site as in their two earlier studies cited just above. Water discharges were net seaward, suggesting that there should have been net export of virtually every constituent measured, but this was not the case. There was no "agreement" between either the direction or the magnitude of transport of TSM and POC. POC was exported on 75% of the tides measured, with influx on the rest. Highest mean concentrations of POC occurred in August, the same for chlorophyll, ATP, and TSM. Net flux of POC for the study was an export of 31 kg per tidal cycle. This material contained about 19% living matter based on ATP biomass estimates. There was no apparent correlation between transport of POC and movements of suspended material.

To study the impact on microbial biomass and POC of freshwater or brackish intrusions into North Inlet from Winyah Bay, Weiland et al. (1979) established 5 sampling stations southward along Clambank

Creek as it meanders and empties into Mud Bay. Presumably sampling took place around high tide, as this is the only time when that particular creek is easily navigable from their northernmost station in the central marsh all the way southward to their Mud Bay station. High tide is also when water from Winyah Bay would have already moved northward into the marsh. POC concentrations almost always explained a significant portion of the variability measured in ATP along the transect. Compared to data on POC and microbial biomass in other North Inlet studies, they found no appreciable effect of Winyah Bay water intrusions on microbial biomass in this creek during the study. Intrusion may have affected the species composition of the microbial community, but this was not examined, just ATP. As found by Erkenbrecher and Stevenson (1978), no single variable explained much about the other variables. They closed with an emphatic admonition against extrapolations from one site to another.

Other early studies in North Inlet involving the carbon cycle were carried out by Chrzanowski and Stevenson (1979) on the flux of POC, TSS and organics (total volatile material, microbial ATP, fungi) through one tidal creek for one tidal cycle. This and other smaller studies provided fodder for larger, whole-estuary flux POC and DOC studies conducted by Chrzanowski et al. (1982, 1983) as tests of the prevailing outwelling hypothesis regarding transport of organic matter from inlets to the coastal ocean. The Outwelling Study established 3 sampling transects across choke-points into North Inlet from the ocean near its mouth across Town Creek and across North Jones Creek, and also across South Jones Creek where brackish Winyah Bay water enters the system from Mud Bay. The majority of the POC was small detrital particles that moved with the water. Trends for POC transports were different in winter and summer. In winter at the two inlet transects, POC concentrations fluctuated in phase with the tides (higher on rising, lower during falling tides) but out of phase in summer. Highest concentrations coincided with highest flow rates during both ebbs and floods. Concentrations dipped during slack waters. At the brackish transect, no transport patterns emerged – they were "erratic". In-phase transports suggested imports of POC from ocean to inlet during times when biological activity is depressed in the inlet. This did occur at North Jones Creek, but not at the larger Town Creek where net water export was measured. POC exports took place when marsh productivity and "activity" were highest in summer and into the fall. Calculations showed net annual POC export through Town Creek, import into North Jones, and exports from South Jones. These three creeks account for about 95% of the water flow through North Inlet – TC 81%, NJ 16%, and SJ 3% of that 95%. The rest flows to and from and between creeks and the surrounding forest and Winyah Bay and cannot be accounted for with this method of sampling. Because of the volume transport from Town Creek, overall net export of POC from North Inlet was estimated to be 87 g m^{-2} yr^{-1}. This was estimated to be between 9 and 16% of net annual aboveground primary production in the marsh.

A platform used in the Outwelling Study

Their analysis of DOC during the Outwelling Study was confined to the data from Town Creek (Chrzanowski et al. 1983), because about 85% of tidal flow volume is through Town Creek. Contrary to the POC data above, the DOC data fluctuated greatly throughout the year, but not in any regular manner. Variations in concentration were great even on an hourly basis during a single tidal period as well as during other longer sampling time intervals. Thus calculations of net imports and exports were somewhat tenuous. Net transports of DOC on an annual basis were as high as 7.5 x 10^9 g C, corresponding to 416 g DOC m^{-2} yr^{-1}. What emerged from the study was that the amounts of

TOC (the sum of POC and DOC) and DOC exported were much higher than expected, suggesting that primary productivity was not the sole or majority source of this dissolved constituent. Other sources of DOC must exist, and the most likely of these was suggested to be forest runoff and belowground seepage of water into tidal creeks. This suggestion stimulated much additional research.

Floating macrodetritus flux and subsequent export to the coastal ocean is part of the POC examined above, but Dame and Stillwell (1984) sampled 72 tidal cycles over 18 months at Town Creek and determined that it accounted for less that 1% of net aboveground *Spartina* production. They suggested that this material was not a major source of organic carbon exported from North Inlet.

For carbon on the larger scales, Dame et al. (1986) documented large net exports of particulate carbon from North Inlet and changes in DOC fluxes suggested that this constituent was coupled with the forested uplands surrounding the inlet. However, the DOC measurements were so variable from tide to tide and season to season that the net DOC export calculated was probably not totally reliable. The Outwelling Study, by measuring whole-inlet fluxes and net annual exports/imports, set the stage for examination of nutrient fluxes at other sites within the inlet on much smaller spatial and much shorter temporal scales. These additional studies were designed to examine variabilities in constituent concentrations and/or to identify particular sources and sinks for individual constituents. One such study was conducted in the Bly Creek basin by Williams et al. (1992) to examine organic carbon transports, and it will be discussed below in keeping with the historical timeline approach to this section on Water Quality.

Dame et al. (1984) looked at how oyster reefs in North Inlet process organic matter using the tunnel previously described (Dame et al., 1985). In essence, although oysters removed considerable amounts of particulate organic matter by their filter-feeding mode of ingestion, they did not ingest all of it that moves across the reef. However, they did significantly reduce the amounts of POC and increase the amounts of ammonia in the overlying flow, i.e., they were a sink for POC and a source of ammonium. Concentrations of orthophosphate, a nutrient that is not utilized by oysters, did not change as water moved through the tunnel. Uptake rates of POC in the tunnel were between 1400 and 4400 mg m^{-2} h^{-1}. The physical effects of reduced water flow via friction as water travels over an oyster reef may be biased more towards sedimentation than towards biofiltration. This study raised many questions about the ecological role of oyster reefs, particularly their role in the biogeochemical cycling of nitrogen.

To quantify how oyster reefs process the primary nutrient elements (C,N,P), Dame et al. (1989) used the portable 10-m long tunnel again. POC was taken up by the oyster reef on 95% of the flooding tides measured and released on 63% of the ebbing tides. Some of this uptake and release was due to sedimentation and resuspension in addition to oyster feeding. Maximum POC uptake rates occurred in spring and summer through early fall when metabolic rates of the oysters are elevated. DOC was released on both flooding and ebbing tides, but some of this was from microbes and benthic algae associated with the reef inside the tunnel. Annual fluxes showed net uptakes of TOC and POC on flooding tides and net release of DOC and TOC on ebbing tides. On balance, there was a significant annual release of DOC and possibly uptake of POC. Uptake of TOC by the enclosed oyster reef was 1200 g C m^{-2} yr^{-1}, but this value was not statistically different from zero. Thus the most consistent fluxes were releases of DOC (and ammonia) from the oyster reef.

Using data from the LTER project's daily 10:00 am water samples (at Oyster Landing, OL, Clambank Landing, CB, and Town Creek, TC) from March 1981 to August 1982, Wolaver et al. (1986) examined variability in POC and DOC concentrations. Their goal was to determine and hypothesize reasons for the observed tidal, seasonal, and annual variability in carbon concentrations in North Inlet. Important findings were that DOC's variability, both spatially and temporally, was best explained by variations in salinity, suggesting that runoff from the forested watershed was a major contributor of DOC to the marsh. DOC concentrations were also lower when streamflow was low. DOC was also associated with groundwater flow and seepage from the marsh surface, biological uptake or sorption onto particles, sampling station, and origin of the water mass. POC, on the other hand, was high in summer and low in winter. Rain events scoured POC from the marsh surface, particulate materials flushing off the marsh surface at low tide, and biological productivity in the water column all contributed to the variability found in POC concentrations. Water flow velocity was also important in the larger tidal creeks as a correlate with POC values.

As part of the Bly Creek Study, Wolaver et al. (1988b) examined the role of the marsh surface in carbon exchanges with a tidal creek during tidal inundation and during exposure at low tide via runoff, seepage and rainfall when it occurred. Is the marsh surface a source or a sink for carbon? DOC concentrations were related to freshwater runoff from the adjacent forest and were highest in late winter and early spring. As concentrations did not vary appreciably from ebbs to floods, the marsh surface was deemed to be neither a source nor a sink for DOC during tidal inundation. Rain events did move DOC off the marsh into the creek, however. POC values were higher in summer, and the vegetated marsh (both high and low) was a sink for POC during tidal inundation. Occasionally high POC values were associated with ebbing waters and rain/wind events. More DOC and POC were exported from the marsh when above normal amounts of water accumulated on the marsh in depressions as the tide ebbed. Rain events were important drivers of carbon export off the marsh surface. Basically none of the predictor variables related well to DOC concentrations because the DOC's main source was the forest via a blackwater stream that ran into Bly Creek. A more complicated scenario for POC involved fluxes associated with tidal height (time of inundation) and the removal of POC as tidal floodwaters encountered plant stems via sedimentation or deposition. On an annual basis, exchanges of carbon between the marsh and tidal creek, suggested that this system was a sink for POC and a source for DOC. The marsh may not be the source of carbon outwelling from North Inlet (Dame et al., 1986) after all.

Sea surface microlayers and foams contain numerous organic-rich components such as proteins, carbohydrates, lipids, fatty acids, etc. Harden and Williams (1989) collected sea foam and POC at two stations in Town Creek from January to December 1985. Their data suggested that neither *Spartina alterniflora* nor benthic microalgae were a major source for POC to sea foam. Rather their isotope values suggested that foam contained *in situ* organic carbon whose signature was not altered by the presence of heterotrophic bacteria in the samples. Isotope values for the foam varied seasonally, suggesting that different sources formed foams at different times of year. Using long-term data on productivity from other investigations, macroalgae were implicated as the source of POC in the foam in winter, while phytoplankton provided the POC to foam in summer. Differences in the signatures between DOC and POC also suggested that some DOC may be derived from terrestrial sources. Future work on DOC and POC should be done using at least dual stable isotope analyses to better identify the source materials. McMahon et al. (1990) also used stable carbon isotopic analysis to link bacterial CO_2 to the dissolved inorganic carbon found in Coastal Plain aquifers of South Carolina.

Williams et al. (1992) measured dissolved and particulate organic carbon (OC) fluxes in the Bly Creek basin for a year starting in June 1983. The 34 sampling efforts were designed to capture diurnal, lunar, and seasonal sources of variability and to identify sources and sinks of OC in the basin that is isolated on three sides and has only one opening into the inlet. Inputs to the Bly Creek basin were measured in a small blackwater stream emptying from the forest and included groundwater flux from piezometer stations, but DOC could not be measured in precipitation because birds used the gauges as perches. Mean DOC concentrations leaving the basin varied between 2.5 and 11.8 mg C L^{-1}, being lowest in summer and fall and highest in late winter and spring. This marsh basin exported 1.65×10^{5} kg DOC for the year, with most export during the period January to May. Maximum export was during mid-February to mid-March, corresponding to times of freshwater runoff as had been seen earlier by Wolaver et al. (1986). Stream input only accounted for about 10% of the total DOC flux from the basin to the inlet, however. Another 10% of DOC flux from the basin could be accounted for by flux from the marsh surface as it drained during ebbing tides, and a smaller flux came from oyster reefs. These researchers could account for less than 25% of the DOC total flux from the Bly Creek basin. Seepage from the marsh and groundwater probably account for the rest, but they also felt that forest runoff, particularly after storms, was inadequately sampled. The estimate for annual import of POC was 2.04 x 10^{4} kg, but the standard error around this mean was larger than the mean, i.e., POC import was probably zero. There was significant import and export of POC when measured over single tide cycles, however. Imports were significant during very high tides, as marsh vegetation promoted settling of POC. Bly Creek is in a younger part of the system, and compared to the whole-marsh exports of carbon, the export of POC relative to DOC becomes less important as the marsh increases in age (Dame and Gardner, 1993).

Wahl et al. (1996) studied organic carbon inputs from three first-order blackwater streams. Two were in suburbanized/residential Murrells Inlet (impounded Gasque Creek and un-impounded Dog Creek) and the third was at the natural forested edge of Oyster Creek in North Inlet, the control comparison stream. Runoff at Oyster Creek was 40% of precipitation and only 26% of rainfall at Gasque Creek. The dynamics of storm flow runoff at the three sites was quite different, primarily because Oyster Creek had a much less steep elevation gradient than the other two drainage basins. Mean DOC concentrations were about twice as high in the forested Oyster Creek where episodic pulsed releases of DOC occurred. The retention ponds of urbanized areas capture the first flush of suburban runoff, while releases from the forest were more gradual. Freshwater storm flow mixes with tidal waters near the outlet of Oyster Creek.

Wahl et al. (1997) measured DOC in drainage from the forested area that runs into Oyster Creek in North Inlet starting in October 1993 until September 1994. This was the pristine control site for a comparative study of drainage and runoff in Dog Creek in urbanized Murrells Inlet 32 km north of North Inlet. Both streams were blackwater. Although total drainage, sediment loads from erosion, septic tank proximity, and a steeper slope prevailed in Dog Creek, mean annual DOC concentration in the urbanized stream was only half as great as in the North Inlet creek. However, the annual load of DOC in the two areas was almost equal simply because of the greater runoff load in Dog Creek. Suspended sediment concentrations were also much higher in Dog Creek. Nutrient loads were also compared between the sites, and nitrate-nitrite nitrogen was 11 times higher in Dog Creek. Nutrient loading there was more or less continuous during the year, whereas the forested site in North Inlet had episodic loadings after rain events. An interesting look at the ionic chemistry of soil in the forest adjacent to North Inlet after it was flooded by storm surge during Hurricane Hugo is provided by Blood et al. (1991).

From April 1994 to July 1995, Aelion et al. (1997) monitored groundwater from wells in both Oyster Creek in North Inlet and in Dog Creek in Murrells Inlet (see Wahl et al., 1997 mentioned above). They also found significantly higher total organic carbon concentrations in the forested Oyster Creek site than in Dog Creek. Denitrification was the major focus of their study.

Bollinger and Moore (1993) measured residence times of water in the upper 10 cm of marsh sediments in North Inlet using radium isotope tracers. Their data suggested that this water has residence times in sediments ranging from less than one hour to as much as 26 hours. Seasonal changes in the storage of organic carbon in the sediments related to bioturbation probably caused a net reduction of radium carrier phases in the marsh sediments during summer.

Data from previous nutrient flux and transport studies served as input to a dynamic budget model of subsystem interactions in North Inlet, in which POC and DOC played significant roles (Childers et al.,1993b). One of the six subsystems, oyster reefs, once again was shown to have significant impacts on organic carbon removal from the water column. The Stella model provided insights as to how each subsystem (subtidal benthos, oyster reefs, upland forest, marsh surface, nearshore coastal ocean) inter-related constituent-wise with the water column subsystem. Model manipulation of the area covered by oyster reefs and the amount of sea-level rise provided ideas for future research. Spatial variability in fluxes of nutrients emerged as a major concern about what has been missing in the Outwelling and Bly Creek Studies. A need for flux studies in older portions of the marsh (Bly Creek is in a young area of the marsh) would supplement what has been learned from whole marsh studies like the Outwelling Study summarized by Dame et al. (1986).

Goni and Thomas (2000) sampled forest litter, soil, sediments, and plants from three locations along transect D from the forest to the short *Spartina* zone in Crab Haul Creek. Living tissues from the forest samples had the lowest ash content, about 5% by weight. Aboveground *Juncus* and *Spartina* tissues ranged between 45 and 52% OC, while belowground tissues of these plants had between 29 and 43% OC. Forest pine litter samples had depleted C isotope composition, while *Juncus*, a C-3 plant, was enriched, and *Spartina*, a C-4 plant, was most enriched. Among their many findings, the humus fraction contained the largest percent OC in all horizons at all three stations, 60-90%. The macro-organic fraction contained 5-40% OC. The sand fraction always had the lowest, < 5% OC. Based on the isotope signatures and biochemical composition of the various fractions of OC, the authors speculate about the many possibilities regarding the origin of the OC measured at each site. For instance, because the *Spartina* site was probably populated by *Juncus* several hundreds of years ago, some of the isotope depletion found in the deeper belowground core section below *Spartina* now could be from old *Juncus* residue. Or some of the residue could have been mixed downward by storm activity and/or bioturbation. Some of the signal could have come from benthic microalgae or methanogenic bacterial biomass. Isotope studies for carbon must usually be interpreted in light of many possibilities as to the source material, and this study recognizes that there are many possible sources for the organic carbon found in saltmarsh sediments.

Goni and Gardner (2003) sampled groundwater from piezometers seasonally during 1997 and 1998 from the Crab Haul Creek transect D (forest to marsh) used by Goni and Thomas (2000) above. In addition they took surface water samples from the creek and from the mouth of North Inlet. They studied the spatial and seasonal changes in groundwater DOC as related to other geochemical and hydrological data existing for the site. Earlier piezometer data for the transect estimated that groundwater flows from the forest to the marsh at a rate of about 8 m (25 ft) per year (Thibodeau, 1997). DOC concentrations ranged from 6 to 120 mg L^{-1} in the study and were highest in the shallow parts of the aquifer in the forest and declined with depth there. Concentrations were always elevated beneath the *Juncus* vegetation zone. Forest groundwater showed the greatest seasonality in DOC concentrations at any location along the transect or in surface waters in the inlet. DOC levels in Crab Haul Creek (higher at low tide) ranged from 3.3 to 13 and ranged from 3.6 to 9.9 mg L^{-1} in the inlet mouth. Plots of DOC versus salinity illustrated the non-conservative behavior of DOC. The authors discussed the areas where aquifer geochemistry affected DOC levels and the carbon cycle: 1) contrast between surface and deep forest groundwater; 2) mid-marsh seasonal changes; and 3) trends in deeper groundwater along the whole transect. Much of the differences seen could be accounted for by heterotrophic decay that increased DIC levels, with the rest of the losses from sorption and chemical precipitation. DOC sorption processes cause formation of the Spodosol soils common beneath the forest. In the mid-marsh, DOC concentrations increased due to evapotranspiration and possibly tidal recharge. Groundwater upwelling was eliminated as a significant cause of increased DOC levels. They found a deep wedge of saltwater in the aquifer that moved landward in dry periods and seaward in times of high precipitation. Overall, despite uncertainties in their calculations, they estimated that groundwater delivery of DOC could account for about 20% of the annual discharge of DOC from North Inlet to the ocean.

Using the piezometer transect network across the upper reaches of Crab Haul Creek, Cai et al. (2003) sampled groundwater periodically from May 1996 to March 1998. The same transects were used by Gardner and Reeves (2002) and Goni and Gardner (2003). Measurements of various carbon dioxide-relevant parameters were used to dissect the diagenetic processes in this shallow groundwater aquifer. The groundwater ranged in salinity from fresh on the forested edge of the transects to 40 at the marsh-side terminus. Concentrations of the constituents were analyzed using graphical dilution lines that showed how the two end members (fresh, salty) of the mixing zone beneath the sediment interacted chemically. Aerobic decomposition, sulfate reduction, and methanogenesis occur along the transects, all having implications for the amount of dissolved inorganic carbon in the groundwater. Without going into details of these biogeochemical reactions here, their question was whether the highly elevated DIC levels in the groundwater were being delivered to the coastal ocean, either directly or via marsh exchange with the tides, in sufficient amounts that they should be considered in calculations of carbon mass balance for the global ocean. Cai et al. (2003) made several extrapolations (all with high levels of uncertainty) that were reasonable based on the available data and showed that discharges of DIC could be significant. They suggested the need for additional study of how and in what amounts this source of carbon reaches the sea.

Maroney (2005, unpublished) did thesis work on samples collected from the Crab Haul Creek Transect D as well. She cited previous thesis work there by Jones (1999, unpublished) who found that DOC concentrations decreased eastward along the transect and were of vascular plant origin. Maroney's study was done to determine the source and compositional changes of organic matter in groundwater along Transect D. She hypothesized that high molecular weight DOM would degrade as it transitioned into the marsh where it will mix with OM of marine origin. Surface and deep groundwater samples were collected in October, 2000, along with surface water from North Inlet. DOC concentrations decreased with both depth and distance from the forest. Percent OC values decreased from high values in the forest (39%) eastward also. Stable carbon isotope ratios of the OM were depleted in the forest and became progressively more enriched eastward where they were most enriched in the North Inlet water. The major source of high molecular weight DOC in the forest region was C-3 plants. This material was still present in the marsh but contained OM of marine origin from tidal mixing. In North Inlet both total DOC concentration and % OC of high molecular weight material were significantly higher than in Crab Haul Creek.

Bernot et al. (2008) measured stable carbon (*del*-^{13}C) isotopes in *Spartina alterniflora*, surface and deep sediment in experimental fertilized plots in North Inlet. They were enriched in the plant and in surface sediments relative to control, unfertilized plots. Thus the stable carbon isotope signature changed as the nutrient status of *Spartina* changed.

Chow et al. (2012) studied the biogeochemistry of the Crab Haul forested area landward and westward of Crab Haul Creek in North Inlet. Their analyses of DOC in the cypress-tupelo wetland found high concentrations in October before the litterfall began in December. The relatively dry period between August and September was when nutrients accumulated prior to the late September rains which release the DOM from detritus layers. DOC concentration increased after the precipitation, from 15 to 42 mg L^{-1}. Later in the year (October into March) precipitation served to dilute DOC concentrations in surface waters of the wetland. Their calculations suggested that fresh litter is a major source of DOC, while old decomposed duff litter is a source of nitrogen. Although runoff from the forest into North Inlet is not large compared to tidal flows, it is still important to understand how sources of dissolved carbon generate material that flows into the inlet.

Dissolved, particulate, and inorganic forms of carbon cycle within and through North Inlet. DOC concentrations are higher during low tides and seasonally during winter and spring. Overall, DOC is exported to the ocean along with a net export of POC. DOC concentrations are higher during El Niño (higher precipitation) years and lower during years of drought. The surrounding forest is a significant source of both DOC and DIC. Long-term, DOC concentrations have declined in North Inlet since 2004. Oyster reefs and the marsh surface are both sinks for POC and sources for DOC. Older portions of the marsh process carbon differently than younger portions closer to the forest.

» Contaminants

An important part of water quality concerns anthropogenically-produced substances that are dissolved in it or associated with its suspended particulates or bottom deposits and porewater. Many different types of pollutants exist (inorganic and organic) and they are input to receiving waters in varying amounts from a variety of sources, some easily identified (runoff flowing through pipes onto the beach – point source), some indistinct and widespread (aerial deposition, nonpoint source runoff from forests, pasture land or agricultural fields). Some contaminants will simply be diluted by the receiving waters, while others may undergo chemical changes or may become incorporated to some extent in sediments. A body of water having contaminated sediments is more likely to have poor water quality.

This section summarizes studies that have measured contaminants in North Inlet, used North Inlet as a baseline to compare with anthropogenitically impacted estuaries, or used sediments and/or organisms from North Inlet in contaminant experiments. Laboratory bioassays are used to test various contaminants for their potential effects on marine and estuarine organisms. Although direct extrapolation of laboratory results to the field situation is usually fraught with uncertainties, having pristine sediments and organisms available from North Inlet makes such studies possible. These baseline studies will become even more relevant for decision makers charged with managing the course of future coastal development because they highlight some of the possible impacts of potentially harmful or unsustainable contaminant management practices in the coastal zone. Comparative studies using North Inlet's fauna, sediments or other assets in a control capacity also serve to remind us of the importance and value of the National Estuarine Research Reserve program in providing empirical, science-based data as guidance for these management practices.

Because North Inlet has the designation of being a relatively pristine coastal salt marsh habitat, it is attractive to use as a control, or unpolluted, sampling site for comparison with other similar coastal habitats that are proximal to urban and industrial development. Sanger et al. (2008) sampled coastal sites from North Carolina to Georgia in a comprehensive assessment of all types of pollutants that can be found in this stretch of the southeastern (U.S.) coastline. They sampled both intertidal and subtidal systems for a wide variety of water quality and contaminants measures in sediments and biota. Amongst the 19 areas sampled, North Inlet was clearly an outlier in that very few contaminants were found to be present at Clambank and in Town Creeks, the only two sites that were sampled in 2005. Thus it is accurate to state that North Inlet, with its predominantly forested watershed, is relatively pristine. The area does, however, contain many contaminants, but most are in quite low concentrations, at or below detection limits. The challenge, then, is to ensure that the NI-WB NERR remains in this relatively pristine condition in the future, even as quantitative analytical detection methods become more sensitive.

North Inlet is unique in that few and/or low amounts of these potentially toxic substances have been introduced to its waters. Fecal coliform bacteria in North Inlet come almost entirely from animal wastes in runoff from the surrounding forest or possibly from birds, as septic tank discharges are minimal. Hydrocarbons from recreational boat traffic are present in low quantities. Winyah Bay, however, receives municipal, agricultural and industrial wastes and as such has been monitored for pollution loads more regularly than North Inlet. Much of the work on pollution in North Inlet has been performed using this relatively pristine site as the reference or control (unpolluted) site, for comparison with other urbanized, but otherwise similar, sites of interest. Vernberg et al. (1992)

report a concise overview of trends in some comparative studies of pollution (primarily PAHs and metals) between Murrells Inlet and North Inlet as a reference site. This was part of the Urbanization of Southeastern Estuaries Study, or USES. Porter et al. (1996) provide details about how such comparative pollution data (between North and Murrells Inlets in their example) can be input to a Geographic Information Processing program to model how urbanization impacts coastal estuaries. Their model used data on nonpoint source inputs, the area of wetlands alterations, vegetation, and oyster recruitment. Porter et al. (1997) also used GIS to provide a management-useful overlay of comparative grass shrimp abundances. This sentinel organism is much more abundant in North Inlet, presumably because of development's impacts on Murrells Inlet tidal creeks. The difference in census sampling of both inlets is startling, as 10% of the areas sampled in Murrells Inlet had no grass shrimp at all and 90% of the North Inlet areas sampled had higher abundances than the highest numbers found in Murrells Inlet.

Further emphasizing differences found between developed and pristine coastal marshes, Weinstein (1996) reviewed anthropogenic impacts on salt marshes, including dredging, contaminants (insecticides, herbicides, heavy metals, trace elements, dioxins, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs)), oil, marina and boating impacts, eutrophication, pathogens, and marsh creation/restoration/mitigation. This is a good overview of the salt marsh pollution literature, most of which is directly relevant to the southeast coast of the U.S.

Blood and Vernberg (1992) provide an overview of pollutants that covers data collected from 1970 to 1985. Information on heavy metals (arsenic, cobalt, lead, zinc, mercury, cadmium, copper, nickel, chromium), dozens of different pesticides, and coliform bacteria are provided there. Most of their information is for Winyah Bay. As they reported, North Inlet's *E. coli* loads were mostly much lower than the acceptable upper limit allowed for shellfish harvest (> 200 colonies per 100 ml), and only a few water samples from North Inlet close to Winyah Bay exceeded that limit. An early study of bacterial contamination in North Inlet by Scott and Lawrence (1982) also found total coliforms and fecal coliform numbers were very low.

The South Carolina Estuarine and Coastal Assessment Program (SCECAP) from 1999-2004 found that coliform bacteria does not pose a problem in the middle sections of North Inlet based on its two sample sites in/near Old Man Creek. The SCDHEC Shellfish Sanitation Program (SSP) 2007 Annual Update Report for Area 05 (North Inlet and Winyah Bay areas) has affirmed this from their Jan 2004 – Dec 2006 data, by classifying the region as an *Approved Area* (Stations 05-12 & 05-14, Figure 40) (Warren, 2007). This means that fecal material, pathogenic microorganisms, and poisonous or deleterious substances are not present in concentrations which would render shellfish unsafe for human consumption. The whole of North Inlet supplies habitat for a large shellfish resource, and there are 15 long-term monitoring sites throughout the estuary to regulate it (Figure 40). The SSP 2007 Annual Update Report classified the upper and lower most sections of North Inlet as *Restricted Areas*; shellfish harvesting is not allowed, except by special permit (Warren, 2007). Waters of a *Restricted Area* contain deleterious or poisonous substances to a degree which may cause the water quality to fluctuate unpredictably, and therefore, pose a human health. The lower North Inlet estuarine stations: 05-01, -05, -06, -07, -09 and the upper station -13 have remained a *Restricted* shellfish classification since Jan 1998, with sites's -05, -06, and -07 shellfish and water quality classification consistently being rated *Restricted*. In the late 1990s, stations -02, -08, and -16 had consistent *Approved* water quality and shellfish ratings; however, starting in Jan 2001, they became "borderline" stations, where water quality ratings remained *Approved*, but the shellfish rating remained *Restricted*. This was due to the unpredictable fluctuation of the water quality in these areas.

No substantial changes in pollution sources had occurred in the North Inlet section of Area 05 since the SSP 2000 Annual Update Report (data review dates: Jan 98 – Dec 2000). However,

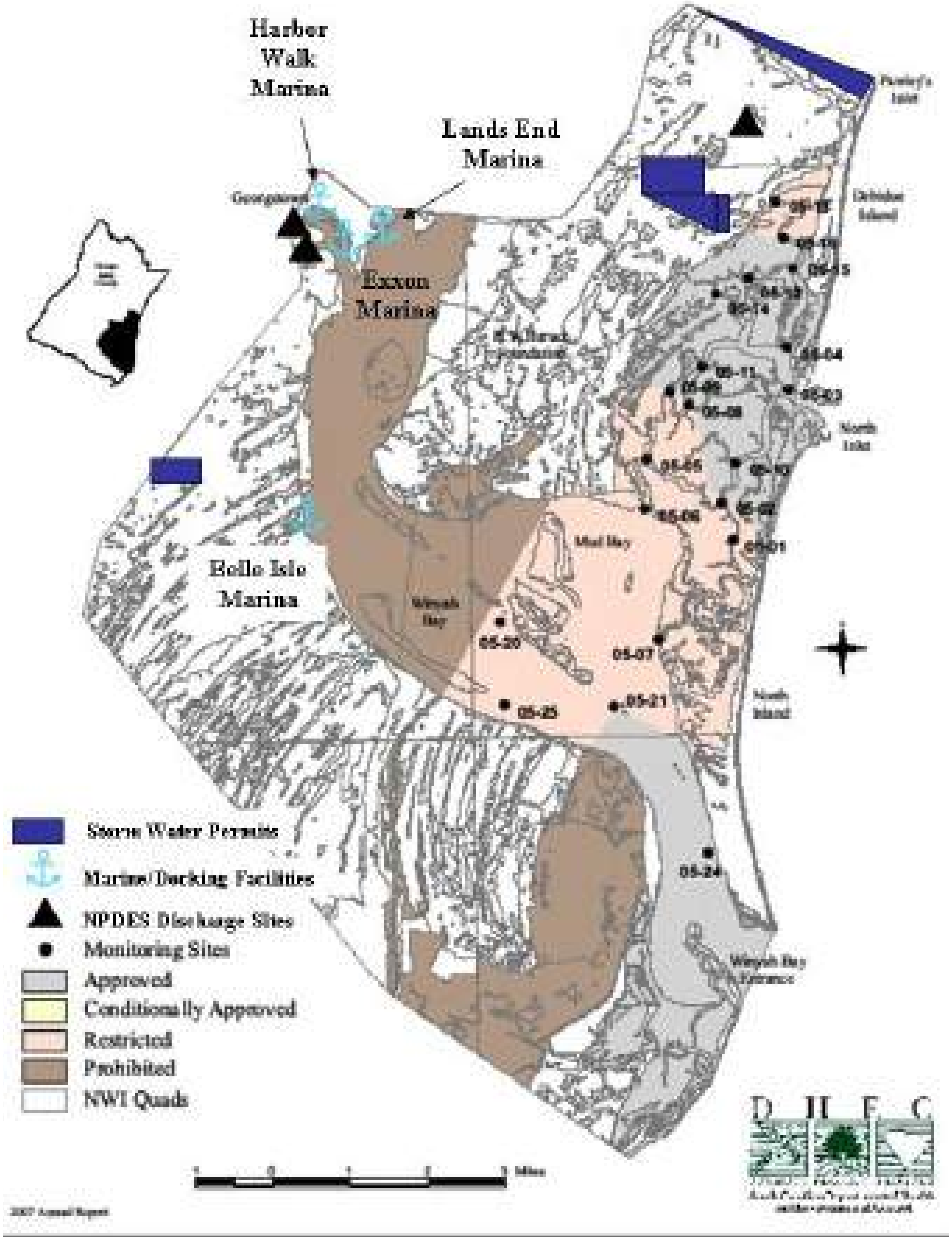


Figure 40. 2007 shellfish management classification for Area 05 (North Inlet and Winyah Bay). Monitoring stations and potential pollution sources impacting shellfish harvesting are also indicated. NPDES discharge sites = National Pollutant Discharge Elimination System sites. Map and assessments are from SCDHEC Shellfish Sanitation Program (SSP) 2007 Annual Update Report for Area 05 (Warren, 2007). Figure is a modified version of the original SSP 2007 base map.

from Jan. 1998 through Dec. 2006, violations of shellfish water quality criteria within North Inlet were and continue to be primarily attributable to nonpoint pollution sources from river flooding into Winyah Bay, as well as, rainfall-induced runoff from natural and engineered systems that drain the surrounding highlands that support substantial wildlife populations, golf courses, and residential developments (Warren, 2007). River flow into Winyah Bay and subsequently into Mud and Oyster Bays adversely impact the water quality in the southern portions of North Inlet. Hydrographic and meteorological conditions, such as strong southerly-southwesterly winds combined with high river flows, complicate water quality predictions and increase the area of intermixing between North Inlet and Winyah Bay/Mud Bay.

DeBordieu Colony, adjacent to the upper (northern) portion of North Inlet, has its own domestic wastewater treatment facility (NPDES #ND00656668) maintained by Georgetown County Water and Sewer District (GCWSD). This facility is in close proximity to waters suitable for the direct harvest of shellfish (Figure 41). Even though this facility utilizes a high degree of treatment, it sprays its effluent onto its forest floor and golf courses. The Colony also has a fairly high degree of residential development and golf course maintenance, and its stormwater, containing various chemical compounds, is "stored" onsite in upland ponds and brackish water impoundments near Debidue Creek. This creek's water quality is highly variable and appears to be impacted by freshwater discharges from these upland ponds. To address this water quality issue, an additional NPDES Permit (SC0048984) was approved in 2010 that enables GCWSD to divert excess treated effluent from DeBordieu Colony in the North Inlet watershed to the Waccamaw River. To the west of North Inlet, ditches from the Belle W. Baruch Foundation property drain uplands and lowlands that contain substantial wildlife populations, such as deer, hogs, raccoons, and squirrels, that potentially could add to the fecal coliform counts; however, the flow rates appear to be substantially less at these sites than at the main culverts along the northern portion of the estuary (Warren, 2007).

Hurricanes and large rainfall events are other causes for shellfish area closures. Whenever a National Weather Service Hurricane Warning is issued, all open areas within the warning area are immediately closed to harvest. These precautionary closures remain in effect pending an evaluation of storm-related pollution impacts. Areas will be reopened when the Department determines that conditions are acceptable for the sanitary harvest of shellfish. Open shellfish areas are also closed upon actual receipt of a 24-hour rainfall total of 4.0 inches or more. Shellfish water quality monitoring stations within the area are sampled for fecal coliform bacteria levels prior to re-opening.

A review of SC Shellfish Program classification data for the 1986 through 2005 annual shellfish reports (data through 2004) indicates relative stability in terms of acreage within individual classification types (Newell, 2006). However, for the 2005 report year (2002 through 2004 data), a moderate decrease from 2004 *Approved* classification acreage was observed; approximately 1300 acres in Georgetown County were reclassified from *Approved* to *Restricted* (Newell, 2006). In general, these reclassifications were due to the influences from rainfall runoff and/or river flow.

NORTH INLET WATER CLASSIFICATIONS

The classification and standard regulation of specific water bodies in North Inlet is found in South Carolina Regulation 61-69 (Bureau of Water, 2006); the Regulation describes waters' desired uses and specific standards for protection. Water quality standards are used to classify and regulate pollution decisions of SC waters; these standards are found in Regulation 61-68 and are based on 1) the character of the body of water and surrounding land, 2) current or future use of the waters and its water quality, and 3) the levels of seven types of pollution (including but not limited to refuse, toxic wastes, fecal coliform, pH, and temperature). The classifications are based on desired uses and not on natural or existing water quality. They are the legal means used to obtain the necessary treatment of discharged wastewaters to protect designated uses. No degradation of existing uses is permitted regardless of classification and no degradation of natural conditions is allowed in *Outstanding Resource Waters* (*ORW*). The upper most and middle water bodies of North Inlet are classified as *ORW* and/or *Shellfish Harvesting Waters* (*SFH*) (Figure 41). *ORW* are waters that receive the highest level of protection because they have an exceptional recreational or ecological importance or value. These types of waters include waters in parks or wildlife refuges, waters supporting endangered or threatened species, waters known to be significant nursery areas for commercially important species or waters which are used for scientific value or study. *SFH* is tidal saltwater protected for shellfish harvesting (oysters, clams, and mussels). This class has the strictest bacteria standard because people often eat shellfish raw. These waters are also suitable for uses listed in Classes *SA* and *SB*. The lower reaches of North Inlet influenced by Mud Bay are listed as Class *SB* waters (Figure 41). Class *SA* water is tidal saltwater suitable for primary and secondary contact recreation, crabbing, and fishing, except harvesting of clams, mussels, or oysters for market purposes or human consumption. These waters are also suitable for the survival and propagation of balanced indigenous communities of marine fauna. Class *SB* water has the same criteria as *SA* waters, except for the levels of dissolved oxygen (DO). Daily DO average for *SA* waters must not be less than 5.0 mg/L, with a minimum or 4.0 mg/L, and for Class *SB* waters, DO daily average must not be less than 4.0 mg/L.

Figure 41. Classification of water bodies in North Inlet based on Regulation 61-69 (Bureau of Water, 2006). Classes: Outstanding Resource Waters = ORW, Shellfish Harvesting Waters = SFH, and Class SB = see text above for definition

POLYCHLORINATED BIPHENYLS

The earliest study of polychlorinated biphenyls (PCB) toxicity using North Inlet fauna was conducted by Vernberg et al. (1977a) on newly-hatched swimming larvae of the common marsh fiddler crab, *Uca pugilator*. These investigators were among the first to test PCBs on non-adult marine life forms. LC_{50} (96-hr) concentrations were between 5 and 50 ppb for the larvae, and Aroclor 1254 was generally more toxic than Aroclor 1016. Adults were much less susceptible to Aroclor than larvae. The experiments with interacting temperature and salinities were difficult to interpret because of high variability in survivorship. Vernberg et al. (1978a) measured respiration with a Gilson respirometer on adult fiddler crabs (males and females from Clambank Landing) exposed to sublethal concentrations of the PCBs Aroclor 1016 and 1254. Over a range of temperatures from 10 - 35 °C, *Uca pugilator's* metabolic responses were basically unaffected by exposure to these PCBs.

Harpacticoid copepods are ubiquitous small crustaceans near the base of the food chain eaten by many estuarine-dependent larval or juvenile fishes, shrimps, and crabs. An abundant harpacticoid species from intertidal creeks in North Inlet, *Microarthridion littorale*, was tested with various concentrations of a sediment-associated PCB called Aroclor 1254 by DiPinto et al. (1993). Ninety-six hour exposures found 50% of the animals dead at concentrations of 251 mg kg^{-1} for females, but only at 117 mg kg^{-1} for males. Reproduction in this copepod was impaired at a very low concentration, 4 mg kg^{-1}, of Aroclor 1254. Chandler (1986) had earlier proposed a standard procedure for collecting sediments in North Inlet used to culture harpacticoid copepods in studies of various contaminants in their sediment-associated phase to which these crustaceans are susceptible.

A trophic transfer study of polychlorinated biphenyls (Aroclor 1254) from sediments to benthic copepods to bottom-feeding juvenile estuarine fish was conducted by DiPinto and Coull (1997). Fish fed clean copepods in contaminated sediments accumulated about 5X more PCB than fish fed contaminated copepods in clean sediments from North Inlet. The fish (spot, *Leiostomus xanthurus*) eats these meiobenthic copepods naturally, but the time course of these experiments, just one feeding bout, was too short for PCB elimination to equilibrate their body burdens over longer periods of time as would occur in nature. The octanol-water partitioning coefficients of the different PCB congeners played a significant role in the short-term results obtained.

TRACE METALS

Sauer and Watabe (1984) collected juvenile mummichog (*Fundulus heteroclitus*) from North Inlet and took them to Columbia, SC, for a study of zinc uptake into the fish's scales. Animals were kept in aquaria dosed with 0.1, 1.0 and 10.0 mg $ZnCl_2$ for up to 10 weeks and then sacrificed. They found Zn in the calcified region of the scale and suggested that this metabolic uptake was a detoxification mechanism. Sauer and Watabe (1988) demonstrated the inhibitory effects of Cd and Zn on calcium uptake by mummichog gills. Sauer and Watabe (1989) then examined the effects of Zn on scale formation in this fish.

Cadmium toxicity to the fiddler crab, *Uca pugilator*, was lethal when concentrations of 110 micrograms per gram in gill tissue were reached (O'Hara 1973a). Accumulation of cadmium by the crab was greatest at high temperatures and low salinities (O'Hara 1973b).

Hutcheson (1974) exposed adult blue crabs, *Callinectes sapidus*, to aqueous solutions of cadmium chloride at several different temperatures and salinities. Uptake and concentrations were highest at low salinities and higher temperatures, with hepatopancreas, gill, and carapace tissues having the highest concentrations. Claw muscle did not accumulate cadmium to an appreciable extent.

Vernberg et al. (1977b) set out to establish a uniform bioassay procedure for sublethal concentrations of cadmium with male adult grass shrimp, *Palaemonetes pugio*, from North Inlet. Uptake of Cd was proportional to salinity at 25 °C and more was taken up under flow-through conditions. Molting frequency was stimulated at low concentrations and inhibited at higher levels. Respiration rates were variably higher in the flow-through system as well. It was concluded that *P. pugio* was too hardy an organism to use in bioassays.

Mirkes et al (1978) found deleterious effects of cadmium and mercury on the development rate, survival, and swimming speeds of larval mud crabs, *Eurypanopeus depressus*. However, there were differential effects depending on which larval stage was tested with which element. For instance, swimming rate was stimulated by cadmium but depressed by mercury, and cadmium was more toxic to some stages than others.

The North Inlet standard sediment from Bread and Butter Creek was used to measure the effects of cadmium on a meiobenthic copepod in laboratory cultures by Green et al. (1993). Three phases of Cd were prepared: aqueous, sediment, and porewater. Each was presented to copepods over a range of concentrations with appropriate sham treatments as controls. The copepod, *Amphiascus tenuiremus*, was most sensitive to the aqueous phase as measured by LC_{50} values. The sediment-associated phase was least toxic. Reasons for such

The copepod, *Amphiascus tenuiremus.*

reduced acute toxicity may have had to do with the digestive tract chemistry of the copepod.

Cadmium's sublethal effects on an abundant burrowing brittlestar, *Microphiopholis gracillima*, in North Inlet were studied by D'Andrea et al. (1996). Echinoderms are infrequently used in marine toxicology studies. Because this animal lives in sediments and normally regenerates tips of its arms that are lost to predators, regeneration measures were used as a physiological assay for effects of cadmium exposure administered to animals in small aquaria. Newly regenerated arm tips were thinner in Cd treatments than those of controls and uptake of cadmium by the animal's calcium carbonate exoskeleton was proportional to the Cd exposure levels tested. Cd adversely affected arm regeneration which would have negative consequences for recovery from tissue loss and survival in the field.

Vernberg and O'Hara (1972) measured the uptake of mercuric chloride in the fiddler crab, *Uca pugilator*, under six temperature-salinity regimes. Mercury toxicity was greater at lower temperatures, and gills transferred Hg to the hepatopancreas more effectively at higher temperatures.

In a comparative study between Murrells Inlet and North Inlet in 1997, oysters were collected and analyzed for methylmercury and total mercury, Hg (Kawaguchi et al. 1999). All but one of the 31 oyster samples from throughout Murrells Inlet were below detection limits for total Hg (<0.1 microgram per gram wet weight). They found 109 micrograms/g in a composite tissue sample in the heavily urbanized north end of Murrells Inlet. All 9 North Inlet samples were below detection limits. However, the more sensitive method used to detect methylmercury was able to detect similar nanogram levels of total mercury in both estuaries. Methylmercury levels were the same in both inlets as well, at about 10 nanograms/g. About half the Hg present in oysters was in the form of methylmercury, and concentrations were about 50% above the national average found in the Mussel Watch Program at the time.

Guentzel and Tsukamoto (2001) measured total and methylmercury in Winyah Bay and North Inlet using "clean protocols" in October 1999. In North Inlet they were interested in the degree to which microbial processes transform inorganic divalent mercury to organic or methylmercury and how much is evaded from the water column to the atmosphere. They used several antibiotic treatments to stop microbial activity and a photosynthesis inhibitor (DCMU) in creek water samples. Abiotic formation of gaseous Hg accounted for about 25-33% of the total evasion rates measured. In Winyah Bay, colored water (essentially DOC) was found to scavenge mercury and is the carrier phase for this element in the estuary. Total Hg declined along the axis of Winyah Bay with increasing salinity. Using data from Kawaguchi et al. (1999), they computed log bioconcentration factors (from water to tissues) in oysters in North Inlet that ranged between 5.0 and 5.1 for total Hg and between 5.7 and 6.0 for methylmercury. Formation of elemental Hg in North Inlet was due either to microbial activity and/or is linked to the light/dark cycles of photosynthesis, probably by blue green algae. Because microbial formation of elemental mercury in the water column reduces the total amount of substrate available for conversion to methylmercury, future studies should examine the role of the microbial food web in mercury cycling dynamics.

Most of South Carolina's lakes, streams, and estuaries have a mercury advisory warning about the danger of eating mercury-contaminated fish (Figure 42). In 2007 all rivers in Georgetown County were under "a fish consumption advisory" (Bureau of Water, 2007). The recommended type of fish and serving size depended upon where the fish was caught. Details are available online at http://www.scdhec.gov/FoodSafety/FishConsumptionAdvisories/. Certain sizes for some species and other species, no matter their size, should not be eaten from any SC bay, estuary, or coastal waters.

Results of the 2002-2006 annual North Inlet National Atmospheric Deposition Program (NADP) chemistry analysis includes mercury and other ions related to water quality (Figure 43a). K, Mg, Ca ranged in deposition amounts less than 3 kg/ha/

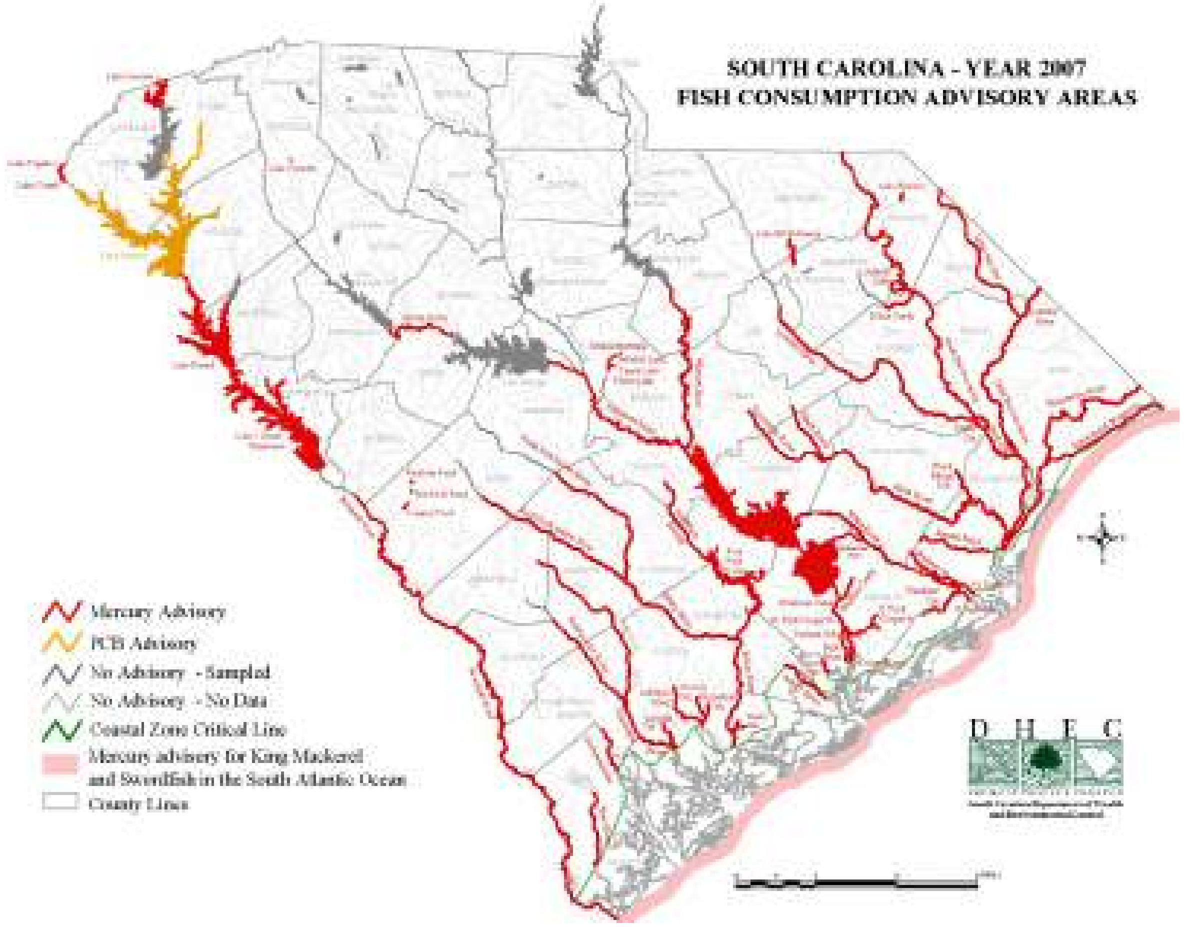


Figure 42. South Carolina 2007 Fish Consumption Advisory Areas. Map derived from SCDHEC online website: http://www.scdhec.gov/environment/water/fish/map.htm.

yr, while Na, and Cl values ranged from 10-45 kg/ha/yr. Ozone and acid rain causing chemicals (NH_4^+, NO_3^-, and SO_4^-) increased in levels in 2003 (Figure 43b). Deposition levels are related to the amount of rainfall (concentration x rainfall), and 2003 & 2005 were unusually rainy years. 2006 had the lowest total rainfall of the span of years. Mercury, as measured in the nearby Cape Romain National Wildlife Refuge, rarely had weekly deposition levels over one $\mu g/m^2$ from March 2004 through April 2007 (Figure 44). Atmospheric mercury levels can vary greatly depending on the location. And according to 2006 values, it appears that North Inlet and Winyah Bay are exposed to low to moderate levels of mercury in comparison to the rest of the east and gulf coast (Figure 45).

HYDROCARBONS AND PAHs

Sanders (1995) compared the concentrations of PAHs in sediments and oysters in a comparative study between urbanized Murrells Inlet and North Inlet as a control. Thirty sites were sampled in each estuary. In Murrells Inlet the highest PAH concentrations in composite samples of oyster tissue were found in animals collected near marinas, high density residential areas, commercial enterprises, or storm-drain runoff. A similar concentration gradient from the more urbanized northern end of Murrells Inlet to its mouth was found in the top 3-5 cm of the sediment samples collected – highest in the tidal creeks and lowest near the mouth of the estuary. Sediment PAHs were not the same as the lower molecular weight, more soluble fractions accumulated by the oysters. Similar gradients in sediments or oysters did not exist in North Inlet.

A more comprehensive comparison of PAHs and trace metals between Murrells and North Inlets was reported by Fortner et al. (1996). Over 30 stations were sampled in the two inlets where

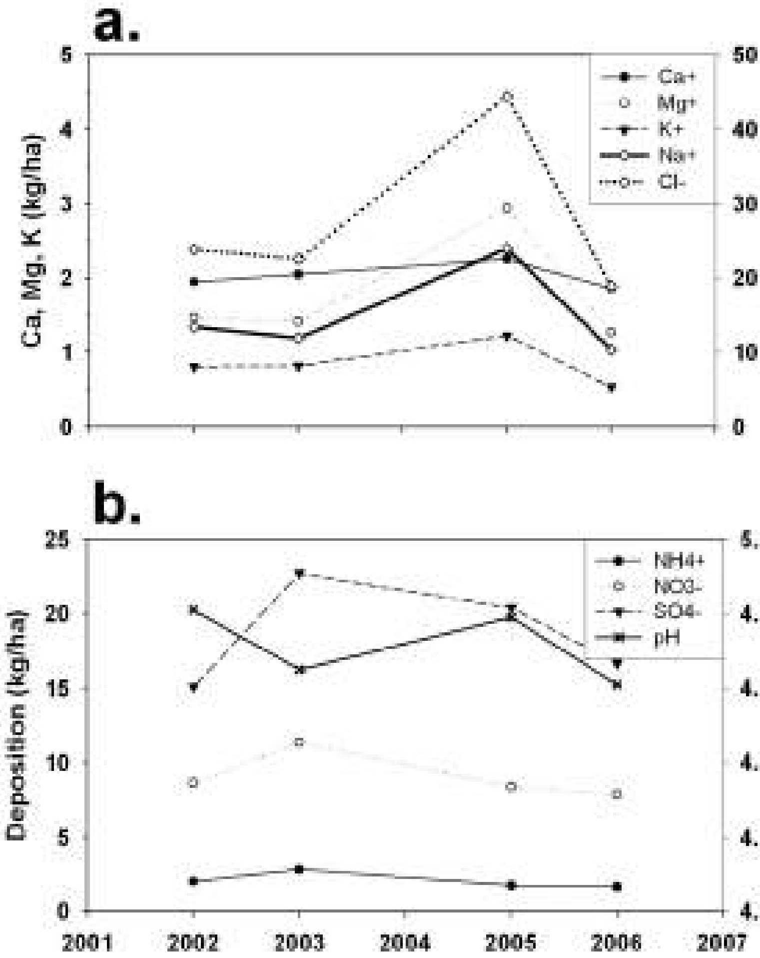


Figure 43. Annual deposition rates for NADP chemistries in North Inlet.
Note: missing data for 2004. Rates are measured in kg/ha.

oysters and sediment were both collected at each station in November 1990. Ten different PAHs and 7 trace metals were analyzed in the samples. Between 30 and 60 oysters were homogenized for the chemical assays. Mean PAH levels were in the 100 nanogram per gram dry weight of sediment level in North Inlet and were significantly higher in Murrells Inlet sediments at just over 500 ng/g. There was wide variation in oyster tissue PAH levels in both inlets. Fluoranthene and pyrene comprised more than 50% of the PAHs found in Murrells Inlet, and the number of PAH compounds found per sample ranged from 4 to 10, depending on station. North Inlet oyster PAH levels were also variable but averaged significantly lower (71 ng/g dry tissue weight) than in Murrells Inlet (452 ng/g). Trace metal sediment concentrations were likewise highly variable (about 10-fold) in both inlets but averaged higher in North Inlet than in Murrells Inlet. This difference suggested there was little anthropogenic input of trace metals in Murrells Inlet. Oyster trace metal levels were variable

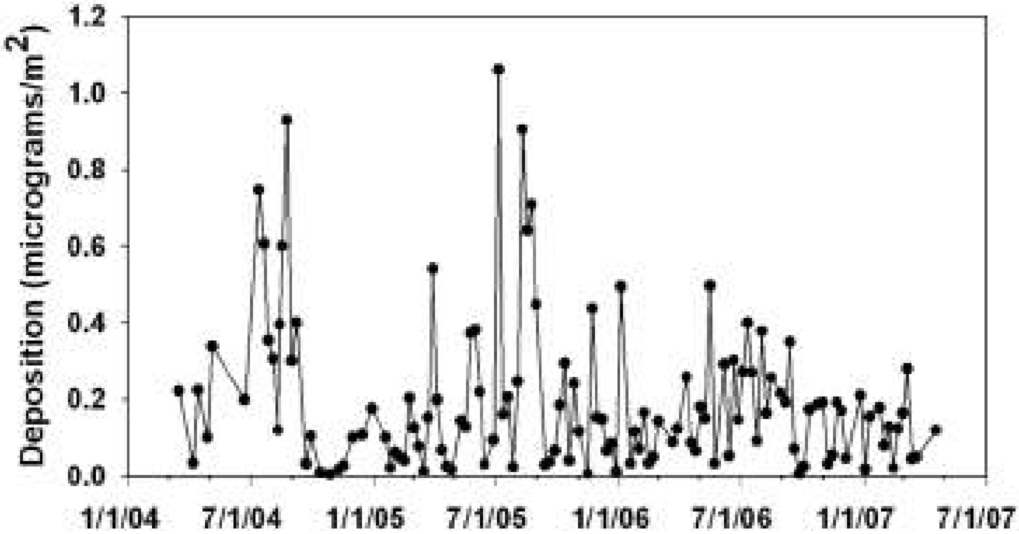
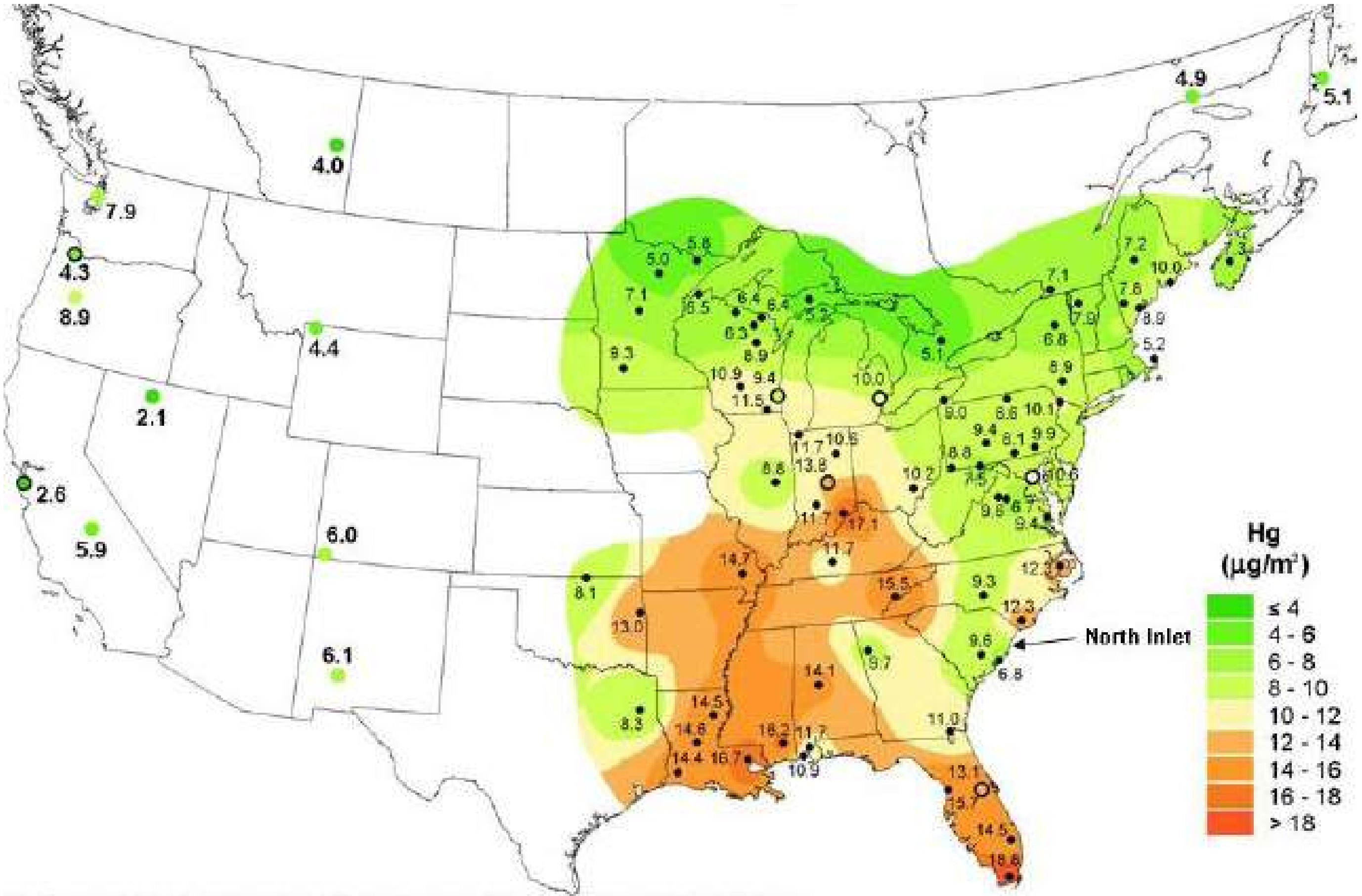


Figure 44. Total weekly deposition rates for mercury (Hg) from the Mercury Deposition Network (part of NADP) in the nearby Cape Romain National Wildlife Refuge. Rates are measured in µg/m^2.



National Atmospheric Deposition Program/Mercury Deposition Network

Figure 45. Total mercury wet deposition for 2006.

and significantly higher in Murrells Inlet, ranging from 560-3100 micrograms per gram dry tissue in Murrells Inlet and from 450 to 2600 in North Inlet. No lead or tin was found in North Inlet oysters. Zinc was most commonly found in North Inlet oysters. Some additional comparisons with other coastal estuaries were made, including Charleston Harbor.

Additional comparative studies between Murrells and North Inlets that focused on the effects of PAHs on oysters were done by Weinstein (1995). He examined changes in PAH body burdens and in the mixed-function oxygenase (MFO) system (cytochrome P_{450} and others) as indicators of pollution stress. These were monitored quarterly for a year at Clambank Creek in North Inlet, and at two sites in Murrells Inlet. MFO components were lowest in North Inlet in October 1993. PAH tissue levels were always higher in Murrells Inlet oysters, often as much as 40 X higher. Seasonal changes in the MFO system were suggestive enough that they may have potential as biological indicators of hydrocarbon impact. Histological differences between the oysters in Murrells Inlet and North Inlet were reported by Weinstein (1997) who found that thinning of the oyster's digestive epithelium is an indicator of fluoranthene exposure in this mollusk.

Chandler et al. (1997a) cultured a common member of the North Inlet macrobenthic community, a polychaete worm (*Streblospio benedicti*), and measured its reproduction under spiked concentrations of six PAHs most often found in Murrells Inlet sediments. This worm is well-known to be pollution tolerant and in these studies suffered no ill effects on mortality or weight gain after as much as 18 days of exposure. However, their vitality declined dramatically from days 18-27 in the fluoranthrene treatments as this PAH accumulated in the worm's tissues.

Fulton et al. (1996) performed yet another comparative study between Murrells Inlet and North Inlet, the reference site. They used *in situ* bioassays, bioaccumulation in oysters, and field population studies to assess the impacts of nonpoint source pollution. Trace metals and PAHs were the focus of their studies. It should be noted that in these types of studies, results are correlative, as no direct cause and effect manipulative field experiments were performed except for the mesocosm lab studies that used contaminated sediments from Murrells Inlet. However, measuring performance of the same organisms in control and test sites certainly can point to differences in the habitat in each and can help identify additional types of studies needed to isolate causative factors. Highlights of their comparison-site findings included no differences in survival of grass shrimp or mummichogs in the *in situ* bioassays, greater accumulations of PAHs in the Murrells Inlet oysters that were translocated to the test site from a distant estuary, reduced growth in sheepshead minnows in Murrells Inlet, reduced numbers of grass shrimp in Murrells Inlet, and reduced molting of meiobenthic copepods exposed to sediments from Murrells Inlet. Murrells Inlet, the urbanized site, clearly had higher levels of contaminants than North Inlet. Variations on this study were also published by Fulton et al. (1993).

Another study of PAHs in municipal runoff by Ngabe et al. (2000) also used North Inlet tidal creeks as their relatively uncontaminated control area that receives these pollutants only from atmospheric deposition and boat traffic. Wirth et al. (1998) used sediments from North Inlet to test PAH toxicity on laboratory cultures of grass shrimp (acute LC_{50} tests) and on a benthic copepod (sublethal reproduction tests). These tests used PAHs commonly found in Murrells Inlet. Sanger et al. (1999) made extensive comparisons of organic contaminants in sediments (e.g., PAHs, PCBs, DDT) of South Carolina tidal creeks, including Crabhaul Creek in North Inlet.

Kovatch et al. (2000) measured the toxicity of PAH- and metal-contaminated sediments to a meiobenthic harpacticoid copepod, *Microarthridion littorale*. They compared the effects of sediments from three locations, with North Inlet being the least contaminated site compared to an Environmental Protection Agency Superfund site (Diesel Creek) and an abandoned shipyard site (Shipyard Creek) in Charleston Harbor, SC. Although contaminated sediments reduced adult survival and reproductive success of the copepod, none of the effects could be related to genetic differentiatons at the population level.

Vo et al. (2004) compared the effects of PAH toxicity on a harpacticoid copepod in culture using sediments from both North Inlet (control) and Murrells Inlet (PAH contaminated). PAHs undergo photolysis when exposed to sunlight, and the degradation products of PAHs may have different toxicities than the intact molecules. Most bioassays using PAH-contaminated sediments are done indoors, so these investigators exposed their test organisms to sediments with and without ultraviolet light exposure to simulate natural outdoor exposure conditions. The contaminated sediments under UV exposure were more toxic to the copepod than those not undergoing photoinduced PAH toxicity. Survival was always higher using North Inlet sediments, whether exposed to UV or not. The authors then developed a model to calculate that 8-16% of the area suitable for meiobenthic copepods in the northern portion of Murrells Inlet was in jeopardy due to increased PAH toxicity from UV exposure.

Another study of light-induced toxicity with the PAH fluoranthene was done by Southerland and Lewitus (2004). Natural phytoplankton communities from North Inlet and Murrells Inlet were exposed to this compound, as were cultures of a benthic green microalga, *Ankistrodesmus sp*. Xanthophyll pigment responses suggested that phytoplankton from Murrells Inlet that were already exposed to higher PAH levels were more susceptible to UV-enhanced fluoranthene toxicity than those from North Inlet.

Li et al. (1990) dosed tall *Spartina alterniflora* taken from North Inlet using PVC cores with a 1x and a 10x chronic (daily) exposure to a modified crude oil mixture for two years in a greenhouse. The cores were fertilized monthly. Both microbial activity and plant growth were monitored. After acclimation for 9 months, the dosing began. The 1x treatment stimulated plant growth and microbial activity for up to 7 months after the oil additions ended, but the 10x treatment significantly reduced growth. They suggested that the microbial community in the cores may have been carbon-limited and that the extra nitrogen fixation that occurred stimulated plant growth. This study attempted to mimic what would happen under the much more likely scenario of chronic exposure to oil-contaminated surface water rather than the well-known destructive effects of acute oil spill exposures on salt marsh flora.

PESTICIDES AND HERBICIDES

Gulka et al. (1980) collected ivory barnacles (*Balanus eburneus*) attached to oyster shells in North Inlet and exposed them to a range in concentrations (1-1000 ppb) of the insecticide diflubenzuron that interferes with chitin formation in arthropods. Mortality and molting frequency over 28 days was measured. Large barnacle mortalities occurred in the second week in both fed and unfed conditions over essentially the whole range of concentrations tested. Molting frequencies increased by about 30% as well, and mortalities occurred mostly when animals were in the process of molting.

Harder et al. (1980) measured the insecticide toxaphene in samples of rainwater collected at various sites in North Inlet from July 1977 to December 1978. Samplers were set out and emptied at intervals that included mostly times of no rainfall, but other samplers were used exclusively during rain events. Concentrations in each type of sampler were similar indicating that washout, not aerial deposition, was the most important transport mechanism from the atmosphere. Concentrations ranged from 13-497 nanograms per kg rainwater, and were highest in summer when toxaphene use is high on crops of cotton, soybeans, peanuts, and grain. Concentrations were below detection limits in winter and early spring. Air samples were also collected and ranged between 0.33 and 7.2 nanograms per kg of air, about the same as seen in air over the western Atlantic ocean. PCBs, DDT and DDE were also found in rainwater samples in North Inlet. They estimated aerial input of 1.2 kg toxaphene to North Inlet from June to September 1977. Ancillary measurements of toxaphene found it present in samples of oysters, blue crab, and mummichog fishes in concentrations between 30 and 60 micrograms per kg wet weight. They also found evidence that toxaphene is degraded, possibly by a reductive chlorination process, in anoxic sediments, but toxicological measurements have not been made for these alteration products. Unfortunately, no toxaphene measurements have been made in North Inlet since this 1977 study.

Bidleman et al. (1981) reported aerial deposition of organochlorine pesticides in North Inlet and Columbia, SC. They used the same rain stations as above to collect several compounds (DDT, toxaphene, PCBs, Chlordane, Aroclor 1254). Based on measures of the washout ratio, they found that most deposition, even during rain events, occurred as particulate fallout rather than from vapor dissolution into raindrops. Other results were similar to those in Harder et al. (1980).

Another pollution survey was funded internally by the Baruch Foundation in 1987-1989. Six sites were tested once per year to obtain baseline levels of contaminants in the upper, middle, and lower portions of the estuary (Crosby, 1989). In 1987, water, sediment, and oyster tissue were tested for heavy metals, chlorinated pesticides/PCBs, and chlorinated herbicides. All compounds, except lead and cadmium, were below detectable limits; these two compounds were found in very low levels in oyster tissue and sediments (Table 3). PAHs and additional heavy metals were analyzed in 1988. No detectable levels of chlorinated pesticides/PCBs, chlorinated herbicides, or PAHs were found in oyster tissue or sediments; however, very low levels of metals were detected in oyster tissue (arsenic, copper, cadmium, chromium) and in sediments (arsenic, copper, chromium) (Table 3). In 1989 the annual survey tested other compounds in oyster and sediment samples where bioaccumulation and concentration are likely to occur. Because golf courses adjacent to the northern section of North Inlet were being managed with organophosphorus

Table 3. Contaminants tested at six sites within North Inlet from 1987 – 1989 (Crosby, 1989). Compounds at or above detectable levels are in ***bold italic***.

Year	Water	Sediment	Oyster Tissue
1987	Cadmium	***Cadmium***	***Cadmium***
	Lead	***Lead***	***Lead***
	Mercury	Mercury	Mercury
	Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB
	Chlorinated Herbicides	Chlorinated Herbicides	Chlorinated Herbicides
1988	Arsenic	***Arsenic***	***Arsenic***
	Copper	***Copper***	***Copper***
	Chromium	***Chromium***	***Chromium***
		Cadmium	***Cadmium***
		Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB
		Chlorinated Herbicides	Chlorinated Herbicides
		PAHs	PAHs
1989	Not Tested	***Arsenic***	***Arsenic***
		Copper	***Copper***
		Chromium	***Chromium***
		Cadmium	***Cadmium***
		Lead	Lead
		Mercury	Mercury
		PAHs	***PAHs***
		Organophosphorus Pesticides	Organophosphorus Pesticides
		Dioxins (2 sites)	Dioxins (2 sites)

pesticides in the late 1980s, this type of compound was also added for analysis in the 1989 study. There was also concern regarding dioxin levels in the environment from nearby metallurgical processes, coal-fired power plants, automobile exhausts, pulp and paper bleaching processes, and various incineration processes. Two sites within North Inlet were sampled for dioxin. No detectable levels of organophosphorus pesticides or dioxin were found in either sediments or oyster tissues in the estuary (Table 3), but 5 of 12 PAH compounds were detected in oysters above levels previously reported for SC oysters. Various metals, including lead and mercury, were also detected in the sediment, with highest concentrations occurring in the southern-most section of North Inlet near Winyah and Mud Bays.

Chandler et al. (1994) tested the effects of a highly lipophilic synthetic pyrethroid pesticide called fenvalerate on meiobenthic organisms from North Inlet (nematodes and two harpacticoid copepod species). This pesticide has both an aqueous and sediment-associated phase. In 96-hr LC_{50} tests, nematodes were most sensitive, the copepods less so. One of the copepods was much less sensitive to the aqueous phase than to the sediment phase. The pesticide was highly toxic to these animals.

Green et al. (1996) tested early larval (naupliar), juvenile (copepodite) and adult life stages of a meiobenthic copepod in acute toxicity tests with concentrations of Chlorpyrifos, an organophosphate insecticide, in its sediment-associated phase. The naupliar stages were much more sensitive in LC_{50} bioassays than the other life stages of the copepod. The sediments used in these tests were from North Inlet tidal creeks and were treated in a standardized manner such that they could be used in quantitatively comparable tests with sediment-associated phases of other organic toxins. Interestingly, the supposedly protective standard criterion for toxicity calculated with equilibrium partitioning theory for this pesticide was at a concentration higher than that which was found to be lethal to this copepod, i.e., supposedly safe levels in sediments were not safe for this species.

Strawbridge et al. (1992) and Chandler and Green (1996) also used North Inlet sediments in their harpacticoid copepod toxicity culture experiments. However, a novel approach to the use of spiked-sediment treatments was published by Chandler et al. (1997b). They took multiple intact sediment cores from a mudflat in North Inlet at low tide, transported them back to the laboratory where they were placed into "culture", and a spiked sediment treatment layer was later placed on top of the original sediment surface. As the deeper sediments became less and less oxygenated over time, the meiofauna migrated up into the spiked layer where they came into contact with the insecticide chlorpyrifos. At the taxon level, exposure had no effects on harpacticoids or nematodes. Three of 4 species of copepods increased in abundance relative to controls. That these experiments gave different results than single-species bioassays was surprising and suggests that survivorship/mortality can be quite different when whole communities are exposed to contaminants.

DiPinto (1996) used a similar experimental set-up as used before (DiPinto et al., 1993) for trophic transfer studies with PCBs. In these experiments, the hydrophobic organophosphorus pesticide azinphosmethyl (APM) was used to label meiobenthic harpacticoid copepods and sediment. Bottom-feeding juvenile fish (spot, *Leiostomus xanthurus*) were fed APM-contaminated copepods in clean sediment or clean copepods in APM-contaminated sediment, and were then sacrificed to measure their body burden of the pesticide as well as levels of acetylcholinesterase (AChE) in fish brain tissue. APM binds with and blocks this enzyme, so it would be utilized rapidly and decline in fish exposed to APM. When feeding on clean copepods in APM-contaminated sediments, the fish accumulated more APM in their bodies than when feeding on APM-contaminated copepods in clean sediments. Relative to controls, fish brains had 23% less AChE activity after feeding on contaminated copepods in 1993, but activity levels were not depressed in the 1994 experiments. AChE levels were also depressed by 21% in fish feeding on clean copepods in contaminated sediments. Surprisingly, APM did not accumulate in the bodies of fish fed contaminated copepods, but did accumulate when they fed on clean copepods in contaminated sediment. Sediments are normally taken into the mouth when spot feed on benthic meiofauna. Thus sediments were a source of APM accumulation in both copepods and fish in these experiments.

PATHOGENS

Perkinsus marinus is a pathogenic protozoan that causes dermo disease in oysters in North Inlet and elsewhere. White et al. (1998) examined the spatial distribution of diseased oysters using a GIS interpolation method called kriging. They sampled oyster reefs twice (September and December 1996) in Murrells Inlet and North Inlet at over 30 stations in each estuary, scored the prevalence of dermo, and mapped the distribution of the disease's prevalence. There were no spatial patterns in the oyster disease in North Inlet, as distribution of the pathogen was random and differences among sites were small. Bushek et al. (2007) studied the effects of nutrient additions and one common herbicide on growth of the parasitic pathogen, *P. marinus*. Concentrations tested were above those found in North Inlet, but only the herbicide negatively affected growth of the dermo-causing organism.

In summary, North Inlet contains only minimal amounts of contaminants or pollutants. Aerial and precipitation deposition appear to be the main routes of entry into the North Inlet system. However, some pathogenic bacteria and other pollutants enter the southernmost portions of North Inlet from Winyah Bay. Many researchers have used organisms and/or sediments from pristine North Inlet in bioassay and toxicity studies, and several comparative studies using North Inlet as the control site have been made of the impacts of anthropogenic contaminants in Murrells Inlet, a nearby developed estuary, that clearly illustrate the value of having the North Inlet - Winyah Bay NERR remain pristine into the future.

WINYAH BAY

Brown Pelicans rest on an island in Winyah Bay.

» Geology and Geomorphology

Although the recent geological history of the area is shared by Winyah Bay and North Inlet estuaries, they have undergone some independent transformations, largely because of the riverine influence in Winyah Bay. About 15,000 years ago when the coast was more than 100 km seaward of its current location, the Pee Dee River most likely occupied its present valley. Evidence of the penetration of the ocean and salinization of the river at what we now recognize as Winyah Bay probably occurred about 5000 years ago. As a result of the prevailing southward long-shore drift over the past several thousand years, the mouths of both Winyah Bay and North Inlet estuaries migrated southward. The area that we now recognize as Mud Bay probably occupied much of what is now the North Inlet salt marsh, and the expansion of the North Inlet salt marsh into Mud Bay appears to be continuing today (Vogel, et al. 1996).

Increases in upstream penetration of salt water into the Pee Dee River and its tributaries resulted in a succession of botanical zones. Accounts of human uses of the rivers in the last several centuries suggest an ongoing conversion of cypress swamps to tidal wetlands as sea level continues to rise and river inflow decreases.

» Tidal Regime/Hydrology

Winyah Bay is a Class B, partially-mixed coastal plain estuary with major sources of river water input and a much greater range of salinity than North Inlet. It drains a 47,000 km^2 watershed originating in North Carolina with six rivers (Lynches, Pee Dee, Little Pee Dee, Black, Waccamaw, Sampit) having a combined mean annual discharge of 450 m^3 s^{-1}. Seasonal and year-to-year variations in discharges vary greatly, but during short-term, severe flood conditions, discharge can be as high as 7,800 m^3 s^{-1} (Blood and Vernberg, 1992). About 90% of the freshwater inflow to Winyah Bay comes from the Pee Dee River. The origin of the Pee Dee River is in the Piedmont and high sediment loads are typical, whereas the Black, Waccamaw, and Sampit Rivers originate on the coastal plain and drain forest and swamps; their waters tend to be dark and clear.

Lower Winyah Bay connects to the Atlantic Ocean through a pair of long jetties that originate from the barrier islands. The north jetty is on North Island, about 14 km south of North Inlet. The inlet separates North Island and the South/Cat Island complex. The tidal range in lower Winyah Bay is about 1.4 m. In Georgetown Harbor (Sampit River), about 18 km up the bay, the range is about 1.2 m. Winyah Bay may be best characterized as a turbulent and turbid system. Surface current velocities in Winyah Bay often exceed 2 m/sec and are especially high in the ship channel and lower Bay where the jetties force water through the narrowest part of the Bay. The irregular and ever-changing profile of the bottom causes large boils and eddies when the tide is flowing strongly in the lower Bay. Vertical and horizontal mixing can be complete during some stages of the tide, but often, during flooding tides, conspicuous lines are formed in the lower Bay where clear, greenish ocean water meets turbid, brown water that ebbed from the upper Bay.

Circulation patterns in Winyah Bay are heavily influenced by tides and wind. Flooding tides direct currents landward, while ebb tides reverse this flow direction. Bottom flow is usually up river (landward) and can carry salty water several kilometers upriver of the Highway 17 bridges, even farther during periods of drought when river discharge is low. Tidal effects can be observed 100 or more kilometers upriver as the flooding tide slows river discharge and results in temporary increases in the depth of freshwater in the rivers. This is followed by decreases in depth as the tide ebbs in the lower Bay. It is not uncommon to see blue crabs, flounders, red drum, striped mullet, and dolphins tens of miles upriver during prolonged droughts, as happened in the year 2002.

The main axis and channel of Winyah Bay orients NW-SE for almost 30 km and has a surface area of about 155 km^2. Because of the high amounts of sediment suspended in the riverine discharge, Winyah Bay's main shipping channel must be dredged one or more times each year to maintain the federally authorized navigation channel depth of 8.3 m, while mean depth is 4 m. Ocean-going freighters regularly use the Port of Georgetown, and sustained dredging is critical for the economy of the area. Due to a shortage of funds, major dredging of the ship channel did not occur between 2006 and 2013, and the accumulation of sediments created channel depths in some reaches that prohibited the passage of large ships.

There are many, mostly marsh, islands in Winyah Bay. A series of islands that lie along the eastern edge of the ship channel in the mid bay were mostly created from dredged materials in the 1800's. In recent decades, dredged materials from the mid and upper bay channel were deposited in upland impounded areas on Hobcaw Barony, Hobcaw Point, or adjacent to the Sampit River. Materials from the lower bay have been loaded into a hopper ship and dumped in the ocean outside of the jetties.

One major feature of Winyah Bay is a particularly shallow area in the middle bay called Mud Bay (called Muddy Bay by many locals). This shallow lagoon lies east of the ship channel, southwest of the North Inlet estuary. Being off of the main stem of tidal flow, current velocities in Mud Bay are lower which favors the accumulation of fine sediments. Most of this area is not navigable even with small boats near low tide, but it is an important area for fishes, shrimps, and crabs. No Man's Friend, Haulover, and South Jones Creeks connect Mud Bay to North Inlet. The dynamics of the tidal exchanges that occur there are described in the North Inlet section.

» Water Quality in Winyah Bay

SALINITY

Winyah Bay's surface salinities are considerably lower than North Inlet's most of the time and range from essentially zero at the surface up-estuary towards the river mouths to oceanic salinities at its juncture with the Atlantic Ocean. There is a salt wedge on the bottom that can extend many miles landward away from the ocean, especially during periods of low runoff, low river discharge, or drought. Allen et al. (1984) documented strong salinity stratifications in Winyah Bay, with haloclines present throughout the year especially at stations nearer the mouth of the estuary. Water circulation in Winyah Bay is complex and salinities at a single location in the middle of the bay can vary by 20 or more in one tidal cycle. High spatial and temporal variability in salinity creates conditions that are physiologically challenging for animals that need to regulate their internal levels of salt. Accordingly, only organisms with wide tolerances and abilities to respond quickly to changes live in the middle and upper bay.

The NI-WB NERR SWMP effort to characterize water quality in Winyah Bay is limited to the operation of a single station in the mid-bay. The Thousand Acre SWMP site is located inside a shallow subtidal channel at the western side of the brackish Thousand Acre Marsh. Tidal exchange is with Mud Bay, the large lagoonal extension of central Winyah Bay. Some typical examples of the temporal variability seen in salinity at the Thousand Acre Marsh monitoring station are presented below.

The data in Figure 46 were collected during a period of low river and watershed runoff. A slight tidal salinity signature is evident as water flooding from the lower bay elevates salinities by 4 or 5 around high tide. However, salinity varies considerably over the course of a year (Figure 47). The intermediate salinities measured on July 3-4, 2010 were preceded by a period of lower salinities in June due to a major inflow of freshwater to the estuary starting around June 1st. Decreasing freshwater inflow through July resulted in much higher salinities by mid-July when another freshet began. The 12-month record showed salinities in the 0-5 range during winter and 10-15 range in the fall.

The seasonal means for 2010 and other years between 1994 and 2010 are shown in Figure 48. The lowest salinity values in the time series occurred during winters, but winter was not the lowest season during every year. The lower overall salinities observed in the 1990s reflect the frequent occurrence of El Niño events in winter and spring during that decade. The major droughts of 2000-2002 and 2007-2010 are also evident with high salinities during those periods. Although not shown in the plot, there was a significant long-term

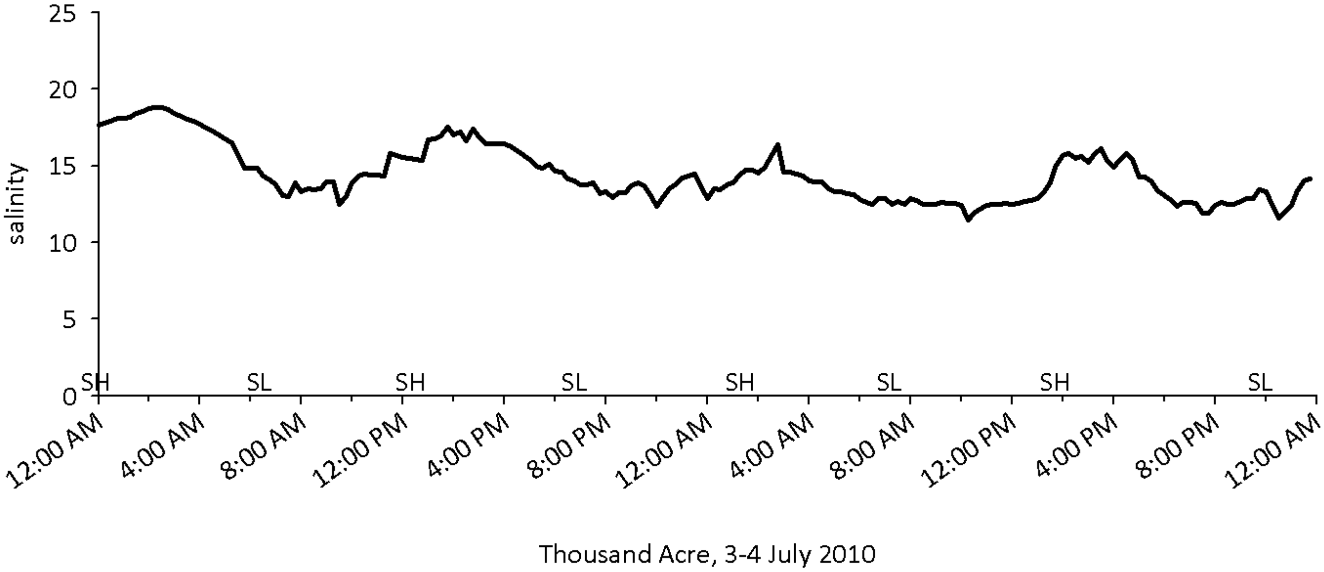


Figure 46. Salinity data collected at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

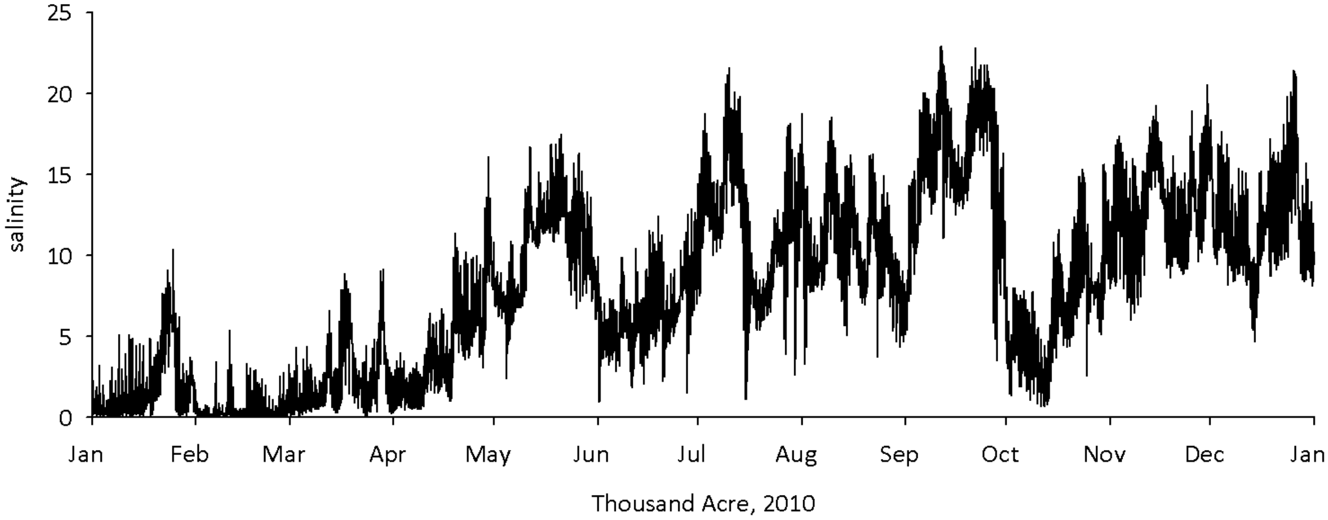


Figure 47. Salinity at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

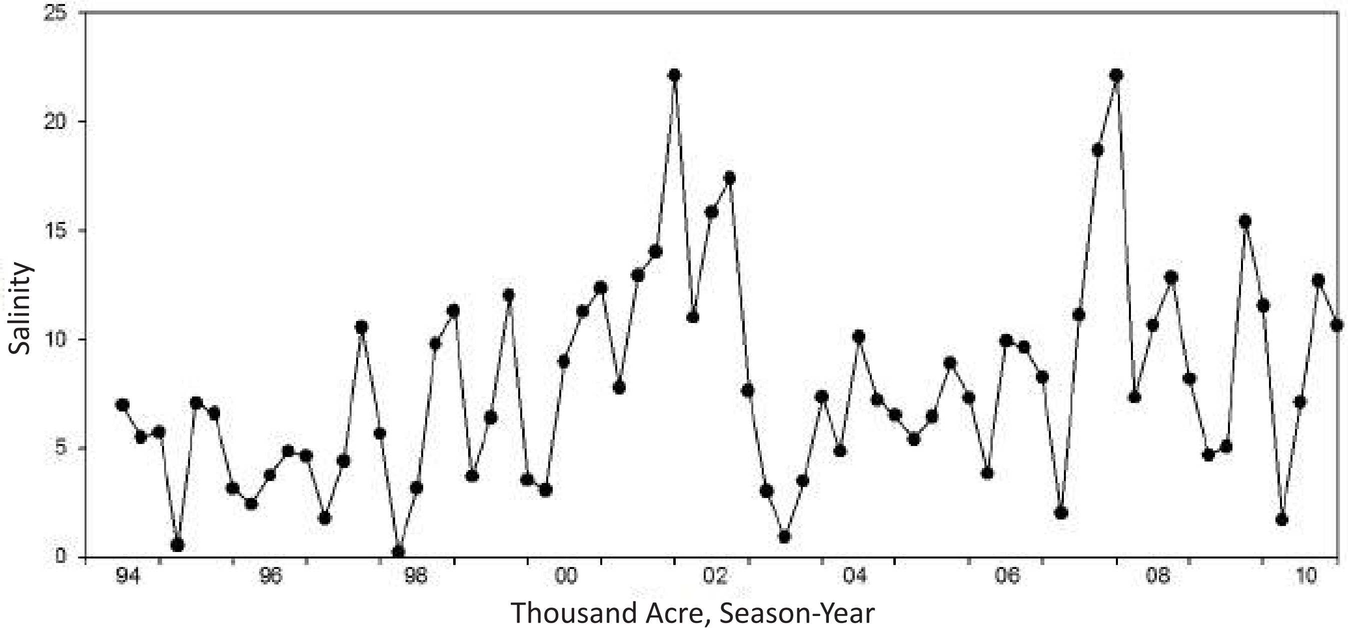


Figure 48. Mean seasonal values for salinity from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

increase in mean seasonal salinity over the 15 year period. This was related to the long-term significant decrease in discharge from the Pee Dee River which accounts for about 90% of the freshwater entering the estuary from all five rivers.

Many other studies in Winyah Bay address salinity, but almost all of these studies were primarily focused on the dynamics of nutrients, suspended sediment, phytoplankton, or animal populations. Goni et al. (2009) measured salinity while examining river discharge effects on particulate organic matter in Winyah Bay. Robinson et al. (2000) is an unpublished undergraduate study on recruitment of benthos as affected by runoff and subsequent changes in salinity in Mud Bay in Winyah Bay.

WATER TEMPERATURE

Winyah Bay's water temperature follows the same seasonal pattern as in North Inlet but is lower (to about 4^{o} C) in winter and often higher (to 32^{o} C) in summer. The average low is 6^{o} C and average high 28^{o} C, and there is a regular decrease in water temperature with depth where there is little to no vertical stratification or thermocline formation most of the time (Allen et al., 1984). Bottom temperatures hover around 4-5^{o} C in winter and around 27-28^{o} C in summer (Allen et al., 1984). The shallowest expanses of Winyah Bay, including Mud Bay and Thousand Acre Marsh, can warm more quickly during warm spring days than the deeper portions of the Bay. Conversely, water in shallow sections of the bay can chill by several degrees during a cold early fall night. The effect of cooler overnight temperatures can even be detected in the summer, as different water masses move past fixed locations with the tides. Figure 49 shows that on July 3 and 4, 2010 water temperature decreased overnight as waters in the shallow Thousand Acre Marsh ebbed down the creek toward the NI-WB NERR SWMP site at the confluence with Mud Bay. The plot also shows a rapid increase each morning during mid-flooding tide, a result of warmer water from Mud Bay entering the creek and displacing the cooler water that had drained past the monitoring station with the previous ebbing tide.

Diel, tidal, and diurnal changes in water temperature are evident in the plot of 15 minute data over the 12 months of 2010 (Figure 50). Water temperature was highest and most stable from

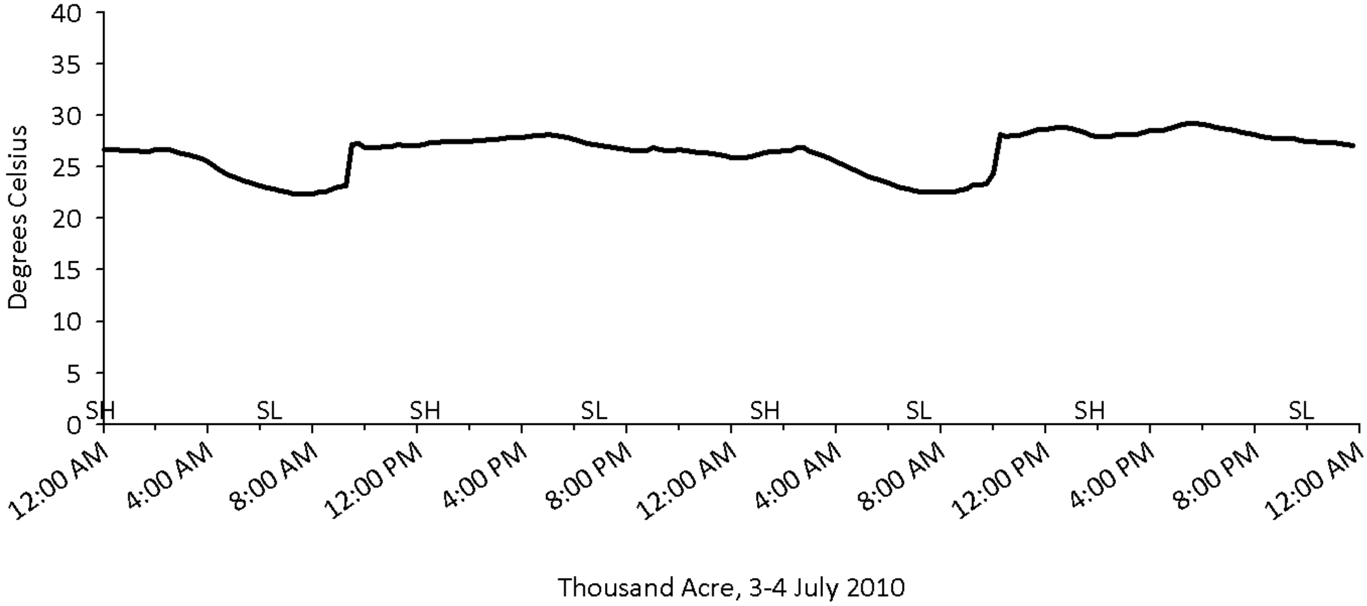


Figure 49. Water Temperature measured at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

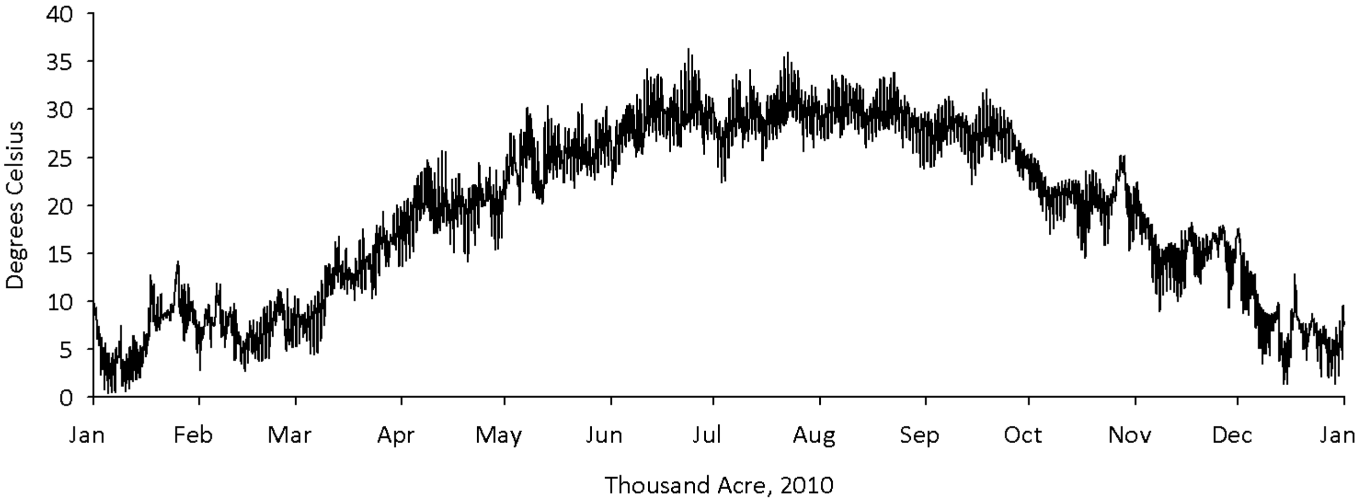


Figure 50. Water temperature at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

May through September. Except for some short intervals of especially warm (~35° C) and cool (~23° C), water temperature was usually between 25-30° C during this five month period. In 2010, the lowest temperatures occurred in January and December, when the shallow waters cooled to 1 or 2° C for days to weeks at a time.

A plot of the mean seasonal water temperatures from 1994-2010 (Figure 51) indicated that winter 2010 was the coldest in the time series. Summer 2010 was the warmest of all of the years. Observed changes in extremes and thus variability in temperature records have become widely recognized in the last decade or two and these are often referred to as evidence for a changing climate.

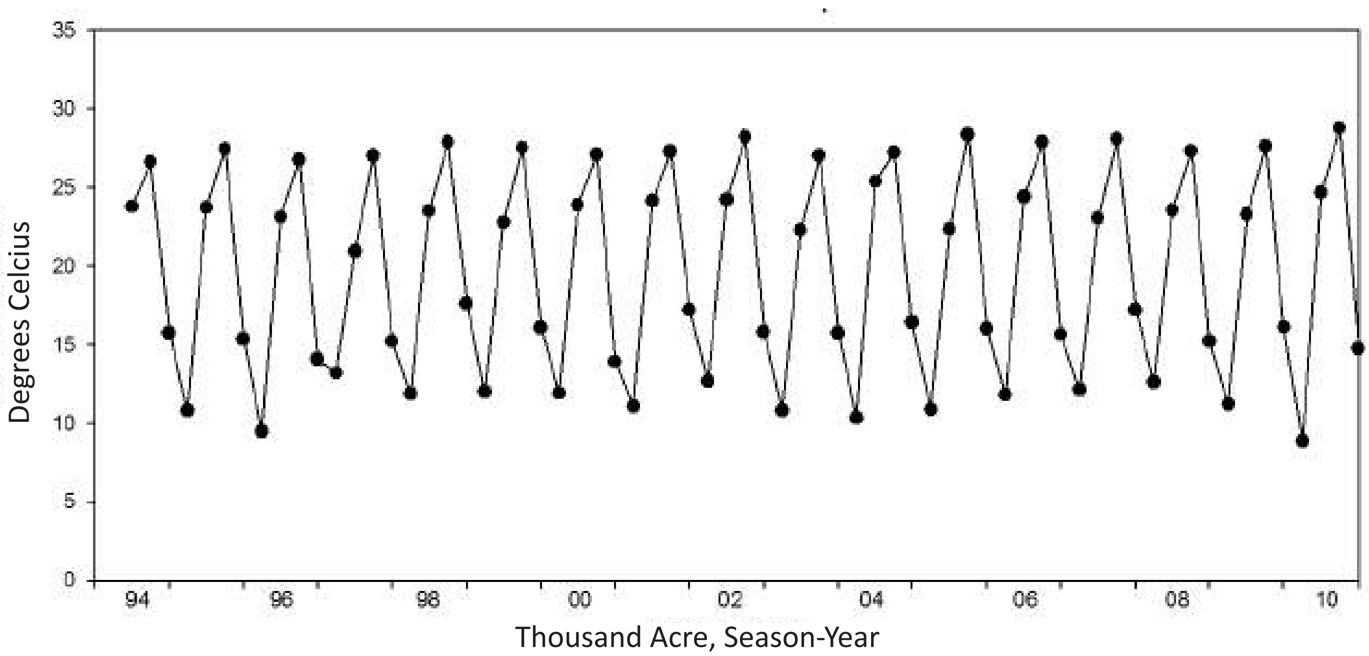


Figure 51. Mean seasonal values for water temperature from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

PH AND REDOX POTENTIAL

The SCDHEC STORET database for Winyah Bay showed no regular pattern of pH change at the MD080 station by the Georgetown bridge (Highway 17) over a ten-year period (1977-1986) when it ranged between 4.9 and 8.2 (Blood and Vernberg, 1992). Surface waters at that station are usually brackish, not salty.

SEDIMENTS AND TURBIDITY

The rivers emptying into Winyah Bay carry runoff and frequent heavy suspended sediment loads that either settle in the estuary or get transported seaward. Non-riverine, direct watershed runoff also enters the system along with aerial inputs of dust particles. The flow of fresh, brackish, and saline waters in Winyah Bay is complex (Kim and Voulgaris, 2005) and responds to the semi-diurnal tidal cycle for miles upstream. Some of the rivers have dams that sequester much of the sediment load that would otherwise move seaward or be deposited in the lower reaches of the estuary. Based on the sediment budget for the drainage basin for North Inlet and Winyah Bay reported by Phillips (1991), only about 4% of the gross eroded sediment reaches Winyah Bay on a yearly average. This is because the system is “transport limited”, i.e., there isn’t always enough flow to move all the sediment in the system seaward. Thus dredging is required to maintain channel depths for ocean going ships to reach the Port of Georgetown, which is about 17miles (29 km) from the ocean.

Secchi disc depths in Winyah Bay are typically less than one meter and can be even less than 0.5 m in Mud Bay (Allen et al., 1984). Turbidity is highly variable in estuaries on times scales of minutes to hours. The data in Figure 52 show that even in a two day period, turbidity can vary by a factor of up to 25. High short-term spikes in turbidity can result from the introduction of a large sediment load following a rain event that eroded sediments off the marsh or from a major disturbance such as a boat wake or resuspension due to a school of bottom-feeding fishes close to the sensor. Typically turbidity is higher around mid-tide when currents are at peak velocity and fine bottom material is most easily resuspended. Figure 52 also shows the tendency for the lowest values to occur around slack tide when the water is clearer.

Short-term spikes in turbidity occur throughout the year but are most frequent and highest during summer when thunderstorm frequencies and the activities of major bioturbators are greatest (Figure 53). Turbidity is lowest from January through March.

Year-to-year differences in turbidity were recorded from 1994 – 2010 at Thousand Acre Marsh (Figure 54). The seasonal pattern for tubidity is less regular than for the other physical properties measured at this site. The highest turbidity values occurred from 1998 – 2002 with the highest value in the time series occurring in winter 1998. During most years, winter is the season with the lowest turbidity of the year. Lower values from 2003 – 2010 could be related to lower rainfall and river discharge following El Niño years in the 1990s.

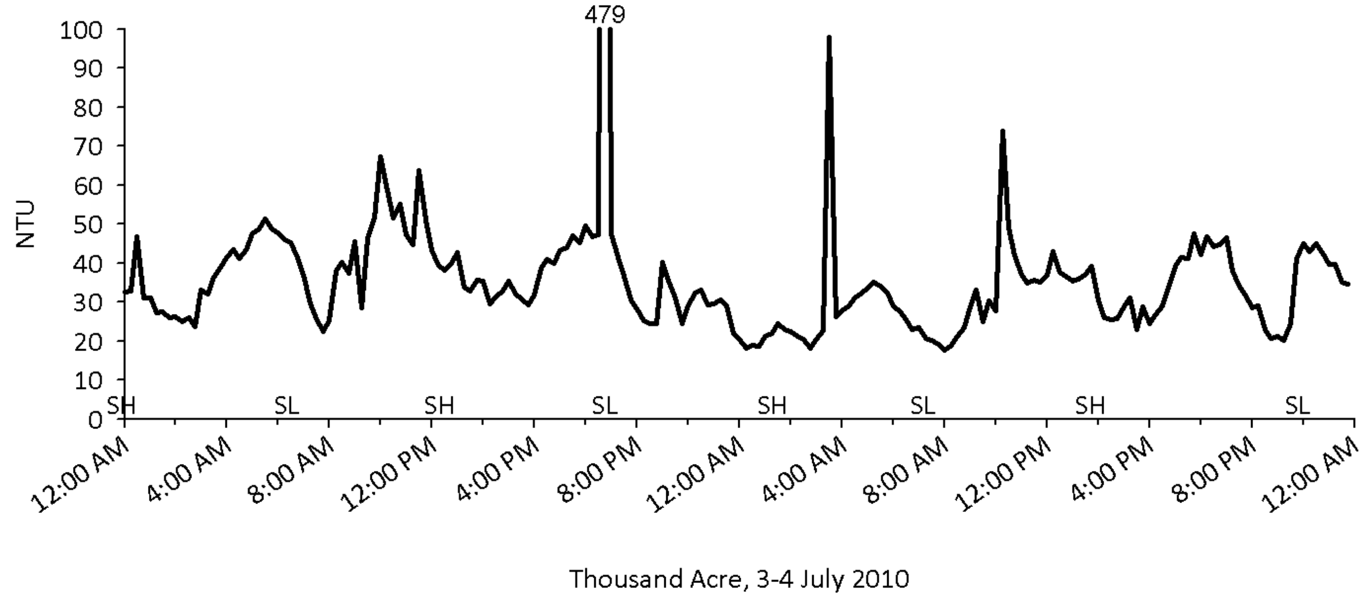


Figure 52. Turbidity (Nephelometric turbidity units) at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

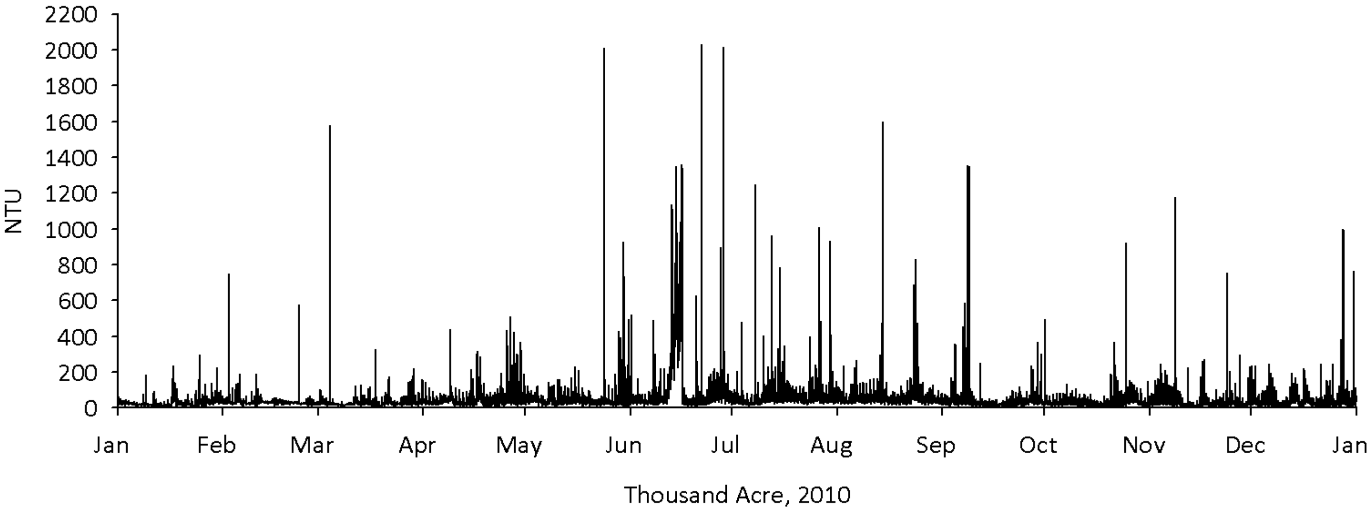


Figure 53. Turbidity (Nephelometric turbidity units) at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

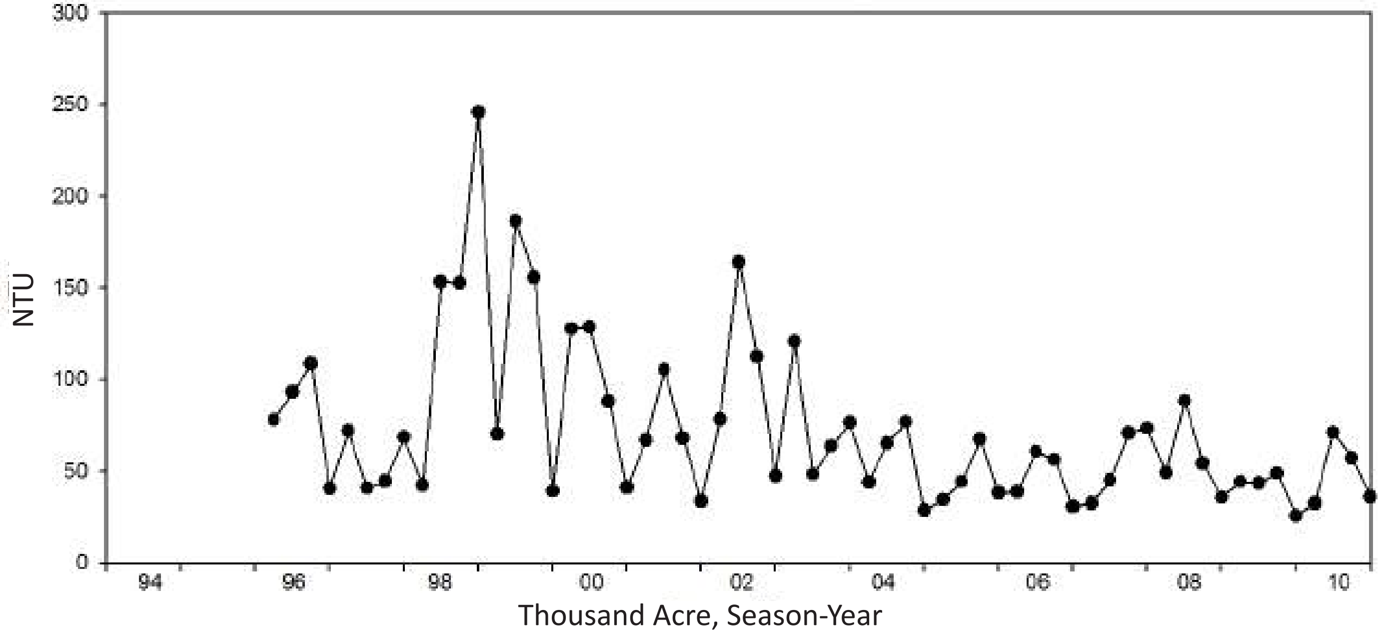


Figure 54. Mean seasonal values for turbidity (Nephelometric turbidity units) from Spring 1994- through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

SUMMARY OF OTHER STUDIES ON TURBIDITY IN WINYAH BAY

Coen (1995) provided a review of the potential impacts of mechanized shellfish harvesting methods. Harvesters typically produce lots of turbidity while bringing clams or oysters up from the bottom. As mechanical harvesters have been permitted and used in Winyah Bay just to the south of Mud Bay, there may be elevated levels of suspended sediments in the water during harvest times.

Patchineelam et al. (1999) constructed a preliminary sediment budget for the Winyah Bay estuary. They determined that only about 50% of the watershed's sediments reach the coast. In Mud Bay, the part of the Winyah Bay estuary that lies within the NI-WB NERR boundary, sedimentation is high, averaging about 5.5 mm per year. They estimated that 80% of the fine-grained sediments (by mass) accumulates in adjacent marshes and mud flats or gets removed by dredging activities and is deposited offshore. Despite the amounts of sediment entering the Winyah Bay system, only a small amount of fine-grained material actually reaches the coastal ocean.

Patchineelam and Kjerfve (2004) continued their work in Winyah Bay by measuring suspended sediment concentrations in the water column in 1996 during a transient estuarine turbidity maximum event. The salt-freshwater interface was pushed 8 km seaward by the exceptionally high river discharges. In the turbidity maximum layer at the pycnocline, sediment concentrations changed between ebb and flood tides. Bottom layers accumulated as much as 30 g/m^3 during slack tides, and sediment was re-suspended by tidal currents. The turbidity maximum layer was enhanced by flood tides and diminished in concentration by ebb tide as turbulence was inhibited.

Goni et al. (2003) measured particulate organic matter in the water column of Winyah Bay at stations along a down-bay transect and in Mud Bay. They were interested in the seasonal changes of these allochthonous (arriving from elsewhere) inputs to the estuary. Suspended sediments and their associated organics were partitioned into their carbon and nitrogen constituents. Using stable isotope analyses, they determined that sediments and their organics landward up-bay from the mouth were terrestrial in origin, while those at the lower end of the bay were from tidal inputs. As organic carbon was the focus of the study, other results will be discussed in the "Carbon" section below.

Goni et al. (2005) sampled the turbidity maximum zone in the water column of the upper reaches of Winyah Bay to study how suspended sediments influence their associated organic matter. Total suspended sediment (TSS) concentrations ranged over two orders of magnitude (50 – 400 mg per liter) depending on depth sampled and stage of the tide and were not correlated with salinity. As this study was conducted outside the boundaries of the NI-WB NERR, their geochemical analyses will not be discussed until later. TSS exhibited non-conservative mixing behavior in the estuary and had higher concentrations in the lower portion of the bay nearer the ocean and with depth at all stations sampled.

DISSOLVED OXYGEN

The NI-WB NERR SWMP water quality monitoring station at Thousand Acre Marsh records dissolved oxygen. Repeatable patterns were evident in a plot of the 15 minute data from July 3 and 4, 2010 (Figure 55) where levels were highest around high tide and decreased through the ebbing tide each day and night. The rapid large increase in dissolved oxygen concentration during the beginning of each flooding tide is interpreted as the arrival of more oxygenated water from Mud Bay. Lower ebb tide values at the monitoring station could be due to the persistence of organic-rich water with high biological oxygen demand (BOD) in the creek.

Short-term variability in DO was also evident in the 12 month record for the site (Figure 56). Due to tidal and diel fluctuations, 8- 12 mg/L changes were not unusual within a day or between consecutive days during the summer. Despite that 'noise' in the data record, DO was generally lower from May through October than during the coolest months of the year.

The plot of seasonal mean values for DO showed more regularity from 2002-2010 than for the 1990s (Figure 57). The lower incidence of El Niño-related rain events and reduced river discharge into Winyah

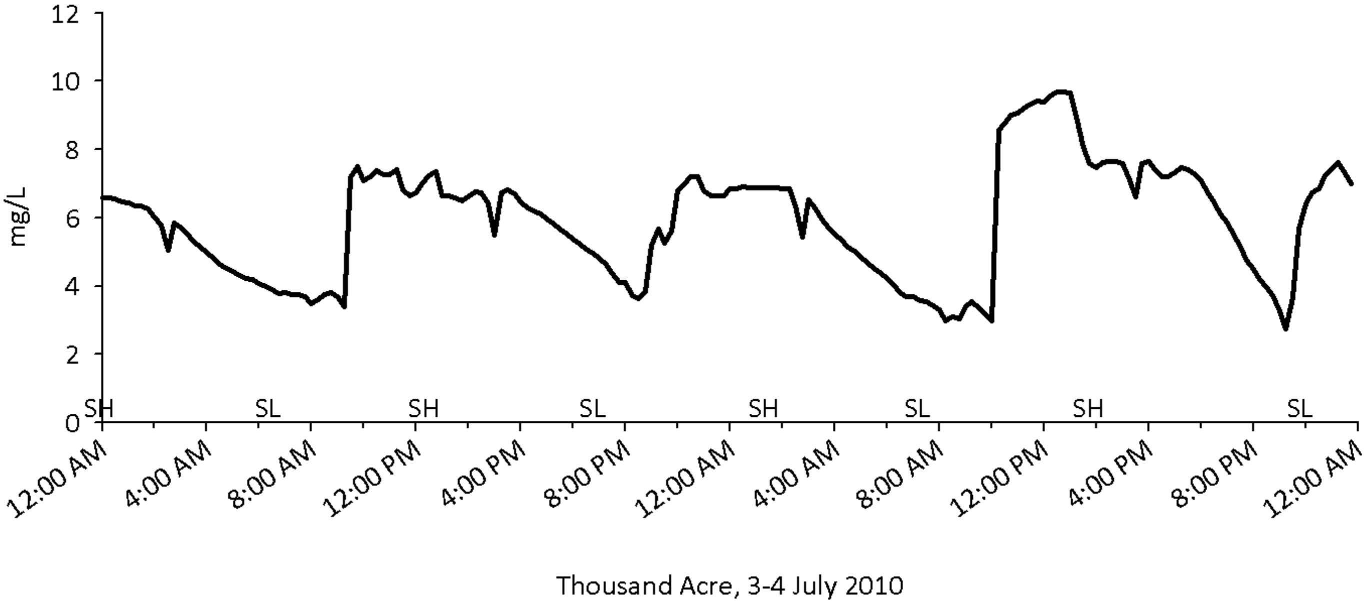


Figure 55. Dissolved oxygen data collected at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

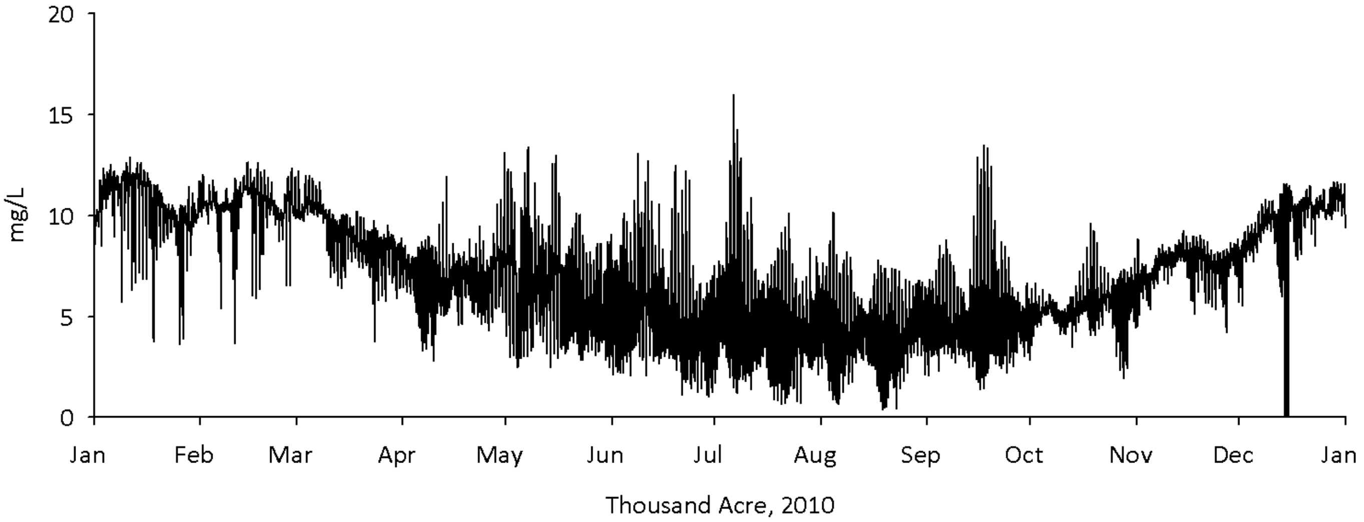


Figure 56. Dissolved oxygen at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

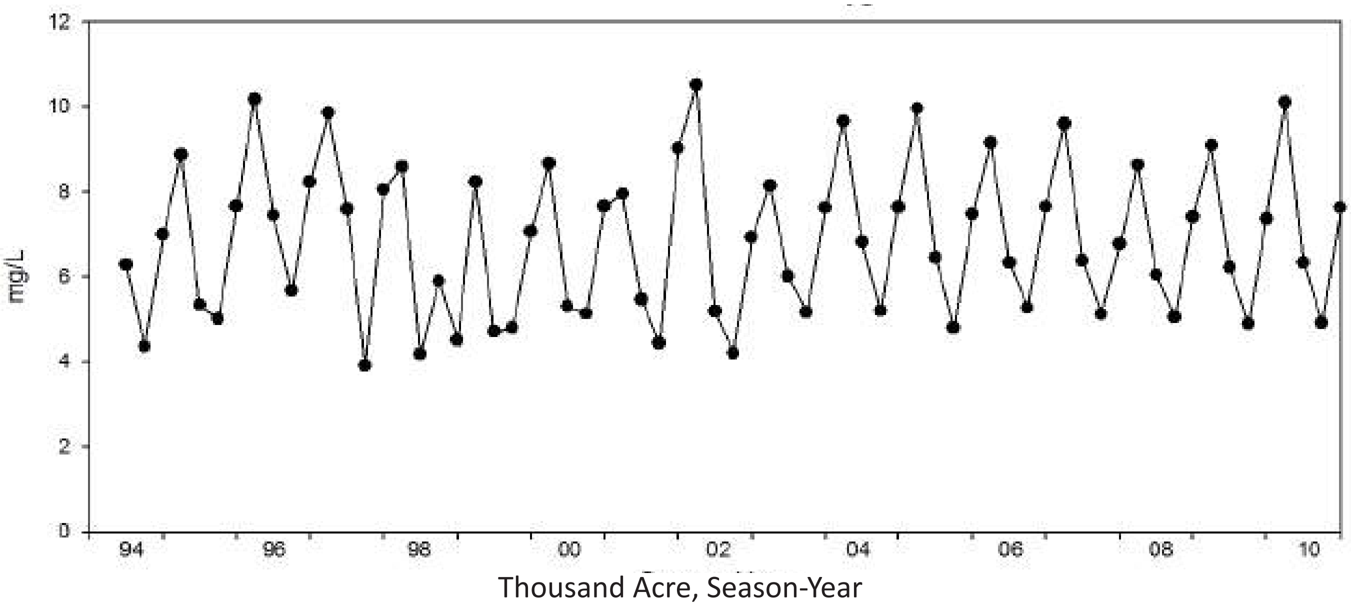


Figure 57. Mean seasonal values for dissolved oxygen from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh..

Bay could have had some influence on this pattern, as major influxes of sediment rich in BOD were less common during winters and springs after 2001.

It is important to remember that the discussion of dissolved oxygen data from the Thousand Acre Marsh SWMP site is not necessarily applicable to Winyah Bay as a whole. This site is clearly influenced by the surrounding marsh, the tidal creek, and source water from the shallow Mud Bay area. Dissolved oxygen is expected to be higher in open waters, especially near the channels where tidal currents are strong. Based on the SCDHEC STORET database for the upper station near Highway 17, Winyah Bay's DO concentration is high and nearly saturated in winter and lowest in summer (Blood and Vernberg, 1992).

» Water Chemistry in Winyah Bay

NUTRIENTS

The NI-WB NERR 20-day water chemistry monitoring database, described in the North Inlet nutrient section, began sampling all tidal stages (day and night) in June 1993. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Thousand Acre Marsh monitoring site can be used to characterize both short- and long-term patterns in Winyah Bay. A 20-day sampling event in July 2010 showed that nitrate+nitrite (NN), ammonium (NH_4^+), and orthophosphate (PO_4^-) concentrations are influenced primarily by tide and not time of day (Figure 58). For this particular sampling period, NN levels were lower during slack low tide, whereas NH_4^+ and PO_4^- were at higher concentrations at slack low tide. Both NN and NH_4^+ levels were about an order of magnitude higher than PO_4^-.

A 2010 yearly plot of these nutrients at the TA site puts the July 3-4 values in context with the rest of the 20-day data for that year (Figure 59). July 2010 NN concentrations ranged from 6 to about 15 micromoles per liter, intermediate between the year's high and low values. Winter and spring had higher and more variable levels of NN, ranging from about 3 to 30 micromoles per liter. Figure 59 demonstrates that NH_4^+ and PO_4^- had the highest values (NH_4^+ with 28 and PO_4^- with 4 micromoles per liter) and the greatest amount of variability from about April/May through December. Winter NH_4^+ and PO_4^- levels were much less variable and had lower concentrations.

A plot of seasonal mean nutrient values shows differences within and among years, as well as long-term trends. Figure 60 indicates that fall NN values are the lowest (between 3 to 7 micromoles per liter), and winter and spring concentrations are typically the largest. NN values were highest from 2003-2007. Concentrations of NN were lower and less variable during drought years (latter part of 1999 through 2002). The long-term trend of NN in Winyah Bay appears to be increasing, with 2008 through 2010 having the highest average seasonal concentrations on record so far.

Thousand Acre Marsh NH_4^+ seasonal averages show an increasing trend from 1994 through 2010 (Figure 60); the latter 3 seasons in 2010 are some of the highest levels in the entire time series. The highest ammonium seasonal average (about 8 micromoles per liter) was observed in 1998, the year of one of the strongest El Niños in 100 years. For PO_4^-, there was a slight increase in values over the seasons/years (Figure 60). Unlike NH_4^+, orthophosphate levels did not increase during the 1998 El Niño; however, the 2003 El Niño had the highest concentrations (≥ 1.4 micromoles per liter) in the entire seasonal series (spring and summer).

SUMMARY OF OTHER NUTRIENT STUDIES IN WINYAH BAY

Between August 1980 and September 1982, Allen et al. (1982, 1984) conducted extensive and intensive sampling in Winyah Bay, including stations in Mud Bay (their PS and MB), and one adjacent to Thousand Acre marsh (their TA station). They measured physical, chemical, and biological components at 14 total sampling sites mostly along the main channel axis. These data still serve as a baseline for future studies conducted in the bay. Orthophosphate was present in low concentrations throughout the year, and it increased when river runoff was high. When primary productivity increased, orthophosphate and total phosphorus decreased greatly. Nitrogen concentrations were closely related to riverine inputs. Short-term variability was as great as long-term, seasonal variability. Total nitrogen, total dissolved nitrogen and nitrate-nitrite followed a general pattern of conservative mixing in the bay. In their earlier study at No Man's Friend and South Jones Creeks, total nitrogen tracked phytoplankton abundance (Allen et al., 1982). That is, it was low when chlorophyll-*a* concentrations were high.

Mackin and Aller (1984) measured the amounts of ammonium, NH_4^+, adsorbed onto sediment particles in Mud Bay and in Cooks Creek in North Inlet. Adsorption was insensitive to temperature changes. Aller and Yingst (1985) examined adsorption kinetics of sediment porewater as affected by the presence/

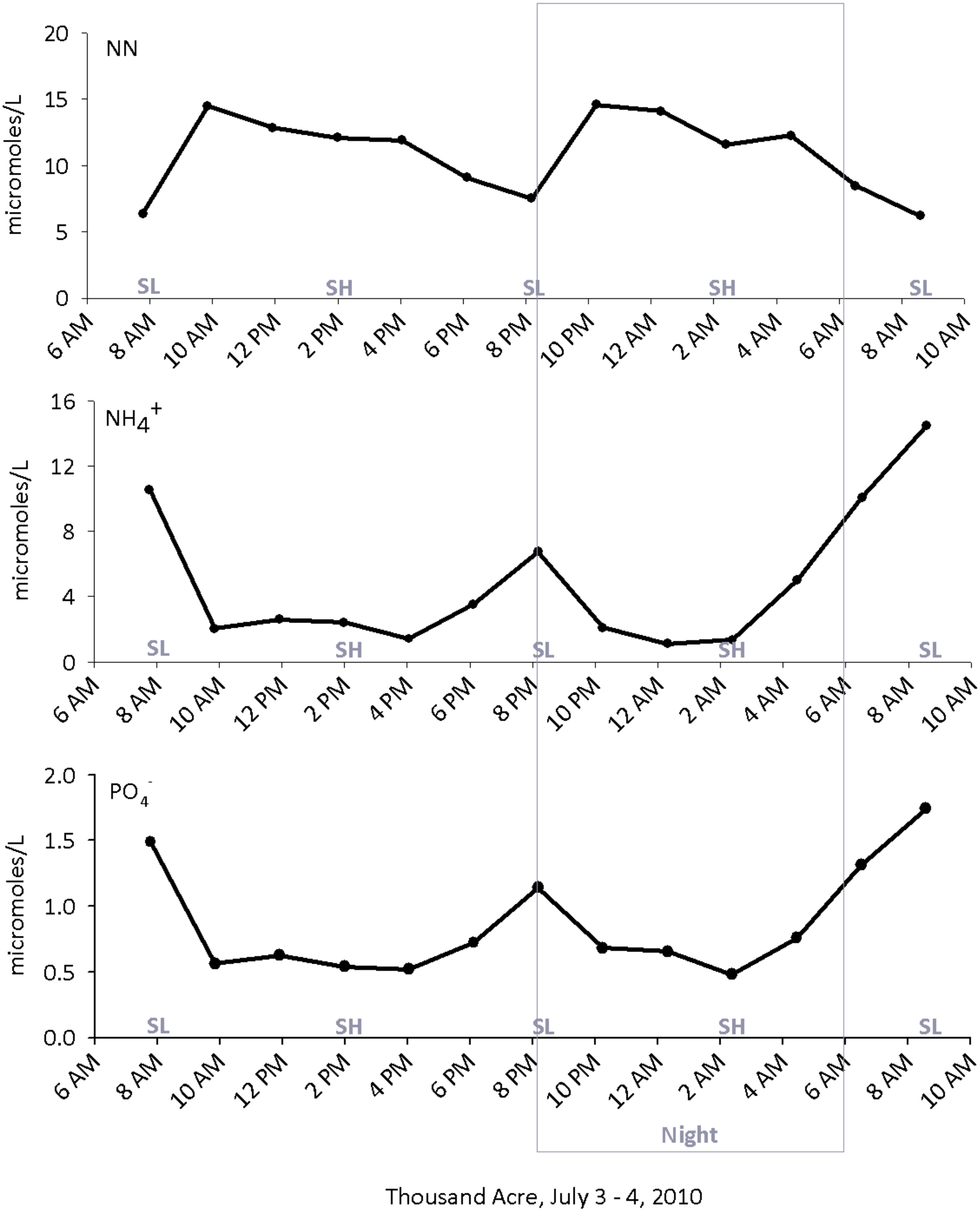


Figure 58. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

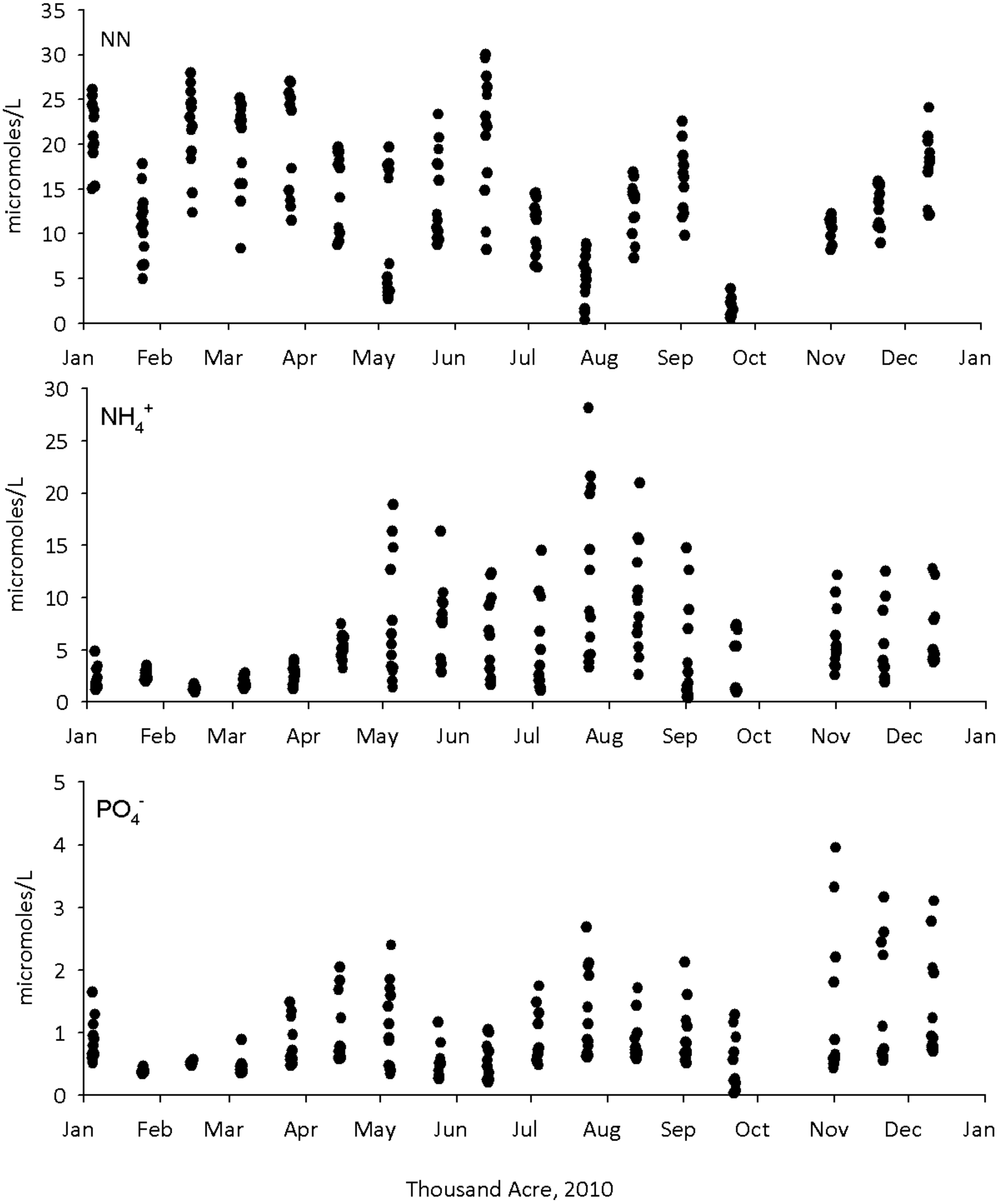


Figure 59. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour sampling event.

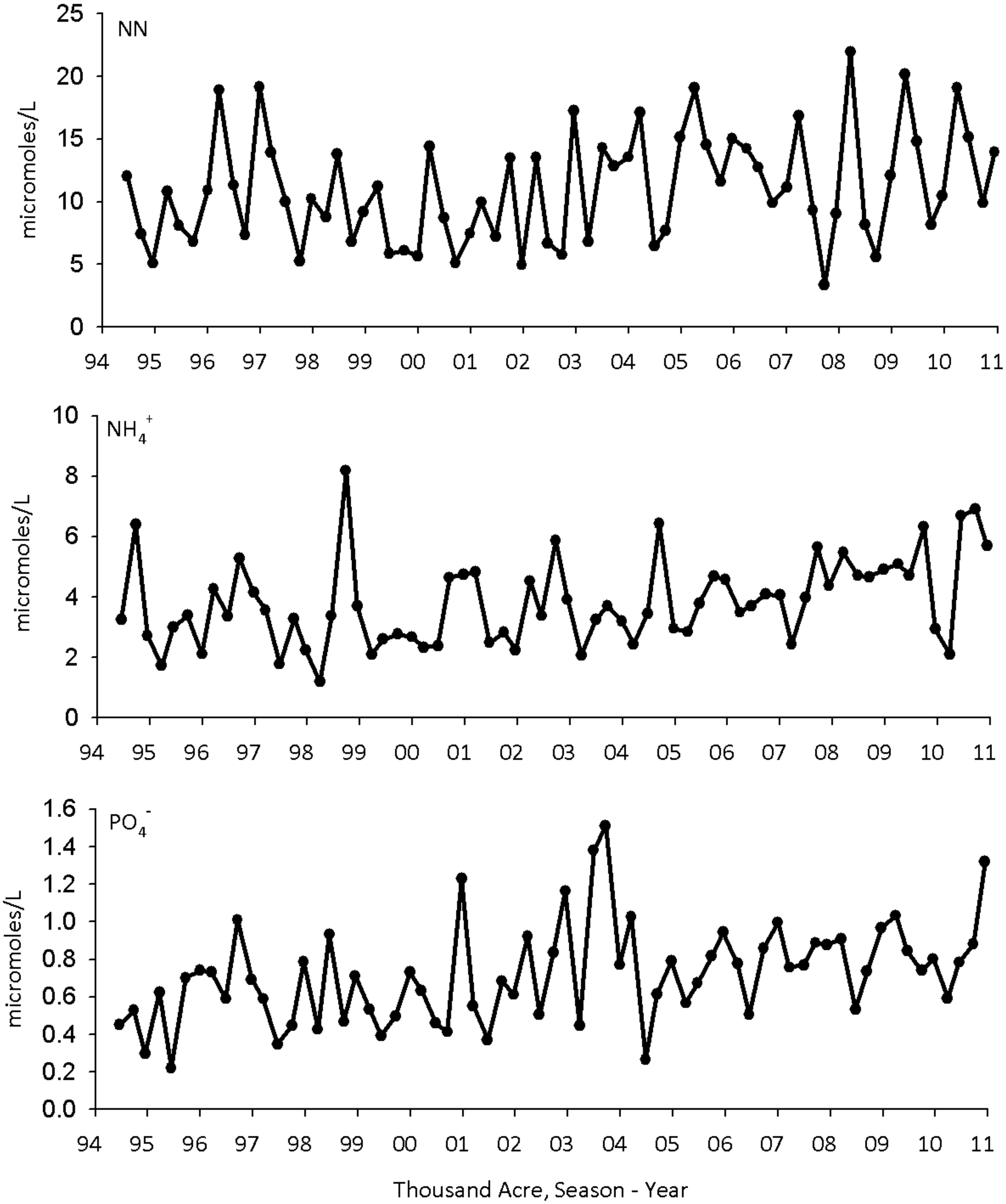


Figure 60. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each sampling event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

absence of macrobenthic fauna. They collected sediment from Mud Bay for their aquarium-based experiments and found that organisms greatly alter the reaction rates for adsorption processes. Models of the process were constructed and validated with their empirical data. Ullman and Aller (1982, 1983) had earlier measured pore water diffusion rates and iodine remineralization rates, respectively, using Mud Bay sediments. Aller and Aller (1998), based on earlier experiments with Mud Bay sediments, concluded that remineralization rates for a variety of pore water chemical and elemental species are greatly altered by the presence of burrowing macrobenthos that irrigate their burrows. That is, decomposition of organic matter is accelerated by the enhanced solute transport activities of these organisms.

Winyah Bay waters enter North Inlet at high tide and under wind stress at other times. This intrusion carries significant amounts of nutrients that are partially utilized within North Inlet and may be exported out the mouth of North Inlet under certain conditions. The connections between these two bodies of water require more study, because continued coastal development's effects on the Winyah Bay drainage basin will ultimately affect the waters of North Inlet.

CARBON

The NI-WB NERR 20-day water chemistry monitoring program also collects and measures dissolved organic carbon (DOC). These collections and results are not formally part of the NERR System-Wide Monitoring Program (SWMP), but they are a part of the USC Baruch Institute's long-term monitoring programs. The NI-WB water chemistry collection protocols require sampling at all tidal stages (day and night). Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Thousand Acre Marsh monitoring site is used to characterize DOC levels on both short- and long-term time frames in Winyah Bay. A 20-day sampling event in July 2010 shows that DOC concentrations were influenced primarily by tide (Figure 61) rather than time of day. Slack low tide DOC values were higher by about 3 to 6 milligrams per liter than during slack high tide. Figure 62 illustrates that this July 2010 sample was typical of DOC concentrations throughout the year; the exception was May when levels were over 25 milligrams per liter.

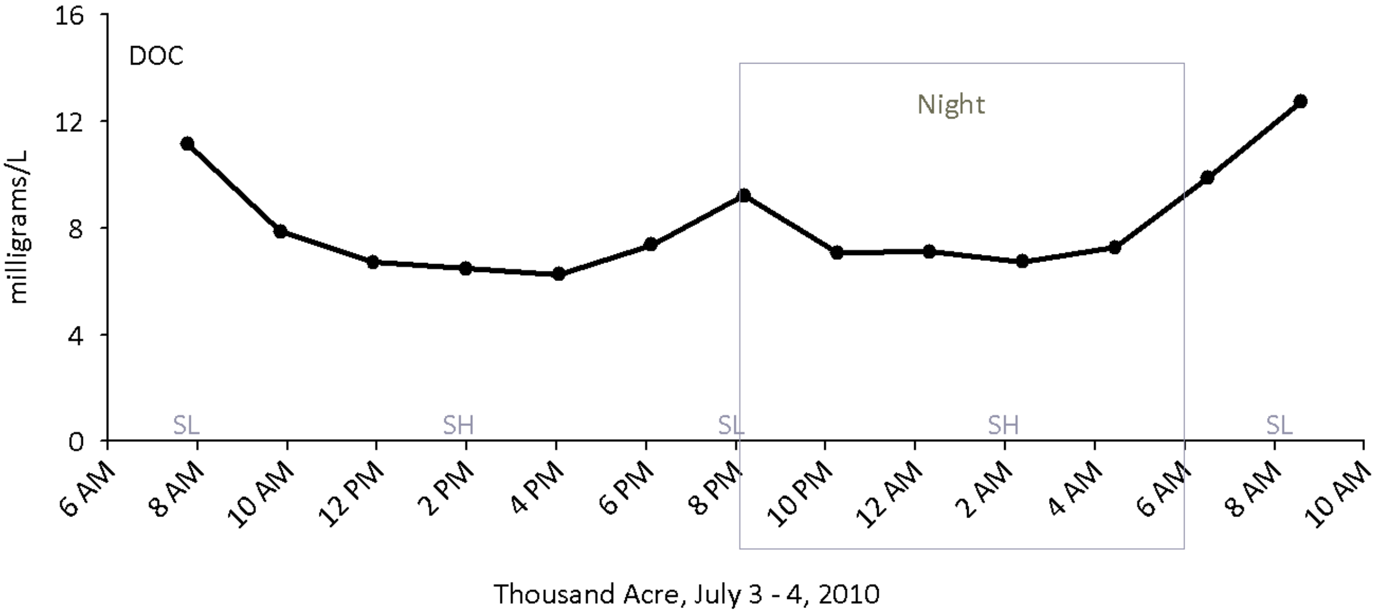


Figure 61. Thousand Acre Marsh dissolved organic carbon (DOC) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

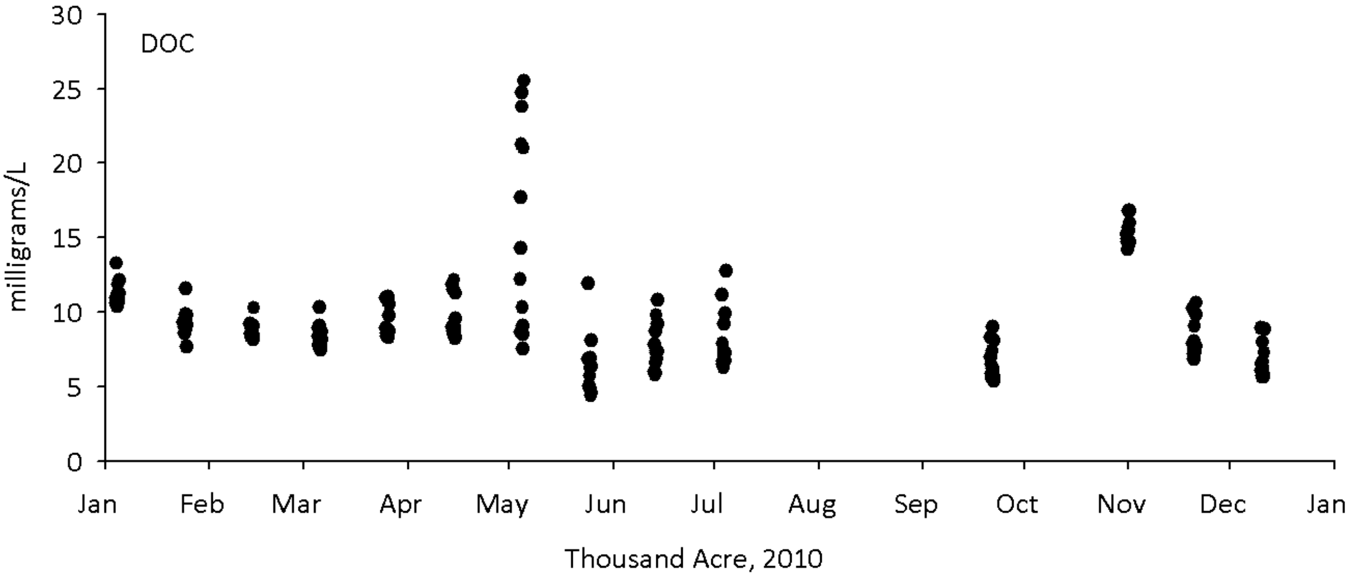


Figure 62. Thousand Acre Marsh dissolved organic carbon (DOC) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour sampling event.

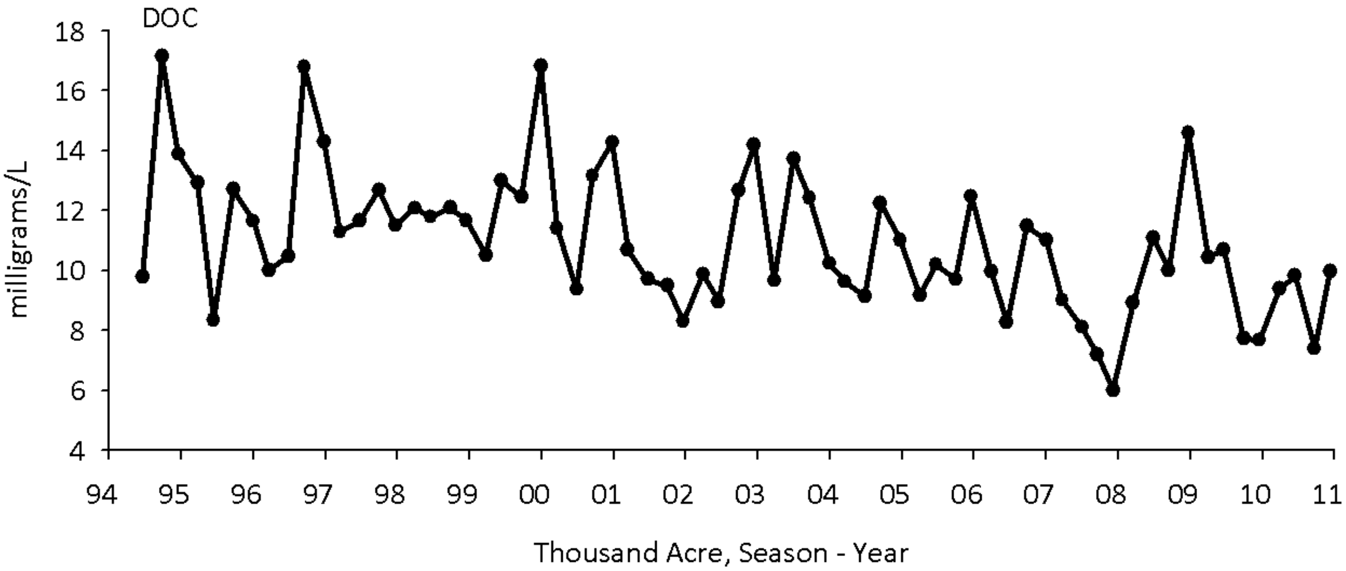


Figure 63. Thousand Acre Marsh dissolved organic carbon seasonal average concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each sampling event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

Figure 63 demonstrates seasonal differences within and among years, with the greatest concentrations of DOC occurring from 1994 through 2000. The strong El Niño years 1998 and 2003, which had larger amounts of rain, did not have high seasonal DOC values. Even though high concentrations were recorded in 2002, 2003, and 2008, a decreasing trend for DOC was evident in Winyah Bay.

SUMMARY OF OTHER STUDIES ON CARBON IN WINYAH BAY

Eddins et al. (1999) collected oxic bottom sediments with a grab sampler from Winyah Bay during five months that spanned the seasons in 1996. Their sampling transect from the mouth of the bay up to the Pee Dee River was entirely along the main channel axis. No samples were taken within the NERR boundary. They measured bulk organic carbon content (as weight %) and the stable carbon isotope ratio, *del*-^{13}C / *del*-^{12}C, on fine and coarse fractions of the sediment. The % OC for the fine fraction ranged between 2 and 10%, while the coarse fraction ranged between 1 and 12%, but only 12 % of the data exceeded 2% for coarse material. The fine fraction exceeded 2% bulk OC at all stations. The upstream stations had more negative carbon isotope ratios than stations lower in the bay. Both size fractions followed this trend. This trend reflects the greater distance of the lower stations from terrestrial sources of carbon in C-3 plants that use the Calvin cycle photosynthetic pathway. Seasonal changes were not observed in either bulk carbon content or stable isotope ratios. Most of the variability in the isotope signatures was likely due to mixing of source material (C-3 and C-4 plants, phytoplankton) in the bottom sediments.

Eddins (1999) collected water samples (top 1 m, bottom 1 m) at the same times and stations mentioned above to measure bulk POC concentration and its *del*-^{13}C stable carbon isotope values. She wanted to estimate what fraction of the POC was derived from terrestrial sources. Both surface and bottom *del*-^{13}C varied linearly with salinity, and bulk POC concentration varied between about 1 and 15 mg L^{-1} with no significant differences between top and bottom water concentrations. The estuary is well-mixed. Seasonal changes in the isotopic values were slight. During the fall sampling period, the salt wedge extended upstream to the farthest station where salinity was 5 compared to 36 at the estuary mouth. A turbidity maximum layer also caused minor variations in POC and stable isotope values. Using end member values from the literature for marine carbon and empirically measured values from the samples collected, a mixing model was used to estimate the contribution of terrestrial carbon to the bulk POC. The percentage contribution increased along the transect with distance from the estuary mouth and ranged between 50 and 90%. Both of these studies have implications for evaluating the inputs, fate, and effects of particle-associated pollutants in Winyah Bay.

Goni et al. (2003) analyzed samples from a Winyah Bay transect that included six stations in Mud Bay inside the NERR boundary. They were interested in determining the sources and distribution of organic matter in the bay and used elemental and stable isotope and organic biomarker analyses to do so. Surface water samples and bottom sediments were collected seasonally in 1998. DOC was measured for all water samples as well as weight % organic carbon (% OC). River and upper bay samples had the highest DOC concentrations, while Mud Bay's and the lower bay's were significantly lower. Mud Bay's DOC levels were highest in March. The % OC in sediment samples ranged between 1 and 5 % but had no discernable trends spatially with stations or seasonally. DOC concentrations in Winyah Bay were typically higher than POC concentrations by almost an order of magnitude. Biochemical markers and other evidence suggested that most of the % OC in Winyah Bay sediments was from terrestrial carbon sources and little from the C-4 source (*Spartina*) that surrounds the bay.

Goni et al. (2005) measured the stable isotopes for carbon in POC samples from Winyah Bay that were associated with the turbidity maximum zone. They found that vascular plants (C-3) and estuarine algae were the source materials for most of the particulate organic matter sampled, with little contribution from *Spartina* (a C-4 plant) or marine phytoplankton. Their study transect was outside the NERR boundary, however.

Goni et al. (2009) revisited Winyah Bay and sampled along its main channel axis, with all stations outside the NERR boundary. The % OC in water samples ranged between 1 and 6% and was positively correlated with river discharge volume. This paper focused more on the physical factors (discharge, wind, sediment transport) that affect materials important in biogeochemical cycles. Winyah Bay is apparently an efficient trap for suspended particulate materials under both low and high discharge conditions. Particle export to the ocean at depth occurs only under very high discharge conditions. This tendency to retain particulates makes the bay more susceptible to pollutants, eutrophication, and salt intrusion.

» Contaminants

POLLUTANTS, TOXICOLOGICAL STUDIES

Allen et al. (1984) provided an overview of the potential impacts of petroleum on fauna in Winyah Bay, particularly fishes, zooplankton, and the larval stages of crustaceans found there. They divided the bay into three zones based on the salinity gradient from 0 to 35: upper (freshwater river inputs, very low salinity), middle (the mixing zone, brackish water), and lower bay (primarily marine waters). Each of these regions has different susceptibilities to hydrocarbon inputs in its fauna, flora and aquatic denizens. Chronic discharges of oil and related products would have long-term negative impacts, particularly in the middle and lower parts of the bay.

Kucklick and Bidleman (1994a) looked at PAHs and pesticides in Winyah Bay and North Inlet in the microsurface and subsurface waters. Atrazine was found in the highest concentrations in May 1990 and was present throughout the year. Fluoranthene and pyrene were found most commonly in both surface microlayer samples and in subsurface waters. Pesticides were not enriched in the microlayer samples, but PAHs were on average 18 X more than in subsurface samples. Kucklick and Bidleman (1994b) measured salinity and fluorescence in water samples in Winyah Bay during 1990 to trace dispersal and distribution of the triazine herbicide, atrazine, entering the bay from rivers and low-atrazine seawater. Atrazine is a pre-emergent herbicide used on corn crops. They deduced that the herbicide behaved conservatively within the flushing time of the bay (< 18 hr). Atrazine and several other herbicides were also detected in much higher concentrations in Winyah Bay than in North Inlet, but most were found there as well but in quite low concentrations. Malathion, used in mosquito control programs, was also found in North Inlet. Organic pollutants are delivered to Winyah Bay and North Inlet throughout the year, some possibly via atmospheric transport, but in highest amounts after times of application to crops in the Winyah Bay drainage basin. Kucklick et al. (1997) also sampled PAHs in surface sediments in Winyah Bay and elsewhere in SC and found them in highest concentrations in the harbor and in areas near urban runoff entering from small intertidal creeks, the largest source of pyrogenic PAHs, whereas petroleum based PAHs had a more rural source.

Dorsch & Bidleman (1982) found hydrocarbon concentrations of 0.7 to 1.8 micrograms/liter in Winyah Bay water using fluorescence to measure dissolved organic matter. This low concentration contributed negligibly to the fluorescence signal given off by DOM. Bidleman et al. (1990) used fluorescence spectrometry to measure hydrocarbons in Winyah Bay and again found microgram levels (0.23 – 9.6 per liter). They also found nanogram quantities of PAHs in water samples, one of which, perylene, was most abundant, possibly having originated from sediment dredging.

Long et al. (1996) reported results of sediment toxicity bioassays performed as part of the U.S. Environmental Protection Agency's EMAP-E (Environmental Monitoring and Assessment Program – Estuaries). Winyah Bay was one of 22 estuaries included in the survey that had been identified earlier as having toxic sediments. Only 9 bottom grab samples from there were tested in June 1993. Three tests, each designed for a different chemical phase of the contaminants, were conducted: amphipod survival on bulk sediments, sea urchin development using sediment porewaters, and a microbial bioluminescence test using organic solvent extracts from the sediments. Winyah Bay's sediments were among the least toxic in the amphipod test. About a third of the porewater tests from each sample were toxic to sea urchin larvae, and about 75% of the samples were toxic in the bioluminescence test. What emerges from these assays is that porewater is more toxic than bulk sediment itself, whereas the microbial assays indicate more of a potential for toxicity than actual toxicity. A similar assessment was made by Long (2000).

Long et al. (1998) should be examined for details of the tests and sediment assays reported above. This report provides comparative data for estuaries in SC and GA as part of NOAA's National Status and Trends Program (within the EMAP program) that monitors sediment toxins as well as body burdens of toxins periodically in fish and shellfish. Sampling in Winyah Bay took place in June 1993, and amphipod bioassays and sea urchin fertilization and microbial luminescence tests were conducted. Cytochrome P-450 assays were run as well. Sediment analyses included PAHs, organic pesticides and trace metals with appropriate quality control standards. This report details the findings for the 9 Winyah Bay samples mentioned in Long et al. (1996). Note, however, that none of the sampling stations was inside the NI-WB NERR boundary. These efforts, though, are relevant because of the connections between this larger body of water and North Inlet. Coller-Socha (1994) outlines toxicity tests done on sediments from the Winyah Bay navigation channel that contained dioxin compounds. Sanudo-Wilhelmy et al. (2004) provide an overview of the relative successes and failures of EMAP and NS&TP, showing that there were two peer-reviewed papers published on dissolved trace metals for the NI-WB NERR up to that time.

Foraminifera assemblages were examined for a comparison between the organic-rich sediments of the Intracoastal Waterway down into Winyah Bay and the less-rich intertidal sediments of Crab Haul and Clambank Creeks in North Inlet. Collins et al. (1995) found an impoverished transported benthic microfossil assemblage consisting of mostly non-living forams in the waterway, the bay, and at offshore stations, whereas the assemblages were rich and abundant in North Inlet. The authors attributed the differences to the high organic loads received by Winyah Bay.

Serum antibody responses were measured on a popular sport fish, the red drum (*Sciaenops ocellatus*) from several locations on the SC coast by Evans et al. (1996). They used an assay for anti-bacterial antibodies in blood serum and found that fish collected in Winyah Bay had the lowest percentage of non-responsive red drum. This low level of anti-bacterial response may have been correlated with the higher level of anthropogenic stress (contaminated sediments) in Winyah Bay relative to other locations.

More recently, assessment of South Carolina's coastal zone's health, known as SCECAP (SC Estuarine and Coastal Assessment Program) was begun in 1999. Every year through 2006, it has been measuring similar contaminants along the entire SC coast, with just two long-term, intermittently sampled sites in/near Old Man Creek in North Inlet and several in Winyah Bay. In 1999 & 2000 SCECAP found that North Inlet sediment samples contained contaminants, but were not in concentrations "that exceeded values considered to be high" (Van Dolah, et al., 2002). Tissue samples from whole body silver perch had detectable levels of contaminants, but did not exceed the FDA criteria for safe consumption. In 2001, however, a spot (Pisces) contained PAH and PCB levels which exceeded the 90th percentile of values for all SCECAP stations from 2000-2002 (n = 180; 60 per year). Every year from 1999-2004, SCECAP rated the mid-section of North Inlet estuary "Good" (the highest rating) based on fecal coliform, toxicity, contaminant concentrations, benthic index of biotic integrity, and water quality (Van Dolah, et al., 2008) (Figure 64). The middle and upper sections of Winyah Bay, however, did not fare as well, with designations in the fair and poor categories. This has remained the same in SCECAP's most recent report covering samples taken in 2005-2006 (Van Dolah et al. (2008).

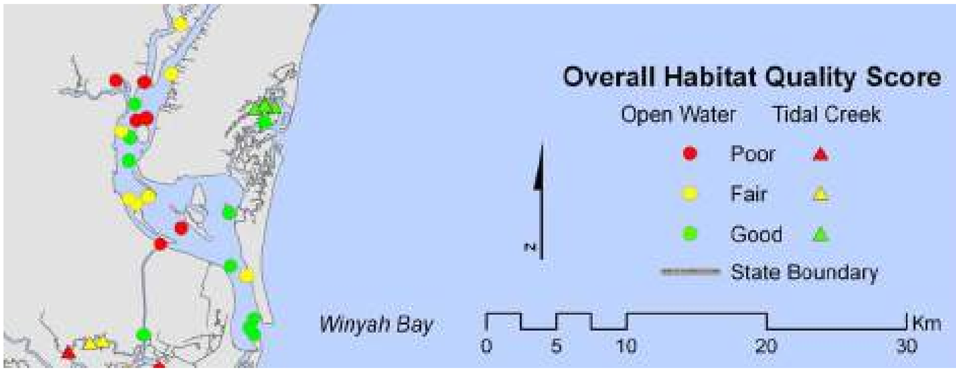
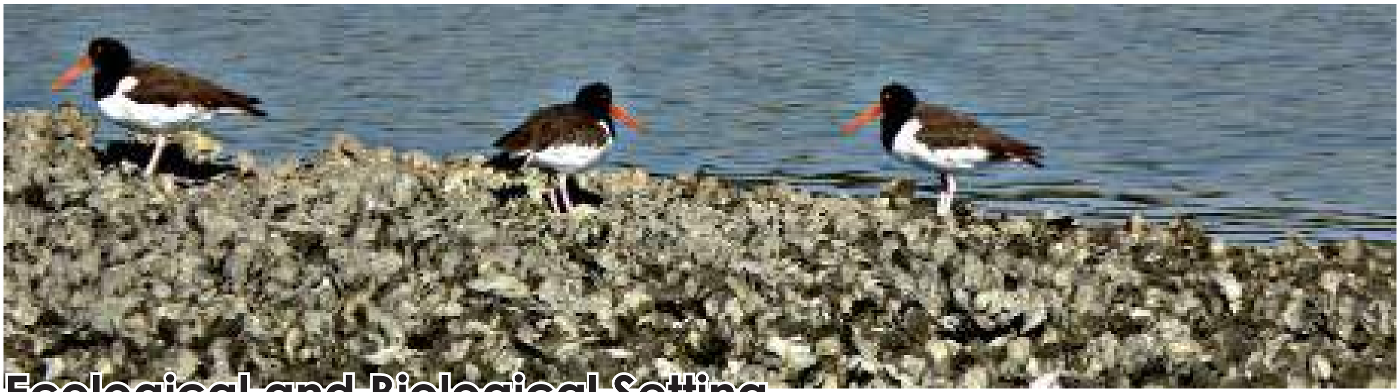


Figure 64. North Inlet and Winyah Bay overall habitat condition from 1999 through 2006. Map and assessment from SCECAP.



Ecological and Biological Setting

Habitats of North Inlet and Winyah Bay

North Inlet and Winyah Bay share many of the same intertidal and subtidal habitat types, but, because of greater freshwater contribution and the associated salinity gradient in Winyah Bay, the marshes and submerged bottom habitats vary more in Winyah Bay than in North Inlet. There are many definitions of the term habitat, but for the purposes of this document we define a habitat as a morphologically distinct subunit of the estuary wherein the depth (or extent of tidal flooding), geomorphology, sediment, vegetation, and most common animals differ from other subunits in the same estuary. For example, the intertidal salt marsh dominated by *Spartina alterniflora* is a different habitat than unvegetated intertidal mud flats. Although boundaries between adjacent habitats can be sharp, they are sometimes irregular and represent transitional stages between two or more habitat types. For instance, some intertidal flats are mosaics of mud, clumps of oyster reefs, and islands of marsh grass. Some of the more commonly encountered transitional or hybrid habitats are characterized within the descriptions of primary habitat types below.

Three major groupings of habitat types can be identified in estuaries based on tidal flooding regimes: subtidal, intertidal and supratidal. Subtidal, or permanently submerged habitats include the water column, hard and soft bottoms, shell rubble, and many man-made structures (e.g., jetties, artificial reefs). Primary intertidal habitat types shared by the two estuaries include high marsh, low marsh, intertidal creeks, mud flats, oyster reefs, low energy sandy beaches, and man-made structures (e.g. pier pilings, bulkheads). Supratidal habitats include areas of upland that periodically receive flooding during storm events. These habitats are described in further detail below.

The National Estuarine Research Reserve System's *Recommended Guidelines for Adoption and Implementation of the NERRS Comprehensive Habitat and Land Use Classification System* (Walker and Garfield, 2006) was developed to help reserves track and evaluate short-term variability and long-term changes in the extent and type of habitats within reserves and to examine how these changes are related to anthropogenic and climate stressors. The plan presents a long-term strategy to develop a standardized inventory of land use and land cover at a base year, and to measure changes over time in reserves and adjacent watersheds of influence. The NERRS has developed a land use/land cover classification scheme and mapping protocols for reserves and their watersheds, classification scheme documentation, and standard operating procedures which detail the methodology for developing and submitting habitat maps to the NERRS Centralized Data Management Office (CDMO). More information can be found at **www.nerrs.noaa.gov**.

Mapping of the North Inlet – Winyah Bay NERR began in 2007 with an inventory of available imagery, methodology and software, and discussions of the mapping boundary. Aerial photo interpretation was chosen as the most accurate method for delineating the marsh habitats within the limited budget for image and software acquisition and availability of GIS and remote sensing expertise and assistance. A total of 5,285 ha of habitat was mapped in the North Inlet estuary using color-infrared (CIR) digital orthophoto quadrangles (DOQ) with a 1-meter ground resolution from the year 2006 (Figure 65). The ten largest habitat subclasses in the North Inlet – Winyah Bay NERR are indicated in Table 4. Almost half (47%; 2,490 ha) of the area is estuarine intertidal emergent wetland (NERRS classification 2261), low marsh dominated by *Spartina alterniflora*. High marsh, including supratidal emergent wetland, and broad leaved deciduous (BLD), broad leaved evergreen (BLE) and needle leaved evergreen (NLE) scrub-shrub accounts for almost a quarter of the area (24%; 1,244 ha). Open water, including subtidal channels, intertidal channels, supratidal pools, and littoral ponds, is the third largest habitat area (11%; 587 ha). The total amount of subtidal channel edge calculated from the map is approximately 310 km. Tidal datums for a benchmark located near Oyster Landing in the NERR are provided in Table 5.

Table 4. Ten largest habitat subclasses by total area in the North Inlet-Winyah Bay NERR

Sub Class	Sub Class Name	Modifier Name	Area (ha)	% Total Area	Total Edge (km)
2261	Estuarine, Intertidal, Emergent, Persistent	Low Marsh	2489.6	47	433.9
2351	Estuarine, Supratidal, Scrub-shrub	High Marsh	665.9	13	162.4
2120	Estuarine, Subtidal, Unconsolidated	Subtidal Channel	587.4	11	309.1
2341	Estuarine, Supratidal, Emergent, Persistent	High Marsh	562.0	11	188.2
6155	Upland, Supratidal, Forested, Mixed	Maritime Forest	374.7	7	65.1
6131	Upland, Supratidal, Herbaceous, Grassland	Dune	160.8	3	56.6
2254	Estuarine, Intertidal, Unconsolidated, Mud	Intertidal Flat	125.9	2	48.2
1243	Marine, Intertidal, Unconsolidated, Sand	Beach	119.1	2	47.4
6143	Upland, Supratidal, Scrub-shrub	Maritime Shrub	51.3	1	17.1
6154	Upland, Supratidal, Forested	Pine Forest	47.0	1	3.5

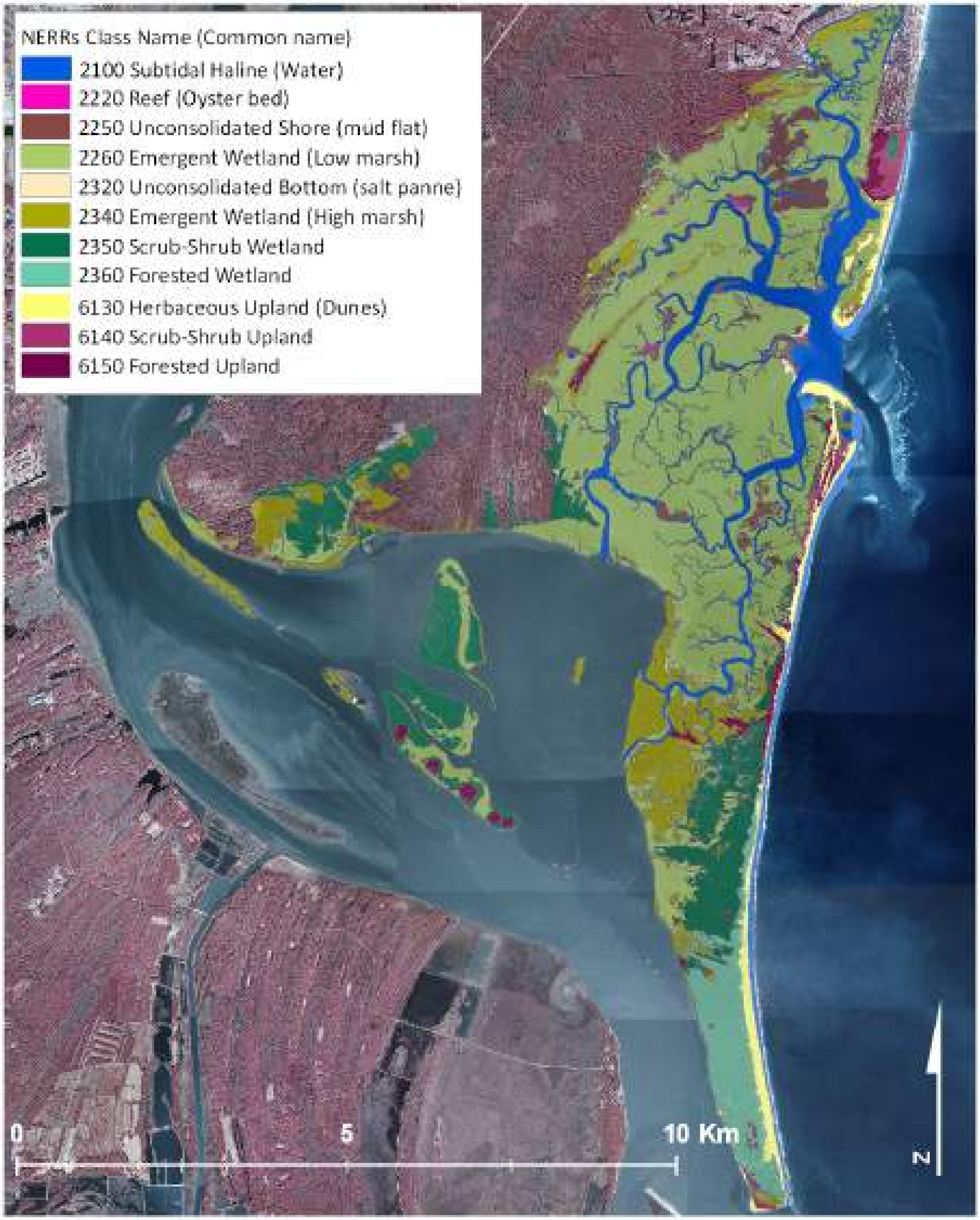


Figure 65. Habitats of the North Inlet-Winyah Bay NERR categorized by NERR class and common name.

Table 5. Tidal datums for benchmark PID DD1345 located near Oyster Landing in the North Inlet-Winyah Bay NERR. Datums are references on the 1983-2001 Epoch.

Mean Higher High Water (MHHW)	1.561 Meters
Mean High Water (MHW)	1.455 Meters
NAVD88	0.826 Meters
Mean Sea Level (MSL)	0.816 Meters
Mean Tide Level (MTL)	0.756 Meters
Mean Low Water (MLW)	0.058 Meters
Mean Lower Low Water(MLLW)	0.000 Meters

» Habitat Descriptions

ESTUARINE SUBTIDAL HABITATS

Estuarine subtidal habitats are those below mean low water (MLW) in which the substrate is continuously submerged by tidal water and the salinity is at least 0.5.

- **Subtidal Channel**

Channels that remain flooded at low tide serve as conduits of exchange of organisms and materials between the marsh and the ocean. Throughout the system, this highly dynamic habitat changes in depth, direction and rate of flow, turbidity, salinity, light penetration, and in many other ways, physically, chemically, and biologically on time scales of minutes.

In general, channel bottoms in North Inlet are composed of sands closer to the inlet and of mud closer to the upland. The most current-scoured channel bottoms are mostly sand and shell. These are generally referred to as hard (as opposed to soft) bottoms. Firm sandy and sandy–mud bottoms cover most of the lower Winyah Bay and channels in the mid- and upper Bay. These are shaped by strong tidal currents. The bottom is often highly irregular with ridges and swales being created and moved by the scouring tides. Little is known about the benthic infauna in these areas.

Accumulations of sloughed and degenerating oyster shell are also found on subtidal channel bottoms in North Inlet. These permanently submerged accumulations usually lie adjacent to living intertidal oyster reefs and support the growth of encrusting invertebrates and fishes, including the juveniles of many snappers, groupers, and other species that occur on similar ‘live bottoms’ in the coastal ocean. In Winyah Bay, shell rubble accumulations appear to be small due to limited well-developed living oyster reefs. However, re-exposed deposits of fossil shells - especially large oyster shells - may provide rubble habitat in some areas in the lower and mid-Bay.

Fine suspended sediments settle to the bottom in waterways with low velocity tidal currents, creating soft or muddy bottoms that support different infaunal benthos than sandy and shelly bottoms. Soft muddy subtidal environments are abundant in Winyah Bay, especially adjacent to the shorelines and in the large lagoonal area known as Mud Bay. These soft-bottom areas are probably maintained by the deposition of fine, river-borne sediments. Shallow subtidal bottoms are generally rich in benthic infauna and provide habitat for the commercially important species of shrimps, crabs, and fishes.

ESTUARINE INTERTIDAL HABITATS

Estuarine intertidal habitats are those in which the substrate is exposed and flooded by tides with a salinity of at least 0.5 during the period of average annual low flow. This zone extends from the mean low water mark (MLW) to the mean high water mark (MHW), but does not include the adjacent zone inundated only by storm surges.

- **Intertidal Channel**

Intertidal channels serve as conduits of exchange for water, dissolved and suspended materials, and motile animals which regularly move with the tides between the channels or pools within the channel beds and the vegetated marsh. More than 1000 intertidal channels of various sizes connect the marsh with subtidal channels in North Inlet. The mouths of intertidal channels are generally close to mean low water, and their sediments usually grade from coarse sandy-mud and shell near the mouth to soft mud further upstream. Because most of the marshes in the mid- and upper Winyah Bay were created and cultivated in the 1800's, most of the shallow channels in that system are straight, man-made canals that provided water flow and small boat access to the rice crops.

- **Intertidal Flats**

Intertidal flats are areas of unvegetated mud or sand found in low energy tidal environments that are exposed at mean low water. They are usually flanked by small subtidal channels or are mostly surrounded by salt marsh at the ends of large intertidal creeks in North Inlet. These ecologically important areas support high densities of meiofauna, macrobenthos, and benthic microalgae and serve as foraging areas for many fishes, motile invertebrates and birds. Intertidal flats are uncommon in Winyah Bay, with most of them being small fringing areas adjacent to marsh islands in the lower Bay. They tend to be composed of soft muds and likely support benthic infauna and nekton similar to those associated with mudflats in North Inlet.

- **Oyster Reef**

American Oysters, *Crassostrea virginica*, tend to grow intertidally in clusters on firm sediments and develop reefs along channel edges in North Inlet. In some locations, oyster reefs form as islands surrounded by water at low tide. Living oyster reefs are uncommon in Winyah Bay, perhaps because of the high loads of fine suspended sediments and the tendency for intertidal shorelines to accumulate mud. Some free-standing reefs occur in creeks in the lower Winyah Bay where, along the edges of some marsh islands, there are poorly-developed reefs associated with accumulations of fossil shell deposited when the ship channel was created more than a century ago. Oysters comprise the only naturally occurring hard structures in southeastern estuaries. Both living intertidal reefs and subtidal accumulations of shells provide substrate for many encrusting invertebrates (e.g., sponges, hydrozoans, soft coral, barnacles, mussels) and algae which, in turn, support small motile animals (e.g., crabs, shrimps, amphipods, polychaetes). Oyster reefs are primary feeding areas for larger motile invertebrates, fishes, and some birds.

- **Low Marsh**

Low marsh comprises the majority of habitat area in North Inlet and is dominated by salt marsh cordgrass, *Spartina alterniflora*. Regularly flooded marshes also occur in the form of *Spartina alterniflora* dominated stands in the lower Winyah Bay, *Spartina cynosuroides* in the brackish portion, and freshwater grasses in the upper Bay. Some sedges and *Typha* spp. (cattails) occur in wet marsh soils. This habitat provides cover for many species of nekton that use the marsh surface during high tide, and is an important nesting habitat for several species of birds including clapper rails, marsh wrens and willets. Snails and fiddler crabs are conspicuous invertebrates, and many shrimps, crabs, and fishes forage in low marshes when they are flooded.

ESTUARINE SUPRATIDAL HABITATS

Supratidal habitats are submerged by tidal flooding less than 5% of the time. This zone extends from the mean high water line (MHW) to the mean higher high water line (MHHW).

- **Estuarine Beach**

In contrast to the wave-influenced or high energy beaches that occur on the ocean-facing sides of barrier islands, low-energy estuarine beaches are more influenced by tidal currents. Sandy-mud environments occur near the mouth of North Inlet and along major subtidal channels. The only low energy intertidal beaches in the Winyah Bay system are located inside of the barrier island on the south side of the inlet, specifically adjacent to the base of the south jetty on South Island. Although they support diverse assemblages of meiofauna and macrobenthos, densities of infauna are lower than in muddy environments. Large flocks of shorebirds rely on these areas during their migratory stop-overs. This habitat also provides important nesting habitat for some bird species and diamondback terrapins.

- **High Marsh**

Proximal to the upland border or surrounding upland islands are areas of marsh that are flooded for short periods of time during every tide or only sporadically. Short-form *Spartina alterniflora* dominates at the lowest end of the elevational gradient in the high marsh. *Salicornia* spp. and other salt-tolerant plants occur in the middle reaches, and *Juncus romerianus*, *Borrichia* spp., and other plants tolerant of infrequent inundation are at the upper limit of the high marsh. Large dense stands of *Phragmites australis* occur in the mid- and upper Winyah Bay. Sediments are usually firm, insect larvae are common in the sediments, and upland mammals and birds commonly forage here.

- **Pannes and Pools**

Pannes are areas of the supratidal marsh where high tide pools form and evaporate, leaving areas of high salinity soils in which few plant species can grow. These areas have not been well studied, but are frequently used as foraging areas by wading birds during flooding tides. Increased flooding due to sea level rise may decrease soil salinity, allowing plants to recolonize and eventually convert these areas to high marsh. Areas of the marsh surface that remain permanently, shallowly flooded are referred to as pools. Water salinity can range from brackish to highly saline.

UPLAND SUPRATIDAL HABITATS

Upland supratidal habitats are any coastal upland area above the highest spring tide mark that is periodically over-washed, covered, or soaked with seawater during storm events to an extent that it affects habitat structure or function.

- **Dune and Maritime Shrub**

An extensive dune system is found on North Island and to a lesser degree on Debidue Island. The dominant plant species are *Uniola paniculata*, *Panicum amarum*, *Croton punctatus*, and *Sabal minor*. This habitat is highly dynamic and is susceptible to storm-induced and long-term erosion. Hardened shoreline structures such as groins and sea walls are of concern as they may prevent the longshore drift of sediments necessary for building and maintaining dunes. Maritime shrub habitat occurs on stabilized sand dunes, dune swales, and sand flats protected from saltwater flooding and most extreme salt spray. The dominant plant species are *Myrica cerifera*, *Juniperus virginiana*, and *Sabal minor*.

- **Pine Forest and Maritime Forest**

Pine forest habitat occurs at the upland edge of North Inlet and the northern edge of Winyah Bay. The pine forest is dominated by *Pinus taeda*, but *Quercus virginiana* and *Sabal palmetto* also occur. Understory species include *Myrica cerifera*, *Sabal minor*, and *Ilex vomitoria*. Maritime forest occurs on protected parts of old, stabilized dunes and beach ridges on North Island and is dominated by *Quercus virginiana*, *Pinus taeda*, *Sabal palmetto*, *Juniperus virginiana*, and *Myrica cerifera*.

CULTURAL LAND COVER

Cultural land cover represents any area modified by mechanical or chemical manipulation more than once per growing season, regularly grazed by livestock, modified to a condition that prohibits sustained plant and animal colonization, or is dominated by built-up or residential structures (Kutcher et al., 2005).

- **Impervious Cover, Unconsolidated and Herbaceous Cover**

Very little of the land area within the Reserve boundary is in impervious cover. This classification includes the buildings of the Baruch Marine Field Laboratory and the NI-WB Reserve offices. There are no paved roads within the Reserve. Cleared land, dirt and gravel roads and parking lots, and managed turf and shrubs occur over a small area of the reserve, mostly associated with the Baruch Marine Field Lab and Reserve offices.

Few clusters of pilings (docks) exist in North Inlet other than a concentrated area of piers and bulkheads along the man-made DeBordieu canal at the extreme north end of the estuary. In Winyah Bay, dozens of piers and short bulkheads, large fields of pilings installed as erosion control structures, and ricefield water control systems and support piers built many decades ago exist along many of the shorelines in the mid- and upper Bay. Stumps and fallen logs from cypress tree stands that died in the last century provide prominent structure to the intertidal and shallow subtidal portions of these same areas.

OTHER GEOMORPHIC FEATURES

- **Hammocks and Middens**

Hammocks are areas of higher elevation surrounded by marsh where upland species can grow. These areas are either the remnants of former dunes or are Native American shell middens. Some of these predominately clam shell refuse piles are more than 30 m (100 ft) across and date to more than 2000 years before present. This habitat is dominated by upland edge species such as *Quercus virginiana* and *Juniperus virginiana*. The leaching of calcium from oyster and clam shells reduces the natural acidity of the soils in these areas and in some cases the resulting calcareous soils allow rare plant communities to develop.

- **Wrack**

Extensive wrack mats comprised primarily of *Spartina alterniflora* stems may be the most ephemeral habitat type in the intertidal and supratidal marsh. Areas of wrack accumulation may create vegetation die off areas that will either remain as intertidal flats or will eventually be re-colonized by marsh plants after the wrack has been removed. These areas may also provide cover habitat for newly hatched diamondback terrapins. Hardened structures such as causeways, retaining walls, and even temporary boardwalks to research sites affect the accumulation and movement of wrack.

- **Eroded Sod Banks**

Some edges of salt marsh are prone to current or wave scour and have nearly vertical rather than sloped profiles. Because of their instability, they do not support oyster reefs or abundances of other infauna. Living *Spartina* usually grows to the edge of these banks and root networks delay erosion of the peaty, firm muds that characterize these areas. Most of the marsh edges throughout Winyah Bay have sharp vertical profiles. The long fetch created by the large expanses of open water in the Bay probably enhances the exposure of sod banks to erosive waves. Sometimes on recently eroded banks, re-exposed, dense accumulations of white shell from a former, older oyster reef that had been buried (grown over by marsh) for decades or centuries become evident. Eroded banks also occur at the upland-marsh edge where tidal channels are migrating inland with sea level rise.

- **Marsh Dieback**

Marsh dieback, also called brown marsh, is the rapid die-off and loss of marsh vegetation. It is characterized by rapid onset (1 to 2 growing seasons) and is often non-persistent. The cause of sudden marsh dieback is still under debate but may be cyclical depending on interactive climate conditions, sea level anomalies, and other biotic factors. Areas of suspected marsh dieback have been periodically observed in North Inlet, but have not been mapped or monitored.

Estuarine subtidal habitat: Subtidal channel

Estuarine intertidal habitats: (left to right) Intertidal channel, intertidal flats, oyster reef, low marsh.

Estuarine supratidal habitats: (left to right) Estuarine beach, high marsh, pannes and pools.

Upland supratidal habitats: (left to right) Dune, pine forest.

Other geomorphic features: (left to right) Hammocks, wrack, eroded sod banks, marsh dieback.

NORTH INLET'S MAJOR BIOTA

» Primary Producers

For a coastal salt marsh like North Inlet (and many others throughout the southeastern US), salt marsh cordgrass (*Spartina alterniflora*) dominates the visible landscape. Many other primary producers also contribute significantly to the salt marsh food web, including phytoplankton, microphytobenthos, macroalgae, and other vascular plants.

PHYTOPLANKTON

Chlorophyll *a* has been measured in the NI-WB NERR 20-day water chemistry program at the SWMP sites since 1994. During the summer, concentrations of 4-12 mg/L are typical for the Oyster Landing site. Diel differences in chlorophyll *a* levels usually occur with lower values being recorded during the dark period, when the primary producers are not actively synthesizing organic compounds (Figure 66). Often, in tidal creeks, a tidal signature can be observed with higher chlorophyll *a* concentrations being recorded during mid tides when the strongest currents are most likely to suspend benthic microalgae. High values around two of the three low tides on July 3 and 4 can probably be attributed to this process.

Diel and tidal variations are evident each month during 2010, but the range is greatest during the summer when phytoplankton densities are at peak annual levels. Highest concentrations were seen during mid summer and lowest values were recorded in winter and spring (Figure 67). This seasonal signature is shown in Figure 68 where summer values are consistently highest and spring is usually second highest. Mean seasonal values of chlorophyll *a* were higher in the 1990s when wetter conditions that reduced salinities and increased runoff prevailed (Figure 68). Drier conditions probably contributed to lower chlorophyll levels after 2001. A long-term decrease in chlorophyll *a* is indicated for Oyster Landing and other locations in North Inlet.

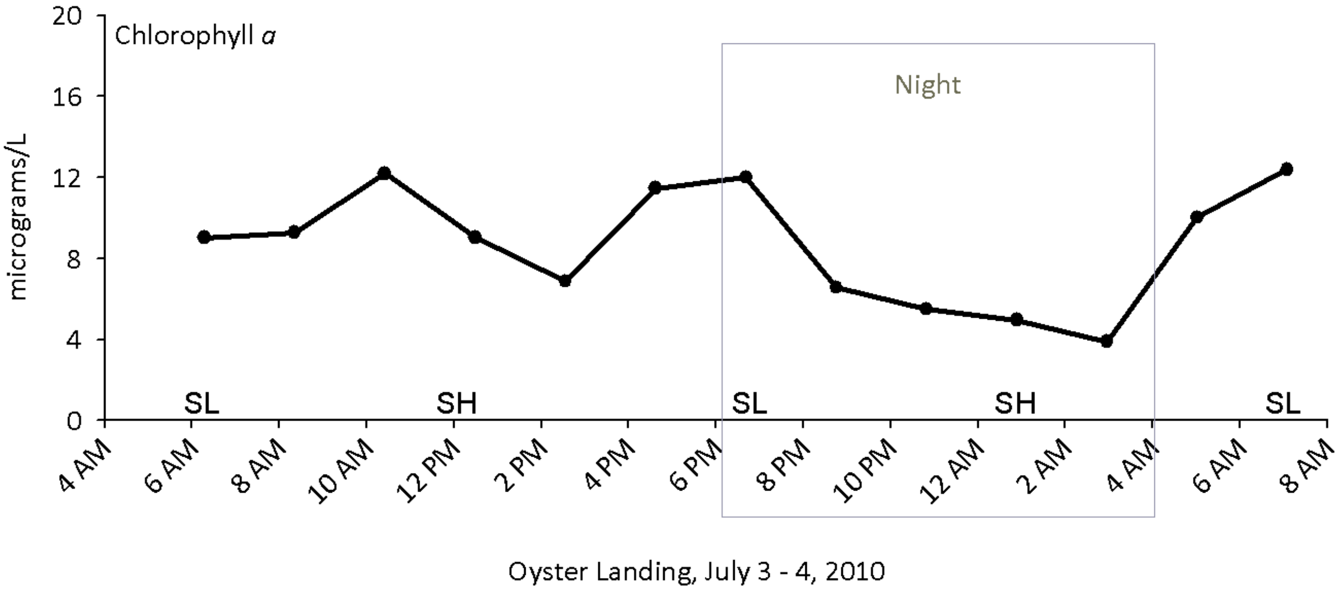


Figure 66. Chlorophyll *a* concentrations in water samples collected every hour July 3-4, 2010 at the NI-WB NERR SWMP Oyster Landing monitoring site. SL = slack low tide; SH = slack high tide.

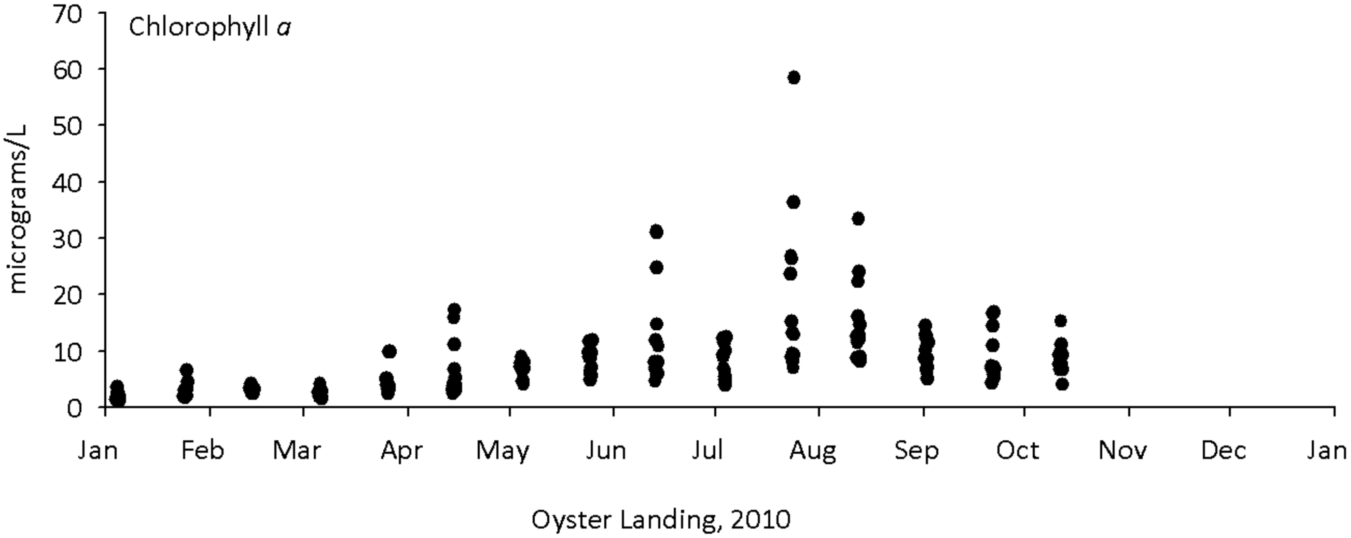


Figure 67. Chlorophyll *a* concentrations in water samples collected every hour during the 20 day samplings in 2010 at the NI-WB NERR SWMP Oyster Landing monitoring site.

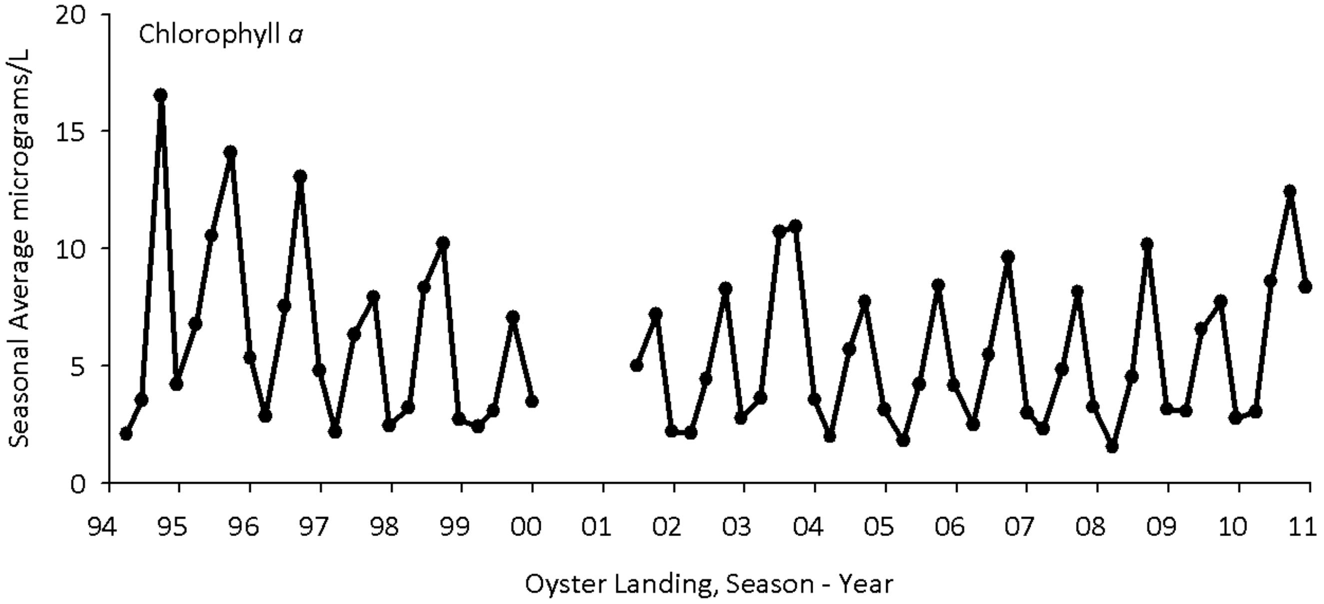


Figure 68. Mean seasonal chlorophyll *a* concentrations in water samples collected from 1994-2010 at the NI-WB NERR SWMP Oyster Landing monitoring site. Data for about 18 months starting in early 2000 were not included because of problems with the analytical processing of the water samples.

SUMMARY OF OTHER STUDIES ON PHYTOPLANKTON IN NORTH INLET

Among the early studies of primary production (PP) were student thesis projects that characterized the phytoplankton communities occuring in the tidally-mixed waters of North Inlet (Sellner, 1973; Vennewitz, 1977; Hall, 1979). These researchers found a diverse assemblage (over 200 species) with numerical dominants that changed seasonally and year-to-year. Abundances ranged from 10^6 to 10^8 cells per liter and their concentrations varied with changes in tidal levels, possibly due to resuspension of benthic algae. Blood and Vernberg (1992) have reproduced the phytoplankton species list originally provided by Hall (1979).

Rates of PP using the C^{14} method varied from 178 to 409 gC m^{-2} y^{-1} (Sellner et al., 1976; Vennewitz, 1977; Zingmark, 1977). These rates varied according to changes in the water temperature cycle and were twice as high at some places than at others. PP in the North Inlet exit plume entering the ocean was estimated by Zeeman (1982) as 639 gC m^{-2} y^{-1}.

Erkenbrecher and Stevenson (1980) examined the effects of changing tidal levels and diel fluctuations on chlorophyll *a* and "pheophytin" concentrations in a high-marsh creek in North Inlet. They found that tidal forces controlled the chlorophyll degradation product concentration but that the chlorophyll *a* biomass changed in a complex pattern involving tides and diel photosynthetic rhythms. They cautioned that tide levels and volume fluxes must be taken into account when measuring PP and phytoplankton species composition as they change with the season in North Inlet.

Vernberg (1981) summarized many findings from the multidisciplinary Outwelling Study performed in North Inlet in the 1970s. Briefly, this study sought to determine whether (and which types of) dissolved and particulate materials, both inorganic and organic, were exported from North Inlet to the coastal ocean on an annual basis (Dame et al., 1986). Among these findings was a net import of chlorophyll *a* from offshore into North Inlet but a net loss of photosynthetic cells within the inlet. Researchers thought that this loss was due to grazing rather than to settling of cells from the water column. The general outcome of these flux studies was in support of the outwelling hypothesis that the estuary is a source of detrital outflow to the coastal ocean. By making comparisons of import/export dynamics between other estuarine systems, Vernberg sought generalities in how coastal ecosystems function. This systems approach resulted in three modeling publications: Dame et al. (1977), Summers and Kitchens (1980), and Summers and McKellar (1981), all of which pointed to gaps in our understanding of the linkages and couplings. The output from these models defined research needs for over a decade in North Inlet. Other studies soon followed with empirical data that allowed these models to be tested. For instance, Dame (1982) found that there was a regular export of macrodetritus out of the inlet, but this flux was less than 1% of the net marsh primary productivity.

Zeeman (1985) measured phytoplankton photosynthesis both just outside North Inlet and farther offshore shortly after Hurricane Dennis passed in August 1981. Using photosynthesis versus light intensity (P vs I) curves, his data showed that photosynthesis was depressed soon after the storm but was elevated at the same stations 10 days later, going from 50 to 200 inshore and from 10 to 75 mg C m^{-3} h^{-1} at the offshore station. The changes were deemed to have resulted from a change in the species composition of the community (dinoflagellates appeared in place of diatoms) and/or changes in the ambient temperature, salinity, and light regime. Nutrient levels did not change significantly over the 10-day lag between samplings.

Dame et al. (1986) calculated that phytoplankton biomass (as chlorophyll *a*) and POC (particulate organic carbon) influxed from the coastal ocean in summer and fall and outfluxed in winter and spring, with net annual export of both to the coastal ocean. The extensive data sets summarized by Dame et al. (1986) also included quantitative measurements of nitrogen and phosphorus (dissolved and particulate), microbial ATP, detrital material, zooplankton, bird biomass, and water fluxes. The conclusion reached by Dame et al. (1986) was that North Inlet is a highly productive bar-built estuary with a strong connection to the coastal ocean that is enriched by outflow from the excess productivity that is only partially utilized within the inlet. That is, they suggested the existence of a feedback loop with offshore phytoplankton taking up nutrients before being imported by tidal flux back into North Inlet where they are consumed and remineralized.

This inflow/outflow dynamic that fuels PP in North Inlet was further investigated by Whiting et al. (1987) who measured nitrogen species (ammonium, nitrate, nitrite) in the water column. They found that North Inlet consistently exported dissolved inorganic nitrogen to the coastal ocean via tidal exchange. They suggested that nitrification within the marsh was the source of this export, thereby strongly supporting the conclusions of Dame et al. (1986).

Earlier monitoring of nutrient levels and the chl-*a* concentration in North Inlet showed that ammonia (NH_4^+) was high at the same time as chl-*a* in the summer. This unusual situation suggested that the phytoplankton were likely limited not by nitrogen as in many other estuaries studied, but by some other factor. Lewitus et al. (1998) surmised that grazing might limit the summertime growth rate of phytoplankton and devised an elegant set of experiments to test their hypothesis. They found that the summer phytoplankton consisted mostly of picoplankton, especially nanoflagellates, with the cyanobacteria *Synechococcus* spp. comprising almost all of the phototrophic picoplankton. Other dominants included the genera *Cylindrotheca*, *Nitzschia*, and *Thalassiosira*. In a series of dilution and nutrient addition bioassay experimental cultures using natural phytoplankton communities, Lewitus et al. (1998) determined that grazing by members of the microzooplankton limited summertime growth of the phytoplankton. Furthermore, they determined that, in contrast with the summer situation, wintertime phytoplankton communities were limited by available nutrients. Their seasonal samplings also showed that the size-structure of the phytoplankton community changed during the year, with smaller forms < 20 microns dominant in summer and larger forms in winter and early spring. Picoplankton (0.2-2.0 microns) and nanoplankton (2.0-20 microns) were abundant in summer, peaking in July and September, while nanoplankton and microplankton (20-200 microns) dominated the phytoplankton's summertime biomass when picoplankton comprised only 1% of the community in July. The picoplankton biovolume peaked in September. During winter the microplankton comprised 26% of the phytoplankton abundance and 77% of its biovolume. The summer-to-winter transition took place when ammonium occurs in excess in summer as nanoflagellates dominate and then becomes limiting in winter when a diatom-based phytoplankton community develops. Thus the phytoplankton community switches from one dominated by microbial loop processes in summer to one dominated by a microplankton-based food web in winter. This study raised many questions about differences in the control on water column primary production in North Inlet from offshore coastal waters where nutrient levels are lower but light intensities are higher.

Following these discoveries about the seasonal switch from microbial- to diatom-based food webs, Dame et al. (2000b) began an investigation of the impacts of oyster reefs in tidal creeks within North Inlet. In this study they examined a group of eight creeks that were to be manipulated later (by oyster removals) in a BACI (before-after control-incident) experimental design. They monitored chl-*a* in the creeks and found changes in concentrations that were consistent with those reported first by Lewitus et al. (1998), i.e., very low (near zero) in winter and highest in summer in all the creeks. Because phytoplankton did not respond appreciably to nutrient addition in their batch culture enrichment experiments in the summertime, they suggested that oyster removals would probably lead to nutrient deprivation of the phytoplankton community especially in winter. They thought that because oyster reefs are a rich source of ammonium via their excretion products, an absence of oysters might lead to nitrogen limitation of PP. Their data also suggested that nitrate and nitrite flow into the tidal creeks adjacent to the forest, an obvious source of nitrogen in these smaller creeks that are more influenced by runoff than by tidal exchanges.

Dame et al. (2002) found that oyster removals did not cause massive changes in most of the parameters they measured in the BACI design. There was elevated recruitment of oyster spat to creeks where oysters had been removed and slightly elevated growth rates of the few oysters remaining in those creeks. Their batch culture nutrient, NH_4^+ addition studies showed that chl-*a* was not usually stimulated. Their dilution experiments demonstrated that grazing was more important as a change agent for chl-*a* than nutrient limitation. Interestingly, they suggested that nekton, water column remineralization, and sediments probably supply enough ammonium to meet phytoplankton demand. There was such complete mixing of water in the creeks from tidal exchanges that removal of the oysters had a much lower impact than anticipated. They suggested that systems dominated by bivalves behave in a complex fashion and do not respond in a linear or very predictable fashion to over-fishing, pollution, or eutrophication.

To estimate the energetic demands and impact of dolphins that routinely visit North Inlet, Young and Phillips (2002) took primary productivity data from Pinckney and Zingmark (1993a, 1993b) and applied several well-established measures of trophic transfer efficiency to measure how much primary production it took to supply the energetic needs of, on average, six resident dolphins for a year. Their trophic model conservatively estimated how much fish biomass the dolphins ate and calculated that 3 to 7% of primary production (all types, not just phytoplankton) was utilized in support of dolphin biomass. Although dolphins clearly do not control primary production in North Inlet, this top-down approach provided an interesting way of thinking about how primary production is utilized in coastal marsh systems like North Inlet. Their paper illustrates many basic ecological principles about trophic transfer efficiency and would be a valuable teaching tool.

Close examination of the North Inlet phytoplankton community's pigment composition was undertaken by Noble et al. (2003) using high performance liquid chromatography (HPLC). Water samples were characterized and compared to those collected in the ACE Basin NERR (located about 150 km or 90 mi south of the NI-WB NERR) to see to what degree these communities were similarly or differentially influenced by differences in the nutrient loads in these two systems. North Inlet is more tidally-influenced than the ACE Basin where input from the surrounding forest and rivers is much greater. Cluster analysis and multivariate principal-components analyses demonstrated that the suite of pigments examined varied seasonally at the two sites and had similar diversities but different compositions. The timing, the magnitudes, and the pigment compositions of the annual summer phytoplankton blooms were quite different in these two estuaries. This pigment-based study (as opposed to one using species-based measures of community structure) makes it difficult to assume that phytoplankton communities in coastal estuaries have common community composition structuring forces. North Inlet has more autochthonous (internal, *in situ*) controls like utilization of regenerated nutrients and grazing, whereas the ACE Basin phytoplankton community was more strongly influenced by nutrient loads from river runoff and changes in light intensity with subsequent changes in turbidity.

The value of the NI-WB NERR as a pristine habitat has allowed it to serve as a natural baseline or unmanipulated control in many comparative studies. Murrells Inlet is similar to North Inlet in that both are tidally-dominated shallow systems, but Murrells Inlet has a much smaller acreage of marshland (3000 vs 9000) and is considerably more urbanized. White et al. (2004) explored the impacts of urbanization in Murrells Inlet on nutrient concentrations and chl-*a* concentrations there and in North Inlet. They found that both estuaries had similar summertime chl-*a* signals with a significantly higher maximum in Murrells Inlet and similar nutrient concentrations (orthophosphate, nitrate, ammonium, silicate, DON) except when large precipitation events occurred. Nitrate concentrations increased with the relatively larger volume of freshwater input to Murrells Inlet after these events. Because Murrells Inlet has a relatively smaller buffer of natural forest and a much greater relative volume of stormwater runoff and drainage/outfalls flowing into its waters than North Inlet, there were great differences in both quality and quantity of nutrients entering the two systems after rainfall events. Their work illustrates the tight relationship between water quality and nutrient sources in an urbanized coastal body of water and the important role of stochastic events (storms) and tidal flushing in regulating water quality in these types of coastal ecosystems. Their results were similar to those of Wahl et al. (1997) in a similar comparative study of nutrient loading.

An additional impact of urbanization and coastal forest clear-cutting practices may be a reduction in the supply of dissolved organic matter (DOM) in runoff that reaches coastal estuaries. Components in DOM are known to bind with dissolved forms of iron, a potentially limiting micronutrient for phytoplankton communities in estuaries. Kawaguchi et al. (1997) also performed a comparative study using bioassays in Murrells Inlet and North Inlet that involved reciprocal transplants of water from each estuary into the other to test whether additions of chelated iron to cultures of natural phytoplankton or to cultures of *Cylindrotheca closterium*, a dominant in the microphytoplankton, would deplete iron and stimulate their growth. They found increased abundances in phototrophic microplankton, nanoplankton, and picoplankton when chelated iron was added to natural populations transferred to Murrells Inlet, but the same additions to North Inlet cultures enriched only the picoplanktonic *Synechococcus* spp. They concluded that iron's bioavailability to estuarine phytoplankton may be reduced by urbanization.

This study was followed later by an in depth and temporally more extensive look at iron limitation of phytoplankton, again in Murrells Inlet and in North Inlet for comparison (Lewitus et al., 2004). They found that bioavailable forms of iron may exist in limiting concentrations in both estuaries. Addition of chelating agents alone or with iron stimulated growth in most cases. In 1996, they again found that addition of chelated iron stimulated Murrells Inlet phytoplankton, but not North Inlet phytoplankton, the same response found earlier by Kawaguchi et al. (1997). Iron addition to phytoplankton cultures from Oyster Landing in North Inlet to which nitrate had also been added resulted in a shift of the community from smaller forms to larger diatoms, suggesting that iron bioavailability, nitrate (but not ammonium) and silicate concentration have an interacting effect on phytoplankton community structure in North Inlet. The authors suggested that coordinated studies of forest biochemistry and iron will be necessary to understand these interactions, especially as they are affected by weather events.

Buzzelli et al. (2004) provided analyses of correlations between chl-*a* and other water-derived measures during the 8-year period 1993 to 2001 at both the Oyster Landing (a tidal creek site) and Thousand Acre Marsh (an estuarine-influenced marsh close to Winyah Bay) monitoring sites in North Inlet. They found the lowest chl-*a* concentrations in winter, highest in summer at both sites, but the Thousand Acre Marsh site had much higher concentrations at all times of year than occurred at Oyster Landing. There were strong correlations between chl-*a* concentrations and total suspended solids and dissolved nitrogen, suggesting that the chlorophyll came from autochthanous phytoplankton production in the water column (produced within the site) rather than from allochthanous (imported to the site from elsewhere) sources in the surrounding watershed. Data from the Thousand Acre Marsh site are presented in the Winyah Bay Primary Productivity (phytoplankton) section of this chapter. These continuing data sets will foster many hypothesis-based research projects concerning controls on water quality in the future.

Gardner et al. (2006), used SWMP data on dissolved oxygen (DO) concentrations from the Oyster Landing site and calculated that North Inlet exports an insignificant amount of DO produced by phytoplankton in the inlet to the coastal ocean where oxygen demand is high. This would indicate that photosynthetic oxygen production by phytoplankton, benthic microalgae and marsh plants and diffusion of O_2 from the air into the water is mostly used to meet heterotrophic demand from organisms and chemical processes that occur within the salt marsh.

A recently developed algorithm, CHEMTAX, is a program for describing the relative abundance of taxonomic groups of phytoplankton based on their expected pigment ratios. Lewitus et al. (2005) used CHEMTAX to characterize a variety of cultured cells and natural phytoplankton samples using waters from both Murrells Inlet and North Inlet. Microscopically unidentifiable flagellates and their diverse pigment make-up created problems for the taxonomic characterizations produced by CHEMTAX, and ground-truthing comparisons were problematic when dinoflagellates were present. Despite these and other issues, their modifications to the CHEMTAX methods using complementary microscope verifications resulted in an improvement of our abilities to assess the taxonomic composition of phytoplankton communities in estuarine waters.

The spectral fluorescence technique is another method for characterizing the composition of phytoplankton assemblages based on the fact that photosynthetic components ("antennae") and accessory pigments fluoresce differently when excited by light. Richardson et al. (2010) characterized natural phytoplankton from both North Inlet and the Neuse River Estuary, North Carolina, using spectral fluorescence measured with the Algae Online Analyser (AOA) in discrete sample mode (for North Inlet samples) and continuous flow mode (on a passenger vehicle ferry in the Neuse River estuary) and compared their results with data using the CHEMTAX methodology. Because the AOA can be used as a community composition monitoring tool, Richardson et al. (2010) were interested to see whether the instrument could be used as an early warning system to alert investigators to the presence of noxious algae or other precursors to eventual harmful algal blooms. Comparisons between the AOA system and the HPLC-based CHEMTAX method showed significant differences, with the AOA providing better (higher) estimates of total chl-*a* in the water. Despite inherent uncertainties in both methods, the authors felt that the AOA could be used reliably as a HAB monitor, especially if it was supplemented with direct microscopic examinations of cells for calibration.

There are many questions left to be answered about phytoplankton communities in the NI-WB NERR and these will need to be studied using multidisciplinary approaches and a variety of technologies. For example, with recent satellite imaging advances, additional analyses of the spectral qualities of phytoplankton will need to be studied in conjunction with estimates of how various other factors affect these qualities, including water turbidity, dissolved organic matter concentrations, and weather patterns. Continued urbanization of our nation's coastlines makes analyses of natural habitats like the NI-WB NERR an integral part of future ecological comparisons related to phytoplankton at the base of the estuarine food web.

In summary, phytoplankton biomass is highest in North Inlet during summer and lowest in winter. The Outwelling Study found that chl-*a* is, on average, inwelled from offshore. These imported cells are lost to grazing and sinking inside the inlet and chl-*a* is exported offshore in winter and spring. Primary productivity is about 400-500 g C $m^{-2}yr^{-1}$. Microzooplankton grazing limits phytoplankton communities in summer when small cells and microbial loop processes dominate the system. Nutrient limitation in winter results in larger cells dominating the community at that time of year. The surrounding forested watershed supplies inorganic nutrients to North Inlet. Comparative studies of phytoplankton in areas nearby North Inlet show that urbanization reduces the availability of iron to phytoplankton. Several new approaches have been used to characterize phytoplankton communities in recent years.

BENTHIC MICROALGAE

Holland et al. (1974) compared the sediment stabilization abilities of six species of benthic diatoms grown in flask culture in a laboratory setting with that of a natural community of sediment microbiota from North Inlet. Several species grown in unialgal culture with sediment produced mucilaginous coatings that prevented sediment resuspension, but three species did not. Control natural sediments incubated under similar conditions also inhibited resuspension of sediments. Although unable to extrapolate these results directly to field situations, the authors suggested that sediment stabilization properties of benthic microalgae (BMA, or microphytobenthos) could have significant impacts on organisms that feed at the sediment-water interface as well as on animal-sediment relationships for meiofauna.

Pearse (1977) used the ^{14}C method to measure vertical migration of benthic diatoms in cores. When more diatoms were on the sediment surface, more radioactivity was present in that layer. When surface diatoms migrated deeper into the sediment, there was less radioactivity present at the sediment surface. Benthic diatoms came to the surface mostly during low tide.

Montagna (1984a) measured the grazing rates of meiobenthic organisms on sediment microbes, including bacteria and microalgae. He used radioactive ^{14}C-glucose to label autotrophs and added them to small cores that were incubated undisturbed for 4 hours. Meiofaunal polychaetes grazed on benthic diatoms more than other meiobenthic taxa. The meiofauna removed about 1% of the benthic diatom community per hour, yielding a turnover time for the benthic diatoms of 6.5 days. He suggested that meiofaunal grazing had a stimulatory effect on the benthic microbial community.

Because of the known rhythmic migratory behavior of members of the BMA, Pinckney and Zingmark (1991) sought to examine how tide stage and sun angle affected BMA productivity in the muddy low intertidal regions of North Inlet. They measured productivity in cores using an oxygen microelectrode and found an endogenous rhythmic variation in productivity that was correlated with diurnal and tidal periodicities. Production values could differ by as much as an order of magnitude over a 12-hr period and were found to range between 28 and 460 micromoles of oxygen per milligram chlorophyll *a* per hour, with the highest values occurring during mid-afternoon low tides. Much lower values were obtained during afternoon high tides. The interacting effects of tidal stage and sun angle caused this high variability. They suggested that other physiological and abiotic variables also can influence BMA productivity and cautioned that large errors can result from extrapolating single short-term estimates to longer time periods. Their results were similar over all seasons of the year.

Pinckney and Zingmark (1993a) collected sediment cores at bi-monthly intervals for 18 months at five different sediment/light habitats in North Inlet to measure BMA biomass and productivity. They found the highest biomass (chl-*a*, averaged over time) in the tall *Spartina* zone and lowest in the shallow subtidal habitat. BMA biomass generally increased in late winter and early spring with lower, relatively constant, levels during the rest of the year. Pheopigments followed roughly similar temporal trends. BMA production tracked the biomass trends and was highest in the intertidal mudflat (2.48 mg C [mg chl-*a*]$^{-1}$ h^{-1}) and lowest in the shallow subtidal and sandy intertidal habitats (1.25 and 1.07), respectively. The highest productivity on an areal basis was in the short *Spartina* zone at 234.2 g C m^{-2} y^{-1}.

Pinckney and Zingmark (1993b) constructed a model of primary production by the BMA community. They concluded that on an annual basis, the short *Spartina* zone provided 45%, intertidal mudflats 22%, tall *Spartina* zones 18%, shallow subtidal 13%, and intertidal sandflat 3% of benthic microalgal production which equaled 3.4 x 10^9 g C y^{-1} as the sum of all five habitats. This annual rate is higher than phytoplankton and macroalgal production but lower than that of *Spartina*. They performed a sensitivity analysis of the model and found that all factors affecting the amount of light received by BMA were important but varied in their relative importance between the five habitats. Their paper includes an extensive list of other habitats in which BMA production has been measured worldwide.

Pinckney and Zingmark (1993c), reported measurements of photosynthesis vs light (P versus I) curves, for intertidal benthic microalgal communities. Because highest rates of oxygen production had been found during afternoon low tides, they measured gross primary production at that time and compared three different methods of calculating productivity. Cores were collected in bare low intertidal areas as well as in the short and tall *Spartina* areas of the marsh, obtaining depth-integrated areal estimates of gross primary production in these areas of the marsh. They regressed P_{max} versus BMA biomass (as chl-*a* in the uppermost 2 mm of the cores). These variables were significantly positively correlated at all three of the study areas (mudflat, tall, short *Spartina*) and chl-*a* specific production rates were three times higher on the mudflat than at either of the other two locations which had similar rates. Comparisons of P versus I curves from these three different light environments showed that BMA were equally efficient and responded similarly to changes in incident radiation. In contrast to the community measures, when photosynthesis production rates are expressed as a percentage of maximum rates over the range of irradiances used, it was clear that the BMA in tall *Spartina* habitats were more efficient at low light levels and least efficient in the short *Spartina* at low light levels.

Additional study of the vertical distribution of BMA biomass was conducted by Pinckney et al. (1994a). Vertical diatom migration occurred mostly within the uppermost 3 mm of the sediment column and may explain much of the short-term variability observed in primary productivity in marine sediments. These dynamics may also be important in the foraging strategies of benthic organisms that are surface deposit feeders. Pinckney et al. (1994b) showed that standard spectrophotometric methods for measuring BMA biomass (as chl-*a*) in sediments overestimated concentrations by about 16% compared to HPLC pigment extractions.

Jackson et al. (2006) examined changes in the biomass of epiphytic BMA on *Spartina* stems over time at two different stem heights (bottom, middle) on three growth forms of the plant (tall, medium, short), for both living and standing dead plants. Standing dead stems harbored more biomass than living stems on both tall and medium growth forms. Differences were less evident for short *Spartina* plants. Generally the bottom portion of the stem had more epiphytic chlorophyll *a* than the middle of the stem, no matter whether live or standing dead plants were examined. Seasonal changes were evident, with more biomass found in spring, though variance over time was high. Tidal currents affected epiphytic biomass as well, but variability from low tide to the next high tide was too great to suggest a consistent effect of flowing water on the epiphytic community. Dead forms held 4-5 times more biomass per square meter of marsh, especially in winter and early spring. Highest epiphytic biomass occurred on tall plants, but compared to sediment biomasses found by Pinckney (1992), even tall forms had about three times less biomass than found in BMA in the surrounding sediments. The importance of epiphytic algae to the marsh's food web cannot be discounted, as many other investigators have found them in the guts of grazers of many types, e.g., periwinkle snails, grass shrimp, amphipods, and meiofauna. However, estimating the productivity of the epiphytic community presented challenges that were addressed later by Jackson et al. (2009).

Earlier compositional characterization of the epiphytic community by Jackson (2004) led to the biomass studies above and to a community productivity modeling effort. Jackson et al. (2009) deduced that the epiphytic community is an energy sink, existing not as a net autotrophic assemblage but as a net heterotrophic community using more energy or carbon than it is able to produce over the year. This was a surprising result, given that so many heterotropic organisms ingest members of this attached microalgal community. Annual production was greater on short forms of *Spartina* than on tall forms, but both were negative for the year. They also found photoinhibition was present at all times of the year, suggesting that these cells are adapted to the low light environment of the plant canopy.

Sullivan and Currin (2000) reviewed the status of research on the community structure and dynamics of BMA in salt marshes, and the pioneering studies of Pinckney and Zingmark and others are cited prominently in that document.

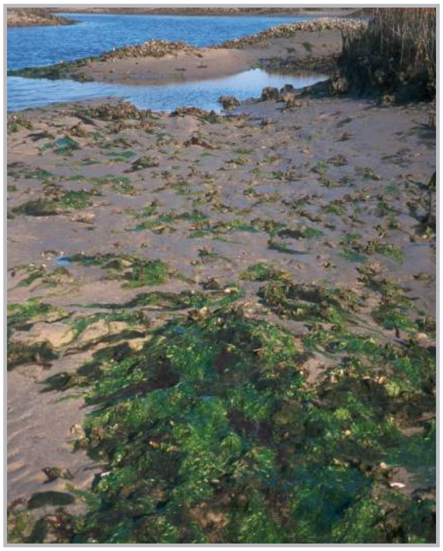
In summary, the benthic microalgal community of North Inlet is, on a per square meter basis, approximately half as productive as phytoplankton communities, but its rate of productivity is highly variable among different habitats. Well-documented vertical migration of BMA contributes to short-term variability in the production rate. Microphytobenthic communities are currently under-sampled in North Inlet.

MACROALGAE

Dame (1982) measured the amount of macrodetritus, some portion of which contained material sloughed off from macroalgae, exported from North Inlet. Export happened on a regular basis but varied seasonally with maximum values in summer. The amount of material exported, however, was small (only about 1%) compared to the salt marsh's net aboveground primary productivity.

Ebeling (1982) characterized benthic macroalgae at three locations in North Inlet (Oyster Landing, Clambank dock, Town Creek from Clambank south towards Winyah Bay) and found 14 species. Five species dominated (*Enteromorpha* sp., *E. siliculosus*, *Ulva lactuca*, *Bryopsis plumose*, and *Porphyra leucosticta*) during the winter months. She determined ash-free dry weights and caloric content of these five species.

Coutinho (1987) examined the spatial and temporal distribution of macroalgae in North Inlet from 1983 to 1987. Eighteen species of greens, 8 browns, and 28 species of red macroalgae were documented. Many species had productions of 1 g C m^{-2} y^{-1} in winter and less than that during summer. One-third of annual production occurred in March, with 84% occurring between December and April. Average net annual production for macroalgae was calculated as 200 g C m^{-2} y^{-1}, being greatest on the flood tidal delta and lowest in the high marsh.



Ulva lactuca is found in North Inlet mainly in the winter months.

Coutinho and Zingmark (1987) measured P versus I curves on 4 species of green macroalgae (Chlorophyta), one brown species (Phaeophyta), and one red species (Rhodophyta) to test whether there was any variability in the shape of these curves during the day. Using three different curve-fitting models on data collected in February and March, most curves exhibited photoinhibition at the higher light levels. They also found no evidence of any endogenous photosynthetic rhythms in these species. Illumination was the largest source of variation for calculating production rates. Additional details of this study can be found in Coutinho's 1987 dissertation.

The only study of macroalgal recruitment was performed by Flavier and Zingmark (1993) who used marble tiles as settlement substrates submerged over a range of depths in a tidal creek. Month-long deployments were recovered during all four seasons of the year, with highest recruitment occurring in spring and summer, lowest in winter. Propagule densities varied significantly with depth and with season, with highest densities generally at zero and -15 cm depths relative to MLW. Most of the settlement took place between winter and the start of spring. Comparisons were made to calculate survivorship and mortalities of the different types of macroalgae found on the tiles. Ulvoids and ectocarps were prominent settlers and generally settled where they were most abundant as juveniles, suggesting that natural densities were set by factors influencing settlement and early post-settlement rather than later in the life history of the algae. Macroalgae may contribute more to summertime productivity in the estuary than was previously thought, based on the presence of high numbers of propagules found on tiles in this season.

In summary, the diverse macroalgal community in North Inlet is less productive than phytoplankton, BMA, or vascular plants. It gains prominence in winter when water clarity is highest and contributes regularly to the macrodetritus inventory of the inlet throughout the year. Macroalgal communities are severely understudied in North Inlet.

VASCULAR PLANTS

Vascular plant research began at the Clambank Landing area of Hobcaw Barony in the late 1960s and was followed by survey and census work that listed species known in the area (Tiner, 1977; Conservation Foundation, 1980: both cited in Blood and Vernberg, 1992; and Zingmark, 1978). The uplands regions of Hobcaw Barony harbor typical maritime low country stands of pines and hardwoods, but there is not very much forested upland acreage within the actual NI-WB NERR boundary lines. Trees and shrubs will not be mentioned here, but a vascular plant list for Hobcaw Barony and adjacent estuarine habitats is in **Appendix C**. Freshwater marshes are also not abundant area wise, but plant communities in old abandoned rice fields (worked in the 1920s) that have converted to freshwater marshes were followed by Baden et al. (1975) and then re-censused 20 years later by Stalter and Baden (1994). They found that the species composition there had changed little over that time. Please consult the Belle W. Baruch Institute of Coastal Ecology and Forest Science of Clemson University for information on uplands forestry studies on Hobcaw Barony proper. Vascular plant research in the North Inlet - Winyah Bay NERR area has included numerous topics, broadly categorized below.

- **Salt Tolerance and Osmotic Stress**

Stalter and Batson (1969) performed reciprocal transplantation experiments in the salt marsh at Clambank Landing. They identified four vegetation zones according to their elevation above sea level: High high marsh (HHM), Low high marsh (LHM), High low marsh (HLM), and Low low marsh (LLM). Each zone had a nearly unique set of plant species present: HHM = I*va frutescens*, *Baccharis halimifolia*, *Spartina patens*; LHM = *Salicornia* spp., *Spartina alterniflora*, *Borrichia frutescens*, *Limonium carolinianum*, *Distichlis spicata*; HLM = dwarf *Spartina alterniflora*; LLM = tall *S. alterniflora.* Thirty plants of each species were transplanted in winter from each zone into each of the other three zones, with re-transplantation into the same zone serving as a control. By 6 months later, most plants did not tolerate transplantation well, but *Salicornia* from the LHM tolerated HLM and LLM, while *Limonium carolinianum* from the LHM tolerated HLM transplantation. Their data also suggested that the dwarf and tall forms of *Spartina alterniflora* were distinct, or "inherent". Follow-up examination of the transplants two years later found that *Salicornia virginica* from the LHM lasted a year in the Upper LM and that *S. patens* from the Upper HM had only a 10% survival rate after two years in the LHM (Stalter, 1973).

Physiological work on salt marsh plants by Cavalieri and Huang (1977) examined the activity of NAD-malate dehydrogenase (MDH) under various salt (NaCl) concentrations. They took six species from the North Inlet marsh for laboratory experiments. *Borrichia frutescens* differed from the other species by being much more salt-tolerant, particularly in its cytosol MDH, but not in its mitochondrial MDH. This succulent was thus better adapted to life in the middle-to-high marsh where soil salinities can become quite high. Follow-up physiological work on enzyme activities (leucine aminopeptidase, peroxidase, and MDH) was done by Gettys et al. (1980) on leaf extracts from *Spartina alterniflora* and *S. patens* collected in North Inlet. They found evidence, based on the activities of this suite of enzymes in response to changes in salinity, that correlated well with the greater salt-tolerance of *S. alterniflora* in the low marsh over that of *S. patens* from the high marsh.

To better understand how salt marsh plants adapt to high soil salinities, salt marsh plants in North Inlet were measured for their proline content in the field and transplants were placed into growth chambers where their exposures to NaCl and polyethelene glycol were manipulated (Cavalieri and Huang, 1979). Proline is an amino acid known to have an osmoregulatory function in plant cell cytoplasm. These researchers measured the buildup of proline at threshold levels of salinity in the C4 plants (*Spartina alterniflora*, *Spartina patens*, *Disticlis spicata*), but the succulents did not exhibit such an adaptation to salinity levels normally reached in their habitat.

An examination of the nutrient status of *Spartina* was performed on short and tall forms of the plant by Cavalieri and Huang (1981). They measured the concentrations of proline and glycinebetain and found that tall plants in the low marsh had sufficient nitrogen for metabolism, osmoregulation, and growth, whereas short plants had to allocate more of their limited nitrogen supply to osmoregulation and hence had reduced growth. Cavalieri (1983) grew plants hydroponically under controlled conditions with varying salt and N concentrations and followed the amounts of these same two osmolytes in the plants as they responded to the nutrient and salinity manipulations. This study confirmed their earlier field observations concerning reduced plant growth at high salinities and greater growth with nitrogen fertilization.

Over a range of salinities, Bradley and Morris (1991b) again used lab culture of *Spartina* collected from North Inlet to examine how the plant managed to thrive under osmotic stress. They measured evaporation from control chambers, plant growth as volume of water taken up during a time interval and incorporated as wet tissue weight, and, by difference, whole plant transpiration. They found that plant growth declined as simulated soil salinities increased. Plant height, leaf area, and total plant biomass were considerably lower at a salinity of 40 compared to 10. Higher salinity thus reduced transpiration by reducing plant biomass. Measures of the rate of ion exclusion by root secretion also increased at increased salinities. This plant manages salt stress by minimizing uptake of salts through its roots and by excreting about half the salt it takes in through its leaves, a remarkable and successful adaptation to harsh, if not sometimes lethal, salt gradients often encountered in the salt marsh.

Morris (1995) studied the dynamics and mass balance of porewater salinity by modeling the movement of both water and salt using a variety of data on rainfall, tidal floodwater salinity, evaporation, evapotranspiration, diffusion, plant excretion of salts, and drainage by gravity. His model ignored any groundwater inputs and assumed that water movement was strictly vertical within the sediment. The model was run for both exposed and flooded sediments. Generally the salinity of porewater remains constant in the upper 30 cm of the sediment, with a salinity drop of only about 2 during rain events in the uppermost centimeter. Porewater salinities were almost 4 units lower at the Oyster Landing site than at the Goat Island site, mostly because of Oyster Landing's closer proximity to freshwater forest runoff. His Figure 1 illustrates the mass balance of salt and water during exposure and during flood tides. Infiltration was also higher at Oyster Landing due to the greater permeability of the soil there. Salt that builds up in sediments from evaporative water loss is lost primarily by drainage, as plant-mediated losses are much less significant. Porewater salinities were always highest in summer and lowest in winter, reaching maxima of about 40 and 50 at Oyster Landing and Goat Island, respectively. Elevation and tidal flood frequency are the major determinants of porewater salinity, however. This modeling effort closely matched empirical data collected at both sites and provided valuable insights about seasonal and interannual changes in marsh productivity.

- **Sediment Aeration and Bioturbation**

Sediment aeration is necessary for *Spartina* roots. Gardner (1973a) studied the drainage characteristics of mid-marsh areas and later (Gardner et al., 1987) estimated the influence of bioturbation by fiddler crabs whose burrowing activities on the creek banks of North Inlet can turn over 7 cm^3 of sediment per square centimeter per year. King (1988) studied bacterial sulfate reduction in creek bank sediments, another process involved in the mechanics of sediment aeration. Following earlier work by Morris and Whiting (1985) on the movement of air into and gases out of sediments of the high marsh, short *Spartina* zone, Bradley and Morris (1990a) measured sediment compressibility in four sediment types in North Inlet and found that the entry of air into the sediments was sufficient to oxidize reduced sulfur compounds like pyrite. Water loss from sediments via evapotranspiration was important in this aeration process during low tide.

Gardner et al. (1988) pursued additional studies on sediment sulfur species in the salt marsh along transects that included short, medium, and tall plants. Their discussion of the roles played by belowground *Spartina* production, evapotranspiration, fiddler crab burrowing, and porewater movement on sulfur chemistry explains much about the variable presence of sulfides and pyrites and iron oxides in the salt marsh. Fiddler crab activities bring sulfides up to the surface that are replaced by iron oxides moving from surface sediments down into their burrows. Sharma et al. (1987) provided strong evidence for the role that bioturbation plays, especially at creek banks, in making iron oxide-rich sediments available to react with any hydrogen sulfide produced by sulfate reduction.

- **DMSP and Grazing Stressors**

Adaptations that limit the adverse effects of high soil salinity help make *Spartina* a salt marsh dominant, but this plant must also cope with reducing sulfidic conditions in the soil. Another plant compound, dimethylsulphoniopropionate (DMSP), was thought to help *Spartina* detoxify excess sulfur. Following earlier studies of DMSP in *Spartina* by Otte and Morris (1994) and Morris et al. (1996), Otte et al. (2004) found that concentrations of DMSP did not respond to changes in salinity or sulphide concentrations in soil, suggesting that DMSP plays neither an osmolytic nor a sulphide detoxification role in *Spartina*. However, Kiehn and Morris (2010) suggested that changes in the DMSP content of *Spartina* under stress may be used by periwinkle snails, *Littoraria irrorata*, as a trophic trigger or signal that attracts snails to plants. The incidence of salt marsh diebacks in the southeast in the past decade has increased, and there is intense debate about whether this is due to top-down (grazing) control or bottom-up (nutrients and edaphic factors). Kiehn and Morris (2009) in a 40-month transect survey found that *Spartina* stem density correlated positively rather than negatively with the density of periwinkle snails in North Inlet and that the snails were more abundant in long-term fertilized plots of *Spartina*. The absence of evidence for any top-down controls on *Spartina alterniflora* biomass or productivity at three locations in North Inlet as well as a low incidence of blue crab predation on snails found by Long (2006) suggests that significant snail grazing impacts are likely greater only on plants that have become stressed in isolated areas.

- **Sediment Composition and Supply Effects**

Part of the slow buildup of salt marsh sediments is due to incorporation of organic matter (OM) as part of the sediment structure. This organic matter comes from several sources, including vascular plants (roots, detritus), terrestrial litter, benthic micro- and macroalgae, bacteria, and settled phytoplankton. The remains of burrowing and other types of animals may also contribute to the sediment's OM content. To examine the various sources of organic matter that get buried in saltmarsh sediments, Ember et al. (1987) took core samples to depths of 40 cm in tall and short *Spartina* areas and also deployed litter bags both above- and belowground. The core samples and litterbag contents (aged for 15 months) were analyzed for their carbon and nitrogen content and for their carbon stable isotope signatures. They found that diagenesis of sedimentary OM takes place deep within the sediment, below the depth to which *Spartina* roots and rhizomes extend (about 25 cm or 10 inches). *Spartina* biomass was not a major contributor to buried OM in the marsh, but the refractory components of this biomass (e.g., lignocelluloses and humins), and the carbon:nitrogen ratios and stable isotope fractionation signatures were consistent with the enhanced presence of these decay-resistant components. Ember et al. (1987) were also able to rule out bacteria as a contributor to the isotope signatures occurring at depth despite the fact that diagenesis of plant material eventually resembles the isotopic signature of bacteria. Bioturbation was implicated as the mechanism by which OM is mixed into sediments, especially in the tall *Spartina* zone along creekbanks. Carbon isotope analyses alone were insufficient for uniquely identifying the various possible sources and types of sedimentary organic matter found in the salt marsh habitat.

Because of their relevance to how the *Spartina*- and *Juncus*-dominated saltmarsh plant communities in the NI-WB NERR will evolve, several studies of sediment supply and redistribution in North Inlet and/or Winyah Bay should be consulted. These include Settlemyre and Gardner (1975, 1977), Wolaver et al. (1986), Wolaver et al. (1988a,b), Gardner et al. (1989), Pillay et al. (1992), Childers et al. (1993a), Hutchinson et al. (1995), Vogel et al. (1996), Goni and Thomas (2000), Mwamba and Torres (2002), Torres et al. (2003, 2004), Voulgaris and Meyers (2004 a,b), Patchineelam and Kjerfve (2004), Goni et al. (2005), Gardner and Kjerfve (2006), Murphy and Voulgaris (2006), and Goni et al. (2009). An important aspect of this sedimentation issue is the erosion impact that major coastal storms and hurricanes may have on North Inlet, Winyah Bay, and similar coastal habitats [see Gardner et al. (1991), Gardner et al. (1992a),and Kjerfve et al. (1994) regarding the impact of Hurricane Hugo in September 1989].

- **Carbon Transformations and Dynamics**

Understanding how carbon moves through ecosystems is fundamental for making predictions about how these systems might change over time. Carbon uptake, transformation, storage, and loss rates occur throughout the salt marsh, but little work has been done to quantify these processes. Morris and Whiting (1986) measured fluxes of carbon dioxide gas from unvegetated portions of sediment in the high marsh and also from the low marsh adjacent to tidal creeks when sediments are exposed at low tide. Loss of carbon dioxide from sediments to the atmosphere varied seasonally (i.e., with temperature), being greater in summer than in winter. Loss was greater from the high than from the low marsh as well. When the marsh sediments are covered by the tide, carbon is lost to overlying waters as dissolved inorganic carbon. The complexities involving microbial respiration in the sediments, living root gas exchanges during *Spartina* photosynthesis and belowground plant production, presence/absence of suitable buried organic substrates for microbial metabolism, porewater turnover, diffusional losses, changes in temperature, etc., make these measurements very difficult both technically and interpretationally. These investigators felt that carbon dioxide loss and fluxes from sediments accounted for a significant, though small, portion of total plant photosynthesis in the salt marsh as *Spartina* fixes carbon taken up from below ground through hollow spaces in its stems.

The question of where *Spartina* gets the inorganic carbon that it fixes during photosynthesis prompted Hwang and Morris (1992) to grow plants from North Inlet in pots in the laboratory under gas-tight conditions. This technique was developed previously by Hwang and Morris (1991) in an investigation of how *Spartina* moves atmospheric oxygen hygrometrically to its roots in anoxic sediments. Huang and Morris (1992) utilized the radioactive ^{14}C method to label gases in the lacunar spaces of the plant (via injection) and then followed the radioactivity's path through the plant. In short, they found that uptake and utilization of dissolved inorganic carbon from interstitial water in the sediment was quite small compared to the amount of atmospheric carbon dioxide taken up and fixed by the plant's leaves.

- **Productivity**

Dame and Kenny (1986) undertook the laborious harvest method of measuring both aboveground and belowground productivity of short, tall, and intermediate forms of *Spartina alterniflora* at three sites (creekside, mid-marsh, high marsh) in North Inlet over 5 years, 1981-1985. They used 0.25 m^2 plots and collected cores to 40 cm depth to measure living and dead root biomass for calculations of net belowground primary production. Leaf litter decomposition was also taken into account using small mesh cages aboveground. They measured highest aboveground biomass in late summer at all three sites, with highest amounts of dead biomass in winter. There was a gradient in mean stem height as well, with the tallest plants creekside and shortest in the high marsh. Variation from year-to-year in above ground biomass was high at all sampling sites. Creekside plants had higher growth during years when precipitation was high and salinity was lowered. Summer rates of decomposition were higher than in winter. Belowground live biomass was highest at the high marsh site. So-called "root-to-shoot" biomass ratios, indicative of the stress a plant is under, varied between 2 and 76 depending on season and site but generally reflected an adaptation to high salinities. Belowground primary production was about the same as aboveground primary production for the creekside site but greatly exceeded aboveground production at the high marsh site. Aboveground average net primary production (g m^{-2} y^{-1}) was 2188 creekside, 724 midmarsh, and 1295 in the high marsh. Average net belowground primary production (same units) was 2363 creekside and 5445 in the high marsh. Their measurements of productivity, among the highest reported for salt marshes, revealed great variability both within sites, between sites, and between years within sites. They also calculated biomass turnover rates as high as 5 y^{-1} for the aboveground portion of tall plants at the high marsh site. This variability suggests that models which incorporate saltmarsh primary production values must take this uncertainty into account. Accuracy of the harvest method utilized here has been criticized by Morris and Haskin (1990) and other investigators cited therein, but this harvest-based study still serves as a comparator for other similar harvest-based studies.

Measuring the aboveground productivity of *Spartina alterniflora* in North Inlet, Morris and Haskin (1990) used a non-destructive method that took into account stem and leaf turnover in permanent plots for more than 5 years. This data record length was sufficient to examine reasons why there was a two-fold interannual variation in production. Their method utilized regression equations of stem height versus stem biomass and monthly measures of stem height of tagged stems on permanent plots. Leaves on stems were also tagged to estimate leaf turnover. Net aboveground production was calculated on both a monthly and annual basis. For plants older than 10 months, leaf loss was a significant part of its annual production. Plants lived for about 18 months, on average. Stem density was greater in the older marsh at Goat Island than in the younger marsh at Oyster Landing by a factor of two or more, with peak density occurring in fall-winter and lowest in June-July. Interestingly, maximum stem density occurred several months after calculated peak biomass. Plant growth rates were highest when stem densities were lowest at both sites. Despite the two-fold difference in stem density, net aboveground production per unit area of marsh surface was the same, suggesting that plants had different strategies for growth allocation at the two locations. Goat Island plants allocated more to vegetative reproduction than to increased stem growth. They also found positive correlations between annual productivity and both rainfall and sea level anomalies, and that both had greatest effects in summer. Thus future variations in the rate of sea level rise could have significant impacts on marsh productivity and subsequent secondary productivity (Morris et al., 1990). Annual aboveground dry biomass productivity ranged between 402 and 1042 g m^{-2} over the 5-yr period from 1984 to 1988. Morris and Haskin (1990) also raised questions about harvest methods for estimating annual production and the effects of spatial variability in standing biomass for examining temporal trends in productivity. Morris has continued long-term monitoring of *Spartina* at Oyster Landing and Goat Island using this non-destructive method. Figure 69 shows the mean annual aboveground productivity of high marsh *Spartina alterniflora* from 1984 to 2008 at Goat Island and Oyster Landing. He has found evidence of an 18.6-yr cycle of productivity, corresponding to the lunar nodal cycle, and an upward trend. The upward trend suggests that the marsh is not keeping pace with sea-level rise.

- **Chemical Composition and Stable Isotopes**

Ornes and Kaplan (1989) analyzed the macronutrient chemical composition (N, P, K, Ca, Mg, and S) of live plants and live roots harvested by Dame and Kenny (1986). They also collected soil samples at intervals down to a depth of 27.5 cm in each season for a year and analyzed them for redox potential (Eh), sulfide, P, Ca, Mg, Fe, orthophosphate, ammonium, total dissolved nitrogen and total dissolved phosphorus. Concentrations of shoot N peaked in winter and decreased to a minimum in July as the increase in shoot biomass at this time caused a dilution of the N concentration. Monthly root N concentrations did not change appreciably during the year but were, on average, higher in the tall form of *Spartina* than in the short form, whereas shoot and root P was higher in the short form than in the tall form. Root N concentrations did not change over time in either plant form. Soil concentrations of ammonium were sufficiently high that they were not limiting to plant growth, leading to the conclusion that other factors limit

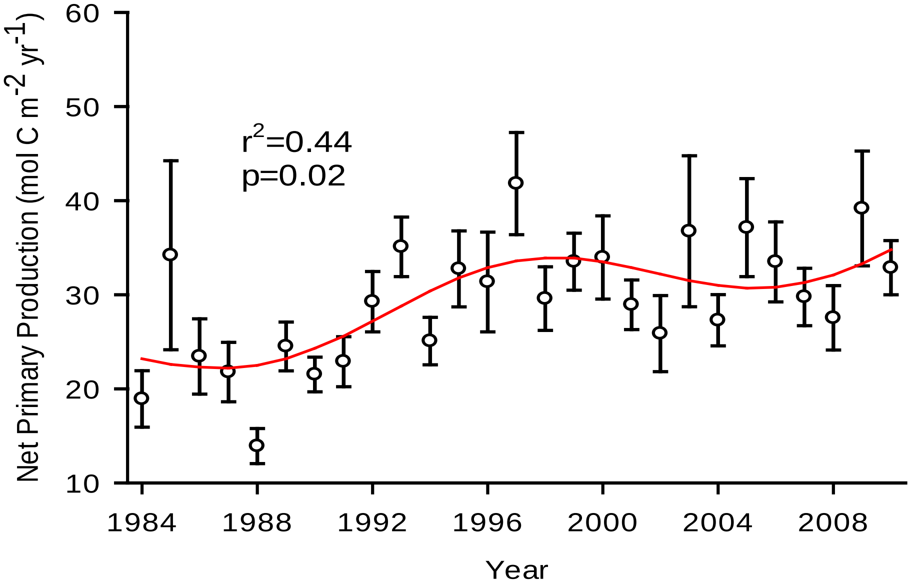


Figure 69. North Inlet mean annual aboveground production of *Spartina alterniflora* as derived by the non-destructive census technique of Morris and Haskin (1990). The red line is the result of an harmonic regression with a period length of 18.6-yr, corresponding to the lunar nodal cycle, and with an upward trend.

the growth of the plant, especially in the high marsh. Interactions between iron and sulfide were implicated as moderators of N limitation. Although N, P, and S changed, Ca, Mg, and K generally did not change over time in shoot tissues.

Following work begun by Ember et al. (1987), Bernot et al. (2008) also measured the stable isotopes of carbon and nitrogen in the roots and stems of intertidal short *Spartina* that had undergone long-term fertilization for between 10 and 20 years, a manipulation started by Morris and his students [see Sundareshwar and Morris (1999), Morris (2000), and Morris et al. (2002)]. Bernot et al. (2008) found that fertilizer-amended plots showed evidence of nitrogen limitation as well as changes in phosphorus uptake that, based on the stable isotope values and their mild fractionation, was due to chronic nutrient inputs from coastal development over time. The impacts of these inputs were confined to the uppermost 5 cm of the sediment column.

- **Nitrogen and Phosphorus Dynamics**

Sundareshwar et al. (2001) looked closely at the role of phosphorus compounds in salt marsh ecology. Because standard methods for measuring bioavailable forms (e.g., soluble reactive phosphorus) do not detect polyphosphates, they used nuclear magnetic resonance spectrometric methods to measure pyrophospahate (Ppi) in a variety of coastal wetlands, including North Inlet as an undeveloped control site. They found that Ppi concentrations were higher where coastal development was higher. They also demonstrated that microbial utilization of Ppi can supplement other forms of bioavailable P by making additional orthophosphate available for plant uptake.

It has been generally believed that *Spartina alterniflora*'s growth is limited by the amounts of available nitrogen. However, observations that salt marshes export nitrogen and that ammonium is abundant in the areas where short forms of this species grow prompted Bradley and Morris (1990b) to examine what factors might be limiting the ability of *Spartina* to uptake nitrogenous nutrients. They examined the uptake kinetics of ammonium as influenced by pH, sulfide, and oxygen concentrations. Uptake varied considerably between oxic and anoxic conditions. Their Figure 4 illustrates how ammonium uptake varies in the high versus the low marsh, especially as influenced by the concentrations of dissolved oxygen and sulfides in the sediments. Their work contributed to the understanding that nitrogen-limitation alone cannot explain *Spartina* growth dynamics, as other edaphic factors influence how the plant obtains this essential nutrient.

Bradley and Morris (1991a,b) studied the ability of *Spartina alterniflora* to take up nitrogen in the form of ammonium ions. They subjected short form plants taken from the high marsh and potted in sand to a broad range of salinities and later measured their short- and long-term NH_4^+ uptake kinetics following the same methods used by Bradley and Morris (1990b). Following Michelis-Menten kinetics, ammonium uptake was quantified according to V_{max} and K_m, the maximum uptake rate per gram of dry plant tissue and the half-saturation constant, respectively. For salinities less than 50 gL^{-1}, V_{max} did not change. However, increasing salinities caused K_m to decrease, thereby reducing ammonium uptake and decreasing the productivity of the plant. Both short-term increases and long-term exposure to high salinities inhibited ammonium uptake. Bradley and Morris (1992) determined the minimum nitrogen concentration in *Spartina* leaf tissue necessary to sustain growth. This concentration was also a function of salinity. Their study supported many other observations that nitrogen limits both tall and short forms of this saltmarsh plant.

Bacterial transformations of nitrogenous compounds in the sediments are an important source of this limiting nutrient for salt marsh plants. Sundareshwar et al. (2003) found that such bacteria in the salt marsh can be limited by available phosphorus. Differential limitation of salt marsh autotrophs by nitrogen and microbial heterotrophs by phosphorus has important implications for the carbon cycle and for management of coastal habitat in the face of continued anthropogenic inputs of fertilizer and sewage that contain both of these essential nutrients.

Based on earlier work by Yoch and Whiting (1986) mentioned in the following Microbial Communities section, Whiting et al. (1986) examined how tightly coupled nitrogen-fixing bacteria are to the process of photosynthesis by *Spartina alterniflora*. Using field-emplaced and laboratory growth chambers with short *Spartina* from North Inlet, they measured acetylene reduction activity (ARA) under conditions of enhanced carbon dioxide that stimulated the plant's rate of photosynthesis. Data from the hydroponic chambers used established that root-associated bacteria were stimulated under these conditions. The evidence that root microflora utilized photosynthates from *Spartina* suggested tight linkages, but how the fixed nitrogen got utilized by the plant remained unanswered.

Morris and Bradley (1999) addressed the issue of chronic eutrophication by reporting on the carbon balance in plots of the North Inlet salt marsh that had been fertilized monthly since 1984 (see Morris, 1988). This N and P amendment resulted in an increase in mean aboveground dry matter production of *Spartina alterniflora* to 3,280 g m^{-2} y^{-1} from control, unfertilized, plot values of 780 g m^{-2} y^{-1} over the period 1985 – 1996. More importantly, soil respiration in the fertilized plots increased significantly and the amount of carbon belowground decreased, but the amount of C loss in the soil could not account for the amount of respiration increase, suggesting that increased primary production was the cause of the disparity. Incubations of plants in the laboratory produced similar results regarding an increase in soil respiration. Thus fertilization can result in an increase in the rate at which carbon turns over in sediments and can result in a net loss of carbon from the sediment. Such losses add additional carbon dioxide to the atmosphere compared to the normal, non-fertilized conditions.

- **Oil Pollution Effects**

The continuing threat of chronic oil pollution in coastal salt marshes prompted Li et al. (1990) to measure the effects of hydrocarbon exposure to *Spartina alterniflora*. They took healthy plants from the low marsh and moved them to the laboratory where daily additions of oil at 1x and 10x concentrations (= 3.33 and 33.3 gC m^{-2} d^{-1}) were accompanied by measurements of plant growth and respiration for almost two years. They also monitored sediment microbial activity. Compared to control plants, those exposed to the 1x treatment exhibited a stimulatory response, while those at 10x were inhibited. Both above- and belowground biomass and respiration rates increased over time, as did soil microbe activities (CO_2 production, methanogenesis, N_2 fixation, denitrification), but all of these processes declined greatly in the higher concentration (10x) treatments. The authors suggested that perhaps the microbes were carbon-limited, while plant growth increased as a result of enhanced rates of nitrogen fixation/mineralization.

- **Hydrography and Marsh Elevation**

The influence of hydrography and marsh elevation on the plant community in North Inlet was mentioned by Schwing and Kjerfve (1980) in their studies of circulation in Jones Creek, a waterway that connects North Inlet proper with Winyah Bay. They identified a nodal point (similar to a fall line or a continental divide on land) in Jones Creek that functioned to limit the amount of exchange between the two larger bodies of water. *Spartina alterniflora* dominated the vegetation northward from the node towards North Inlet, while on the southward side of the node towards Winyah Bay a more diverse plant community existed (i.e., *Juncus roemerianus*, *Spartina cynosuroides*), without a dominant species.

- **Models: Light, Nutrients, Marsh Elevation, and Sea Level Rise**

Morris (1989) modeled how *Spartina alterniflora* intercepts incident solar radiation on its leaf surfaces. He found that the highest leaves, being vertically oriented, absorb less sunlight and heat than horizontal leaves. From his model's results, it would appear that this halophyte maximizes light absorption and uses water quite efficiently, all the while minimizing its heat gain from the sun.

A comprehensive examination, done via numerical modeling, of the fates of carbon, sulfur, and oxygen during diagenesis in salt marsh sediments was done by Gardner (1990). Pyrites, sulfur reduction, and organic matter oxidation were followed in a depth profile in the sediment. These processes all have bearing on marsh productivity as will be seen in greater detail below. In another modeling effort, Gardner (2005) examined the marsh's discharge of groundwater through the creek bank into the tidal channel. The model was complex and served to illustrate that there does not seem to be any sort of "underground estuary" in North Inlet that supplies nutrients to creek waters. This underground estuary concept had been proposed by Moore (1999). Rather two-thirds of the seepage occurs mostly near the intersection of the tidal water level with the creek bank (one third comes out in the creek bottom) and reaches volumes of approximately 5-10 liters per longitudinal meter of creek bank per tide. This seepage was proposed as a mechanism by which sulfides are flushed from marsh sediments, thereby resulting in enhanced rates of primary productivity at the creek's edge by *Spartina alterniflora*.

Mean annual sea level changes from year-to-year by an average of almost 3 cm, a variation imposed on the even longer-term rise due to climate change. In addition, mean monthly sea level varies over the solar cycle by 24 cm (about 10 inches) on average. When these changes result in anomalously high or low flooding of the marsh surface, the salt content of the soil can change considerably. Morris (2000) studied long-term relationships between *Spartina* productivity and changes in sea level, noting that net annual aboveground production varies by a factor of two, higher when sea level is higher, lower when less water covers the marsh and soil salinities are higher. Thus hydrography and marsh elevation interact to influence primary production by vascular plants in the coastal ecosystem. This theme and additional work by Morris et al. (2002) on sediment accretion in North Inlet led to development of a model that predicts how stable the plant community will be relative to sea level rise. There is an interesting feedback between plant growth, sediment elevation, and relative sea level rise. A comprehensive review of controls, biotic and abiotic, on the productivity of *Spartina alterniflora* by Mendelssohn and Morris (2002) is a useful resource for those interested in how this plant dominates southeastern salt marsh plant communities.

Researchers examine relationships between *Spartina alterniflora* productivity and sea level.

Because marsh elevation above sea level is such a strong correlate with marsh productivity, Morris et al. (2005), using LIDAR and ADAR imaging data, computed the frequency distribution of this elevation in North Inlet. They found a normal distribution for elevations in which *Spartina* occurred with a median elevation of 0.349 m. *Juncus roemerianus* marsh, however, had a median elevation of 0.519 m above the North American Vertical Datum 1988. Their data suggests that the marsh has not kept up with the slowly accelerating rise of sea level in recent decades. However, an earlier study by Vogel et al. (1996) suggested that the marsh surface is accreting vertically at a rate of 2.7 mm per year, while sea level is rising between 2.2 and 3.4 mm per year, i.e., the marsh is keeping pace with sea level rise and is adding enough sediment to also expand laterally landward. The question about whether *Spartina* and other marsh plants will thrive in the future under continued sea level rise remains to be answered, but additional work on this elevational correlation by Scott (2010) found that marsh surfaces closest to sediment sources (e.g., nearer Winyah Bay) had higher mean elevations than areas at greater distances from sediment sources. The elevational differences, however, were small, and the LIDAR data suggested that none of the North Inlet marsh is presently undergoing submergence from sea level rise.

Mathematical models are a prime tool for predicting the future state of the environment. Because of the extensive work and long-term data that exist for North Inlet's *Spartina alterniflora* population, Mudd et al. (2004) constructed a model of how these plants respond to tidal inundation, sedimentation, submergence time, and changes in its own aboveground biomass. The model relates to how the elevation of the salt marsh platform will evolve under future sea level rise. The model revealed that there is much work still to be done on how water flow and sedimentation rate are affected by emergent vegetation, and how accumulated sediments compact as their accretion rate changes.

Creating a model that incorporated long-term data on belowground biomass of *Spartina* in North Inlet, Mudd et al. (2009) explored additional aspects of how salt marshes might thrive or decline with future increases in sea level. Sedimentation includes both inorganic and organic particles. Incorporation of organic carbon in the model demonstrated that carbon accumulation in the salt marsh is related, non-linearly of course, to supply of inorganic sediment and sea level rise. The model suggests that the response of salt marshes will be greatly dependent on supplies of sediments to estuaries. Because coastal development often alters the sediment supply in rivers leading to estuaries and alongshore on beaches, the carbon budgets of coastal salt marshes could change in significant ways. Mudd et al. (2010) proposed two models that build upon earlier efforts to understand feedbacks between plant growth and sedimentation (of both organic and inorganic particles) as well as the effects of organic particle sedimentation on methods used for dating marsh sediments. These models of biologically-mediated sedimentation show rather convincingly that most of the rate of sediment accretion in the marsh can be explained by the enhanced particle settling due to reduced turbulence amongst *Spartina alterniflora* stems, particularly in the fertilized plots from which Morris et al. (2002) used data in his model of how the marsh grows under sea level rise. Morris (2004) suggested that the feedback between plant growth and the growth rate of marsh elevation is relevant for coastal areas that are sinking relative to sea level.

Morris (2010) summarized previous work and extends a one-species model for *Spartina alterniflora* in North Inlet to a generalized two-species model that incorporates the various feedbacks between biological and physical factors that affect the competitive abilities of, for instance, invasive plant species. This model examines geomorphological displacement and competition such as occurs when *S. alterniflora* becomes established in new habitats. This coastal macrophyte management issue is currently under intense examination on the west coast of the United States.

Sufficient research has now been done that several investigators have used a compendia of data, all using North Inlet as a core representative piece, to summarize predictions of what will happen as climate change becomes more dramatic (e.g., Day et al, 2008). Data for non-tall forms of *S. alterniflora* along the Gulf and Atlantic coasts of North America incorporate North Inlet measurements that Kirwan et al. (2009) included in a methodologically comparable examination of latitudinal trends in productivity. Kirwan et al. (2010) also utilized North Inlet data to model adaptability in the response of coastal marshes to sea-level rise. It will be interesting to see which of or whether any of the predictions made by Dame et al. (1992) come to fruition.

- **Summary for Vascular Plant Research**

In summary, vascular plant communities, especially those dominated by *Spartina alterniflora*, in North Inlet have been studied more than any other segment of the photosynthetic biota present. Early studies examined plant physiologies and adaptations to changes in soil porewater salinity, and later manipulative studies revealed relationships between plant growth and many environmental variables. Belowground biomass of *Spartina alterniflora* receives oxygen via movement of porewater, from bioturbation activities, and thus tolerates hydrogen sulfide toxicity via actions of sulfate reducing bacteria and these other oxygenation processes. The plant's salinity tolerance results from its osmoregulatory capabilities. Evidence suggests that both tall and short forms of *Spartina* in mid and low marsh levels are regulated by bottom-up forces, primarily nitrogen limitation, with top-down grazing impacts negligible in this regard. High marsh plants are regulated by salinity, not nutrients. The buildup of salt marsh sediments around *Spartina* is a consequence of organic matter accumulation via bioturbation and settling of suspended sediments in the low turbulence zones of the vegetated portions of the marsh. There has been a net increase of sedimentation over time sufficient to match the rate of sea level rise. Annual net dry aboveground productivity of *Spartina* varied by a factor of two during the year and stem density was highly variable, being greater in older portions of the salt marsh. Long-term fertilization of *Spartina* created higher carbon turnover rates and greater loss of carbon dioxide from sediments relative to controls. Flushing of sulfides from porewater at the edges of tidal creeks enhances growth of the plant there. *Spartina* productivity also responds to annual changes in sea level, being higher when sea level is higher and lower when sea level is lower. Edaphic factors (e.g., sediment dynamics, porewater nutrient levels, and the sediment's microbial activities) play important roles in regulating saltmarsh plant communities. Models of plant interactions with and responses to changing stressors, especially sea level, have revealed several phenomena that require additional investigation. Overall the saltmarsh plant community of North Inlet is healthy and productive. However, current research suggests the marsh may not be keeping pace with sea level rise.

» Microbial Communities

The earliest microbial studies in North Inlet concerned how microbes were affected by the twice daily change of the tides. Research evolved afterwards and transitioned from the traditional lab-based studies of microbial communities cultured from the environment to the examination of their abundances and functional characteristics *in situ*, and most recently to an integrated, multidisciplinary approach. Modern molecular methodologies hold great promise for understanding more deeply how diverse microbial communities change over time and influence the type of coastal ecosystem represented by the NI-WB NERR.

Early concerns about water quality in the area centered on human health and the fecal coliform loads that harvestable species (e.g., clams and oysters) might carry. Nelson et al. (2005) reviewed microbiological and water quality data from the years 1967-1990 relevant to land use change at an urbanized site, Murrells Inlet, and at a pristine site, North Inlet. While increasing urbanization had been accompanied by increasing trends in fecal coliforms at Murrells Inlet, the construction of a sewage system decreased these loads starting in 1980. At North Inlet, construction of the Baruch Marine Field Laboratory in 1977 had no measurable impact on water quality above that which existed from natural sources of bacteria in the natural background. North Inlet has thus always been viewed as a relatively pristine, natural site, remaining comparatively uncontaminated by human interventions. This important attribute was critical for its selection as an LTER site and as a National Estuarine Reseaerch Reserve.

Following a rough chronology of research and topical themes, the earliest studies of microbes in North Inlet were conducted by L. Harold Stevenson and his students. Stevenson was also a co-editor with R. Colwell in 1973 of the first volume of the Belle W. Baruch Library in Marine Science entitled “Estuarine Microbial Ecology” dedicated to a pioneer in the study of marine microbiology, Professor Claude E. Zobell.

The earliest studies of microbes themselves, particularly bacteria, in North Inlet emphasized culturable species/taxa and employed classical physiological laboratory assays. Erkenbrecher and Stevenson (1975) examined the influence of tides on the concentrations of microflora in two tidal creeks in North Inlet. They found that aerobic heterotrophic populations in the water column peaked just before low tide due to resuspension and became lowest during high tides due to dilution from the influx of coastal seawater. Average concentrations ranged between 10^4 and 10^5 mL^{-1}, with lower concentrations at the Clambank station where bottom sediments were sandy, hence having less sediment in suspension compared with the muddier Oyster Landing station. They cautioned that microbial populations are quite different from creek to creek and that extrapolations from creek-scale studies to larger areas can be in error. A similar conclusion, though at a much larger spatial scale, was found in a comparison of the microbial communities in two SC marsh systems (ACE Basin and North Inlet) almost 30 years later by Johnson et al. (2006).

Sizemore et al. (1973) sampled sediments and water on the landward side of Debidue Island in North Inlet to measure the abundance and distribution, within the sediment column, of bacteria having proteolytic capabilities. On tests of 204 stock isolates and random isolates from the estuary, 44% of sediment organisms were proteolytic, while 49% of those from the water also exhibited the ability to degrade protein, casein in this study. Seasonal changes in these percentages were slight, and the population of proteolytic bacteria was highest at a depth of between 2 and 8 cm in the sediment. An earlier techniques paper established the protocol for these studies and was followed by a physiological scoping paper on the role of dissolved oxygen in proteolytic activity (Sizemore and Stevenson, 1970, 1974).

Coull (1973) reviewed the extant literature on the role of microbes in the ecology of marine meiobenthos, small metazoans that inhabit marine sediments globally. Coull posited the importance of bacteria and other microbes as food for meiofauna and in decompositional processes involving these ubiquitous organisms that have been studied extensively in North Inlet. Coull's students later measured meiofaunal grazing rates on sediment microbes and bacteria in North Inlet (Montagna et al., 1983; Montagna, 1984a, b).

In a study of the fungal community, Cowley (1973) sampled soil from 7 stations along an intertidal transect in North Inlet from the tall *Spartina* to the upper edge of the high intertidal *Juncus* zone to quantify fungal species. He found much greater biomass of culturable species in the *Spartina* "debris" between the *Salicornia* and *Juncus* regions but considerably more diverse communities at the other stations.

Pitts and Cowley (1974) sampled fungi and discovered that sediments in and around the burrows of *Uca pugilator* contained a red yeast (*Rhodotorula mucilaginosa*). When crabs were active in October, 94% of the animals examined contained this same yeast in their mid-gut. In winter (February), less than 8% contained the yeast. Because several other mycoflora were found in the sediment, the authors suggested that this red yeast is a selected dietary component of this fiddler crab species. Cowley and Chrzanowski (1980) sampled yeast from the sediment and in the midguts of the fiddler crab, *Uca pugilator*. They found that two species of yeasts were abundant around their burrows at Clambank Landing, North Inlet, as well as in their guts. They suggested that yeast ingestion could supply B-vitamins to crabs that might experience a vitamin-deficient diet.

Physical-chemical factors and the effects of changes in the tide on microbial communities (Erkenbrecher and Stevenson, 1975) and the flux of microbial biomass as it is affected by the tide were studied by Erkenbrecher and Stevenson (1977). The same two investigators also examined changes in ATP (a proxy for microbial biomass), chlorophyll *a*, POC, and suspended materials during four 40-hr time series during the year and found that a high marsh creek was an exporting system for these materials (Erkenbrecher and Stevenson, 1978). They also found a close association between bacteria and suspended matter in that study. Stevenson (1978) suggested that many of the bacteria in aquatic systems must adapt to large changes in their physical environment (e.g., solar insolation, oxygen concentrations, nutrient substrate concentrations, etc.) or else they will die. He proposed that an alternative strategy for survival in the face of a changing environment is for bacteria to become physiologically dormant. At that time, this hypothesis was quite controversial.

A study of microbial communities as they are influenced by freshwater input into North Inlet from Winyah Bay found that salinity had little influence on or relationship with total microbial biomass (as ATP) in the salt marsh creeks of North Inlet (Weiland et al., 1979).

Chrzanowski and Stevenson (1979, 1980) contributed to tests of the Outwelling Study hypotheses by quantifying fluxes of fungi and total microbial biomass (again as ATP) during synoptic sampling events across a 320-m transect in Town Creek near the mouth of North Inlet. They found that fungal biomass fluctuated out of phase with the tide, with low values at high and high values at low tides. Their data also suggested that fungi are mostly associated with particulate organic matter that gets resuspended into the water column by ebbing tides. As part of the Outwelling Study, studies of total microbial biomass (ATP) along three transects across major creeks in North Inlet were coupled with water flow measurements to estimate fluxes of ATP to and from the coastal ocean. Stevenson et al. (1980) found that the ATP density (mg ATP per cubic meter) in the water column was highest during high tides, with a net import of approximately 40 mg ATP per second in the two creeks that connected directly with the ocean, and net export across the transect of a creek that empties into Winyah Bay. The complexities of flow over time both horizontally and vertically and during periods of stratification made these measurements difficult (Chrzanowski et al., 1981; Kjerfve et al., 1981).

The utility of using ATP as a reliable measure of total microbial biomass was called into question by Stevenson et al. (1981) who demonstrated that the luminescence from the luciferin/luciferase reaction for measuring ATP does not come exclusively from the ATP nucleotide. Additionally, they provided evidence for past overestimation of ATP due to different methods of peak height estimation and water filtration used by different investigators. Wilson et al. (1981) also showed that, on average, bacterial ATP comprised only about 25% of the total ATP measured in high marsh water samples where sediment-associated microbes were abundant.

The study of microbes in North Inlet took a methodological leap in the early 1980s with the introduction of newer analytical techniques and instrumentation, e.g., epifluorescence microscopy and SEM (scanning electron microscopy). These instruments allowed quantification of the "planktobacteria" (= bacterioplankton) and for the first time the actual numbers of bacteria in various types of samples were measured in North Inlet (Wilson and Stevenson, 1980).

Although direct counts of bacteria were not conducted in most studies of microbial biomass in North Inlet, the use of ATP as a surrogate measure served to answer many of the flux questions posed by investigators, especially at smaller spatial and temporal scales. Chrzanowski and Zingmark (1986) sampled water moving across the marsh in a flume constructed in the Bly Creek basin near the field lab synoptically with samples taken from a transect across Bly Creek. Their measurements of ATP suggested that microbial biomass was passively filtered and removed from the water column by the tall form of *Spartina* along the creek bank and that the high marsh was the place where microbial communities separated into different components.

Chrzanowski and Zingmark (1989) measured bacterial abundance, biomass and secondary production in surface water samples collected at three stations in North Inlet: forest, high marsh creek, and low marsh creek. All sites were within a single drainage basin and were sampled bi-weekly for a year. The forested stream had lower abundances, biomass and production rates than the two marsh creek stations. Abundances and growth rates were higher during low tides at these two marsh creek stations as well. Bacterial secondary productivity co-varied with salinity. The results suggested that bacterial dynamics (growth rates) were more closely associated with individual water masses than with any aspect of the landscape.

The activity of nitrogen-fixing bacteria in salt marsh sediments associated with *Spartina* roots was investigated by Yoch and Whiting (1986). They measured the short-term effect of ammonium additions on acetylene reduction activity *in situ* in the short *Spartina* zone of the marsh. Ammonia inhibited nitrogenase activity in sediments and in both dead and live roots. The kinetics of this inhibition and its impact on nitrogen-fixation requires additional study. Gandy and Yoch (1988) determined the relative contribution of sulfate-reducing bacteria (SRB) and fermenting bacteria to nitrogen fixation in salt marsh sediments and on the roots of *Spartina alterniflora*. They collected sediment cores from between *Spartina* culms from the high marsh near Clambank Landing and removed roots while maintaining anoxic conditions. Using amendments and inhibitors, they measured acetylene-reducing activity (ARA) and showed that activation of dormant bacterial cells, not cell growth, accounted for measured ARA. Furthermore, 70% of the ARA in the uppermost 5 cm of the sediment was due to SRB, while ARA between 5 and 10 cm depth in the sediment was due to fermenting bacteria. SRB were found to be abundant on *Spartina* roots.

Other studies were done by time-series sampling of flooding and ebbing tidal waters in portions of the marsh confined in linear flumes (e.g., Chrzanowski and Spurrier, 1987). Microbial biomass was measured as concentrations of ATP normalized to unit areas of marsh surface, with fluxes determined by volume transport of these water concentrations over time. Although these ATP measurements had many methodological sources of error and high variabilities (see Stevenson et al., 1979), they served to illustrate that the marsh surface was neutral with respect to transport of microbial biomass, receiving as much from large tidal creeks within the marsh as they exported to them (Chrzanowski and Spurrier, 1987).

In the aftermath of the Outwelling Study, what was learned there stimulated many other investigations of microbial ecology in North Inlet. Trophic selectivity was the focus of work by Wetz et al. (2002) who examined changes in the suspended microbial community as it passed over clumps of oysters in a flume. They found that the oysters, *Crassostrea virginica*, removed mostly phototrophic nanoflagellates and diatoms but left heterotrophic nanoflagellates, cyanobacteria, and heterotrophic bacterioplankton largely unaffected.

In the 1990s, new molecular techniques were utilized to examine the ecological roles these ubiquitous microbe-sized organisms play in the coastal ecosystem. These new techniques do not require the organisms to be cultured, hence the >95% of viable but non-culturable species/taxa could now be examined with regard to their biodiversity/relatedness and, in conjunction with classical microbiological methods, their ecological significance in different habitats within the salt marsh ecosystem. For instance, physiological studies of *Spartina alterniflora*, the salt marsh cordgrass, have shown clearly that these plants are nitrogen-limited and that their growth rates are affected by numerous environmental variables, e.g., temperature, salinity, light regime, macronutrient concentrations, etc. (e.g., Bradley and Morris, 1990b). Cordgrass success in the marsh, however, results from interactions with specialized microbial communities associated with their roots (see below).

Particle- or surface-associated bacteria present challenging problems for enumeration and process-related characterization. The study of microbial communities in the sediments and on plants in North Inlet started in the late 1980s and early 1990s with studies by D. Yoch, R. Lovell and others from the Dept. of Biological Sciences at the University of South Carolina in Columbia, SC. For example, Whiting et al. (1986) examined acetylene-reduction activity (ARA) in root-associated bacteria that function in nitrogen fixation in the salt marsh grass, *Spartina alterniflora*. They found that N-fixation was enhanced rapidly when photosynthesis was stimulated, suggesting that ARA was dependent upon plant photosynthate as an energy source. Sediment respiration, ARA, methanogenesis and denitrification were examined in microcosm experiments involving the stimulatory effects of chronic hydrocarbon exposure in *Spartina* by Li et al. (1990). Steward and Lovell (1992) devised an improved method for measuring uptake of radiolabel by sediment bacteria. Ansede and Yoch (1997) investigated sediment bacterial involvement in the production of DMSP (dimethylsulfoniopropionate) lyase using water and sediment samples from North Inlet.

In the 1990s Lovell and his students participated in multidisciplinary investigations with several benthic ecologists interested in the production of secondary compounds made by burrowing invertebrates, particularly infaunal polychaete worms found in the muddy and sandy marine sediments of the NI-WB NERR. Steward et al. (1992) looked at the relationships between bacterial abundance and activity, microalgal biomass, and meiofaunal distribution in sediments containing biogenic bromophenols in North Inlet. An additional examination of how bacteria respond to the presence of bromophenol, a secondary metabolite that is produced by marine polychaete worms, was made in a study by Lovell et al. (1999).

To maintain its high rate of primary productivity, *Spartina* maintains a supply of nitrogen through the nitrogen-fixing capabilities of its associated diazotroph community, the function of which was inferred using molecular microbiological techniques (Bagwell and Lovell, 2000a,b). Spatial and temporal dynamics of the rhizosphere diazotroph assemblage on several species of salt marsh plants has been studied in depth by Bagwell et al. (1998), Piceno et al. (1999), Piceno and Lovell (2000a,b), Lovell et al. (2000), Bagwell et al. (2001), Lovell et al. (2001a,b), Brown et al. (2003), and LaRocque et al. (2004). An overview of these and other such studies is provided in Lovell (2005), but diazotroph studies have continued to the present as well (e.g., Lovell et al., 2008; Gamble et al., 2010; Davis et al., 2011; Lovell and Davis, 2012).

Additional multidisciplinary work was done by Phillips and Lovell (1999) who examined the distributions of total bacteria and active bacteria in biofilms that occur inside the lining of the tubes built by the marine infaunal polychaete worm, *Diopatra cuprea*, a macrobenthic-sized animal commonly found in tidal creeks in the NI-WB NERR. Matsui et al. (2004) examined sulfate reducing bacteria that occur within this worm's tubes. It should be mentioned that these studies on worm tube microbiology were built upon earlier work on the biogeochemical microenvironments of worm tubes and burrowing crustaceans where significant heterotrophic and chemoautotrophic metabolic activities were measured (Aller et al., 1983). Aller's work continued with microcosm experiments (Aller and Yingst, 1985) in which non-steady state concentrations of ATP and bacteria at the sediment surface were consistent with the concept of "microbial gardening" by macrobenthic bivalves and polychaete worms. Aller and Aller (1998) later confirmed the role of microorganisms in remineralization processes mediated by macrobenthic fauna.

Dang and Lovell (2002a) used hybridization probes and fluorescence techniques to enumerate and characterize the marine Rhodobacter group collected in seasonal, size-fractionated samples from Oyster Landing, North Inlet. Species from this group comprised about 25% of the particle-associated and 18% of the free-living bacterial assemblage and confirmed that the Rhodobacter group is present year-round in the water column of this tidal creek. Dang and Lovell (2000, 2002b) had previously established that members of this group are among the early colonists on clean surfaces and occur throughout the salt marsh, suggesting their prominence in biofilm formation on many types of surfaces in this habitat.

In a complex set of experiments designed to better understand ecological couplings between the microbial food web and primary producers involved in the microbial food web and the "microbial loop", De Lorenzo et al. (2001) utilized a subtraction methodology – elimination of certain functions necessary for metabolic operations – on artificial substrates that had soaked in a tidal creek and accumulated a natural consortium of microorganisms. By incubating these consortia in the presence of metabolically inhibiting substances (an antibiotic mixture, DMSO, a photosynthesis inhibitor, and cyclohexamide, a eukaryotic growth inhibitor) they were able to deduce the existence of an interdependent nexus of interactions between primary producers and protozoan heterotrophs in the water column that also involved the benthic microbial heterotrophic community. Interactions amongst these components of the microbial loop varied seasonally, with a more active microbial loop in summer and a more linear food web structure in the fall. This study is a good example of how researchers have progressively broadened their studies from individual elements of the coastal ecosystem towards an integrative approach.

Molecular examinations of the bacterioplankton communities in the ACE Basin and in North Inlet by Johnson et al. (2006) revealed that there were great differences in their respective community structure. Using denaturing gradient gel electrophoresis (DGGE), they found that the communities under the different salinity regimes in each area were remarkably different. The free-living bacterial community in North Inlet was consistent with that found to develop with the summer phytoplankton bloom there that is associated with a typical microbial loop dynamic in the water column. Characterization of the bacterioplankton in North Inlet by Johnson et al. (2006) was also consistent with that necessary for the dynamic coupling between phytoflagellates and bacteria documented by Lewitus et al. (1998). Such close examination of bacterial dynamics in the waters of the NI-WB NERR serve as a nice complement to ongoing comparative analyses of bacterial production (BP) and phytoplankton biomass (as chl *a*, CHLA) that has been conducted by the NI-WB NERR at the Oyster Landing SWMP station. Changes in the BP:CHLA ratio in North Inlet reveal covariance between heterotrophic and autotrophic processes, but additional sampling of bacterial assemblages as well as direct measure of phytoplankton production rates will be necessary to quantify this linkage more completely (Apple et al., 2008).

Indole-3-acetic acid (IAA) is a plant growth regulator (auxin) that is produced naturally and is well-studied, especially in terrestrial plants. Gutierrez et al. (2009) collected *Spartina* and *Juncus* in North Inlet and grew them in the laboratory until bacterial outgrowths occurred on their root systems. These outgrowths were then isolated and grown in culture medium and tested for their ability to produce IAA. Eight *Vibrio* strains and five species-level clades containing numerous isolates and presumptively five new species were also found to produce IAA, the first time that estuarine or marine bacteria have been found to do so. This discovery suggests that diazotrophic strains in this genus may be coupled tightly with plant productivity because stimulation of root growth by the auxin results in more nitrogen-fixing capacity for the plant. Such interactions have relevance for carbon cycling but remain largely unexplored in estuarine habitats.

A combination of molecular and physiological methods was used by Gamble and Lovell (2011) to identify strains of Vibrionaceae and *Vibrio parahaemolyticus* in the sediments of North Inlet. Some of these bacterial strains are known pathogens, especially among people who have eaten contaminated shellfish or who have skin wounds. After measuring the abundance of these strains over the seasons in intertidal creek water, interstitial pore water and fiddler crab burrow water, they found highly increased numbers ("hot spots") of these bacterial strains in the burrows. Thus burrows engineered by *Uca* serve as refugia and enrichment zones for Vibrionaceae , particularly in burrows in the *Juncus* zone and also in short- and tall-form *Spartina* zones. Given the short generation times (10-90 minutes) of these bacteria, the burrows act as incubators before the bacteria are flushed out by tidal flow. Based on known fiddler crab burrow densities, tens of trillions of these bacteria enter tidal creeks with each change of the tide. The authors suggest that this finding of high numbers of potentially pathogenic bacteria in a relatively pristine environment deserves additional study.

Several microbiological investigations have been initiated recently but as yet are unpublished. D. Kim and S.H. Jung are listed in the 2011 compendium of "Current Research, Monitoring, and Education Projects", compiled by P. Kenny at the Baruch Marine Field Laboratory, as measuring microbial diversity in soil samples (with a DNA sequencer) along transects in the NI-WB NERR at locations affected by varying degrees of erosional disturbance events. Lovell and Matsui continue their collaboration examining how infaunal burrowing or tube-building marine macrobenthic organisms (polychaete worms) influence sediment microbiota. They will use fluorescent *in situ* hybridization (FISH), microelectrodes, and fluorescent redox potential probes to examine sulfate reducers in these microhabitats. Matsui and Fletcher continue their work examining the distribution of bacteria on the roots of marsh plants (*Spartina* and *Juncus*) and also employ FISH of 16S rRNA and confocal laser scanning microscopy in their work. Lovell is also continuing his earlier studies (with Dang) of man-made surface colonization by microbes and biofilm formation in North Inlet, studies with implications for the possible prevention of marine biofouling.

Microbiological studies in the North Inlet portion of the NI-WB NERR have made great advances, both conceptually and methodologically, over the last four plus decades. Interesting questions about their community dynamics remain, and their role in virtually all biogeochemical processes in the terrestrial and aquatic habitats of the reserve awaits deeper clarification, definition, and understanding. However, much has been learned during this time, and some major findings include that microbial biomass (as ATP) is greatest at high tide, with offshore import to North Inlet and export of ATP to Winyah Bay. About 25% of total ATP in the water column is bacterial in origin. There was some evidence that tall, creekbank *Spartina* passively filters microbes from the water on rising tides and that microbial communities differentiate once in the high marsh. The marsh surface is neither a net source nor a net sink for bacteria, and oyster reefs do not appreciably filter out heterotrophic bacterioplankton. There is an abundant and diverse mycoflora in North Inlet sediments. More recent studies of microbial communities no longer require that microbes be culturable, and direct counts show concentrations of up to 10^5 aerobic heterotrophic cells per ml in the water column. Diazotrophs and other root-associated groups take up photosynthate and stimulate *Spartina* productivity via their nitrogen-fixing capabilities. Microbial loop processes dominate during summer, with more linear food web interactions in the rest of the year. Linkages between bacterial production and concentrations of chlorophyll-*a* have been found, emphasizing the important role of particulate organic matter in microbial communities of the water column. Rhodobacter is an abundant group in the water column and may contribute to the formation of biofilms on clean surfaces. The stimulatory effects of benthic infauna and even low chronic levels of hydrocarbons have been documented as enhancing microbial activity. *Vibrio* strains (pathogenic) exist in North Inlet's sediments, particularly in fiddler crab burrows where tides regularly flush *Vibrio* populations into the tidal creeks. The diverse community of microbiota is intimately linked with all aspects of biogeochemical cycles studied in this coastal ecosystem.

» Benthos

The benthos of the NI-WB NERR is a highly diverse group of organisms. The benthic community undergoes dynamic changes in abundance and species composition during the year, and one of the greatest research challenges is to understand what factors cause these large temporal changes and how these changes affect the ecosystem. Hundreds of studies on benthos in North Inlet have been published, and standardized monitoring of the benthic fauna continues today, albeit at a somewhat reduced level of effort now compared to earlier years. There are probably very few other sites in the world with such an information-rich dataset on both macrobenthos and meiobenthos available to researchers as exists for the NI-WB NERR. None can match the initial frequency (biweekly) and duration of benthos monitoring information available.

RESEARCH HISTORY OF BENTHIC STUDIES: A BRIEF SUMMARY

Much of the worldwide research done on intertidal and subtidal benthos is conducted on rocky shore, hard-bottom communities existing at higher latitudes. A major attribute of the NI-WB NERR is that it provides relatively easy access to researchers for the study of soft-bottom benthic communities. The area is representative of many other coastlines in the southeastern United States as well as other sub-tropical coastlines dominated by salt marsh plants rather than submerged aquatic vegetation (seagrasses) or mangrove communities.

The benthos of the North Inlet estuary and surrounding environs was not known very well until after 1969 when the Belle W. Baruch Institute for Marine Biology and Coastal Research was created and researchers were allowed access for scientific study of the area. Clams and oysters had been harvested here for centuries, evidenced by the presence of many large Native American shell middens in the marsh. The early 1970s studies concerned ecophysiological adaptations and energetics of intertidal organisms, single species' ecology and pollution biology, quantitative distributional surveys of both macro- and meiobenthos, and taxonomy. Work progressed from there to manipulative studies focused on the role of benthos in the estuarine food web and evolved into long-term monitoring studies in different habitats so that natural changes in abundance and diversity of benthic fauna could be measured and mechanisms causing season-to-season and year-to-year changes might be elucidated. Additional studies on mechanisms promoting site-selection and settlement of the free-swimming larvae of benthic animals were conducted in ensuing decades as more benthic ecologists and scientists from many other disciplines and institutions joined forces with faculty at USC and elsewhere to utilize the relatively pristine NI-WB NERR as a study site. This has broadened the research base considerably.

HABITATS/SETTING

Whether intertidal or subtidal, the benthic community also varies in species composition according to differences in the physical structure of the habitat and the availability of food present. Biotic forces such as competition, predation, parasitism, and the arrival of drifting planktonic larvae to an area also influence the type of benthic community that lives in any particular habitat. Acting together, these physical and biotic forces create large-scale patterns in the distribution and community structure of benthos, both laterally and vertically with respect to the location of sea level as it changes with the tide.

INTERTIDAL BENTHIC COMMUNITIES

• Open coast surf zone

This habitat is physically dominated by wave action/storms and thus harbors a benthic community dominated by organisms that can withstand or escape the rigors of physical wave disturbance. There have been no formal studies of the surf zone meiofauna on South Carolina's beaches, and it is unknown whether beach nourishment has any permanent effects on the community. According to Ruppert and Fox (1988), the macrobenthic animals inhabiting the surf zone are numerically dominated by small, fast-digging, bivalves (in the genus *Donax*) and annelids (worms) that burrow through the sediments at depths of a few centimeters where they are not readily eroded by wave action. Mole crabs in the genus *Emerita* can become very abundant in the spring and summer. Overall, the macrobenthos is much less abundant in the surf zone than elsewhere, with only 10s to 100s of individuals per square meter.

Beaches on the landward side of barrier islands are exposed to less wave energy than the open coast. However, this particular habitat just inside North Inlet's mouth has not been sampled quantitatively.

• Vegetated marsh

The most visible portion of the salt marsh is vegetated by several plant species but dominated by the smooth cordgrass, *Spartina alterniflora*. Zonation of the plant community is conspicuously associated with the amount of inundation and exposure to air induced by the semidiurnal tides. The tallest form of cordgrass grows at the edges of tidal creeks in the low marsh. Shorter forms grow in the higher portions of the intertidal area, the high marsh. The highest intertidal areas are covered by sea lavender (*Limonium carolinianum*), glasswort (*Salicornia virginica*), and the rush (*Juncus roemerianus*). Several other plant species occupy the supratidal zone between the high marsh and the forest. Sediments in the vegetated marsh are muddiest in the low marsh and grade into larger grain sizes with increasing elevation into the high marsh which is comprised of sandy muds. The most visible macrobenthic fauna in the vegetated marsh are fiddler crabs, mud snails, and periwinkle snails. Many other less visible taxa are present (e.g., polychaete worms). The subtidal portions of the vegetated marsh host a variety of fauna including crustaceans - particularly grass shrimp, penaeid shrimp (seasonally), crabs, and amphipods – mollusks, annelids, and other taxa. Motile organisms move from subtidal regions into the vegetated portion of the marsh to feed and for protection from predators. Both meiofauna and macrofauna are abundant in the intertidal and subtidal vegetated marsh. Detritus formed from dead stems and leaves of *Spartina* first collects as piles of wrack in the intertidal zone where it later decays and gets mobilized as small particles. These particles get colonized by bacteria and are ingested by a variety of fauna that live in the sediments and water column. Thus the vegetated marsh is essential both for habitat and for the food web it supports.

• Unvegetated mud and sand flats

This portion of the salt marsh is home to numerous burrowing worms, clams, and fiddler crabs. The sediment here is contoured by fast-moving tidal currents, and ripple marks are common on the sand surface. Mudflats are pock-marked by shallow pools, many of which are made by stingrays during times of high tide. Several coastal bird species use these flats as foraging and feeding grounds. When the flats are exposed during warm times of year, thousands of fiddler crabs emerge from their burrows and engage in behavioral displays as part of their mating ritual. The surface of the flats is usually covered by a thin film of benthic diatoms and other algae that migrate vertically within the uppermost few millimeters of the sediment in their search for optimal levels of sunlight. Mud-flat fauna, however, are adapted to much less rigorous physical conditions, as evidenced by the accumulation of finer grained (smaller sized) sediments that would otherwise wash away quickly in faster-moving currents at high tide.

The large Debidue sand flat opposite the mouth of North Inlet is more exposed to the elements (wind and waves) than other flats in the area. Samples of macro- and meiobenthos collected biweekly for 4 years at the Debidue sand flat demonstrated the high spatial and temporal variability in abundance that is characteristic of physically-controlled communities. No seasonal trends in abundance were discernable in either the macro- or meiobenthic sizes of the impoverished benthic fauna.

- **Oyster reef**

Intertidal and subtidal oyster reefs are one of the most prominent biological features of southeastern US salt marshes. They are comprised of the eastern oyster, *Crassostrea virginica*, that grows as clusters of individuals cemented together.

Oyster reefs process prodigious amounts of particulate organic matter during feeding and expel equally large amounts of fecal and pseudofecal matter that becomes colonized by free-living microbes. This organic material then serves as food for a host of deposit-feeding invertebrates such as polychaete worms, shrimp, and other smaller crustaceans like ostracods. Thus many studies of oyster reefs have been done in the context of reefs as connected systems whose intake and output of organic matter can be budgeted in energetic terms. Isolated oyster reefs have been "enclosed" for before and after study of the changes that occur in various water constituents (particulates, nutrients, etc.) flowing across and over a reef.

Oyster reefs occur allong many of the creek edges in North Inlet.

Oyster reefs also serve as unique, hard-bottomed living space for a variety of animals restricted to this habitat and seldom found elsewhere. A list of invertebrate organisms found within oyster reefs can be found in Fox and Ruppert (1985) and in **Appendix D**. They include polychaete worms from several different families, several species of small crabs, and a diverse group of snails, sponges, anemones, sea stars, and shrimps, among others. Small fishes can also be found living within oyster reefs, and motile nekton frequent these areas in search of food during high tide. Many locals find the edges of oyster reefs to be especially good places to cast baitfish or shrimp in hopes of catching large red drum and other fishes.

SUB-TIDAL BENTHIC COMMUNITIES

- **Creek bottoms (shell hash) and tidal pools**

The bottoms of subtidal creeks and larger pools of water that do not become empty at low tide are perhaps both the most-studied and the least well-understood habitats in the NI-WB NERR. Their community composition has been monitored extensively through time by examining dredge and epibenthic sled collections made from the bottom of Town Creek.

Animals collected in this manner are most abundant in the warmer months of the year. However, there have been very few studies conducted that examine how this creek bottom habitat is actually utilized by the organisms that reside there or that use the habitat for transit, yet many species are found only here. Currents usually are strong enough to scour the finer sediments away, leaving bits of oyster and other bivalve shell material (shell hash) exposed on the bottom. It is one of the few places within the salt marsh that has hard substrate colonized with many attached colonial organisms (soft corals, bryozoans, sponges) adapted to life in fast-moving water (tidal currents can exceed 2-3 knots along the bottom).

MACROBENTHOS

There are many different soft-bottom benthic habitats in North Inlet and very few hard-bottoms. To characterize temporal changes of the macrobenthic community, two representative sites were selected for sampling. Both had been sampled for meiofauna on a long-term basis beginning in 1972, so having data for communities of both size-classes from the same sites was attractive. However, macrobenthos at several other locations in North Inlet had been sampled before the start of the LTER program. Among the earliest quantitative collections were those made on intertidal sandbars located in major tidal creeks by Holland and Dean (1977a). These areas were dominated by suspension-feeders in their sandy portions and by deposit-feeders in the muddy-sand areas. Two haustoriid amphipod (Crustacea) species dominated the fringe areas of the sandbars in these tidal creeks. Between 15 and 44 total macrobenthic species were found in their surveys at three sites, each of which had four discretely different habitats for which the macrobenthos was characterized. Seasonal changes in the sandbar community were reported by Holland and Polgar (1976) who found that differences in the reproductive patterns and life histories of the numerically dominant amphipods controlled the dynamics of the community. Both these publications were based on dissertation studies by Holland. Holland and Dean (1977b) also studied razor clam biology in North Inlet in a different area of the marsh.

As part of the National Science Foundation's Long-Term Ecological Research program, the macrobenthos was first sampled on a regular, biweekly, basis in 1981 at two subtidal sites – the Debidue sand flat and the muddy Bread and Butter Creek (Michener et al., 1986). The sandy site sampling effort was discontinued in 1985 because core-to-core variability in abundance was too high to detect anything more than very large, irregular, changes over time. These data are not included here. Since then, long-term sampling has continued only at the Bread and Butter site. Macrobenthos sampling frequency was decreased to quarterly in 1998 due to a lack of funding for the labor-intensive processing and specialized identification of benthic fauna, with sorting currently only to major taxon and total abundances being tabulated at this taxonomic level. Unfortunately, many (4 of 8 replicate cores) of the macrobenthos samples collected quarterly since 1998 remain uncounted, but analysis of prior data suggested that just 4 core samples per date were sufficient to document seasonal changes in abundance. All macrobenthos samples collected are preserved in buffered formalin and have been placed into semi-permanent archival storage on the premises.

Macrobenthos at the subtidal, muddy long-term collection site in Bread and Butter Creek undergo dramatic but regular changes in abundance each year (Service and Feller, 1992; Edwards et al., 1995). The pattern starts with high numbers of organisms (primarily polychaete worms and bivalves) in the coldest months, with densities over 50,000/m^2 (Figure 70). Coincident with the arrival of many transient epibenthic and nektonic predators in late winter and early spring, the macrobenthic community begins a rapid decline in abundance throughout the spring that continues into the early summer. Summertime lows of only a few thousand individuals per square meter persist until fall, at which time recruitment of new individuals into benthic populations begins (Service and Feller, 1992; Feller et al., 1992). This pattern has been

Macrobenthic core sampling.

seen in detail in the early portion of the long-term collections made biweekly for many years and still remains visible as an annual pattern even with the most recent samples that were collected on only a quarterly basis. Although changes in macrobenthic community structure (relative abundances of individuals of each species and numbers of species) are no longer documented in the quarterly samples, based on recent data, there is little reason to believe that major shifts have taken place through time, but this is an unanswered question. The community has always been dominated by polychaetes, mostly in the spionid, capitellid, and cirratulid families, oligochaetes, and a less rich bivalve community. Because they are numerical dominants, all of these taxa show high seasonality signals (Figures 71 and 72), but the seasonal signals are less clear for some other taxa such as shelled gastropods (Figure 73). Individuals from many polychaete families are found each year, and the number of families varies from two to about six (up to 13 in the entire time-series). Many other taxa have been recorded in North Inlet and are listed in the Baruch database along with metadata (information about the sampling protocol) (**www.baruch.sc.edu**).

The long-term record for total macrobenthos abundance (Figure 70) hints at some potentially interesting cyclic phenomena on the order of 14 years. However, with the decrease in sampling frequency and sample size, the resulting loss of precision in seasonal, annual, and inter-annual changes in abundance, suggests many more years of data will have to be collected before such cycles could be substantiated statistically. Likewise, it will take a dramatic change in abundance over time to even suggest that an effect of global climate change could have taken place. There are many other less statistically noisy ways to measure long-term climate change than by monitoring soft-bottom benthic communities. Several biotic and abiotic forces are likely at play in causing these wide seasonal swings in macrobenthos abundance each year, but the only one that has been examined in any quantitative detail is predation by fishes and shrimp (e.g., Service et al., 1992; Beseres and Feller, 2007a,b; Pollack et al., 2009). Predation losses are significant, but this alone cannot account for the seasonal declines in springtime that have been documented on a regular basis. Many questions remain about recruitment, competition, and food webs as drivers of changes in macrobenthic community structure.

As seen in other soft-bottom habitats around the world, certainly competitive interactions among and between species are possible in the macrobenthos, and changes in water temperature or dissolved oxygen concentration must also drive some portion of the observed changes, but none of these abiotic factors has been examined in other than a correlative manner in North Inlet.

A study of oyster recruitment by Michener and Kenny (1991) at three locations in North Inlet using settling plates and tubes showed that variability of recruitment among tubes and plates was as great as between sites and among intertidal elevations. Settlement and recruitment patterns of oysters was affected by both physical and biological factors which operate across several scales, making it difficult to compare studies of settlement conducted at different spatial and temporal scales. Other studies of recruitment (the settling of planktonic larvae of benthic organisms to the bottom) by Luckenbach (1984a, 1987) suggest that post-settlement processes are important in determining the future size of bivalve and other populations in North Inlet. Changes in the salinity regime also have large impacts on recruitment of planktonic larvae to the benthos (Richmond and Woodin, 1996, 1999). Recruitment can also be impacted as a consequence of predation activity (Wethey et al., 2001), and signal cues for settlement come in a variety of ways (Woodin et al., 1995). Many more manipulative and other types of experiments must be done to understand what causes the observed wide seasonality of the macrobenthic community in North Inlet.

The following list provides a brief sense of the diverse benthic research undertaken:

- Oyster reef energetics (for *Crassostrea virginica*, Dame, 1972), filter-feeding (Dame et al., 1980), and macrobenthic fauna inhabiting oyster reefs (Dame, 1979), intertidal versus subtidal growth (Crosby et al., 1991)

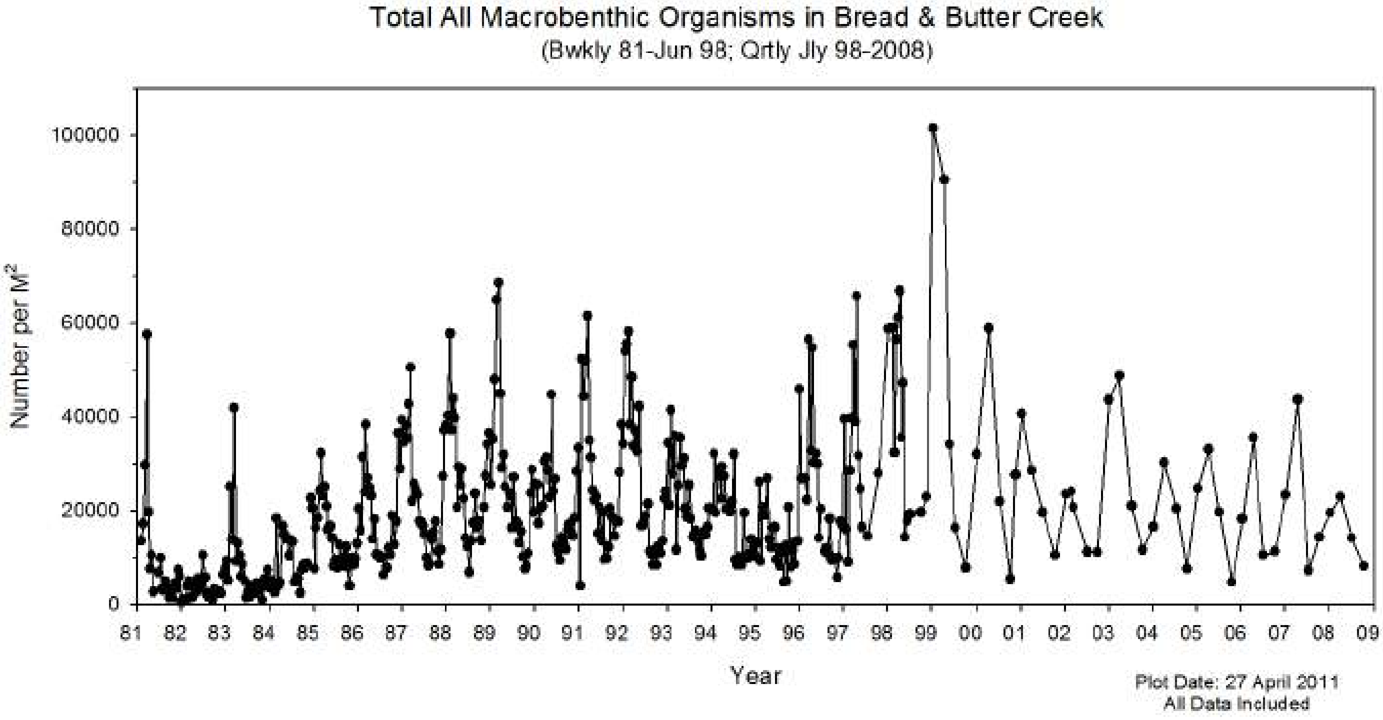


Figure 70. Total macrobenthic organisms in Bread and Butter Creek.

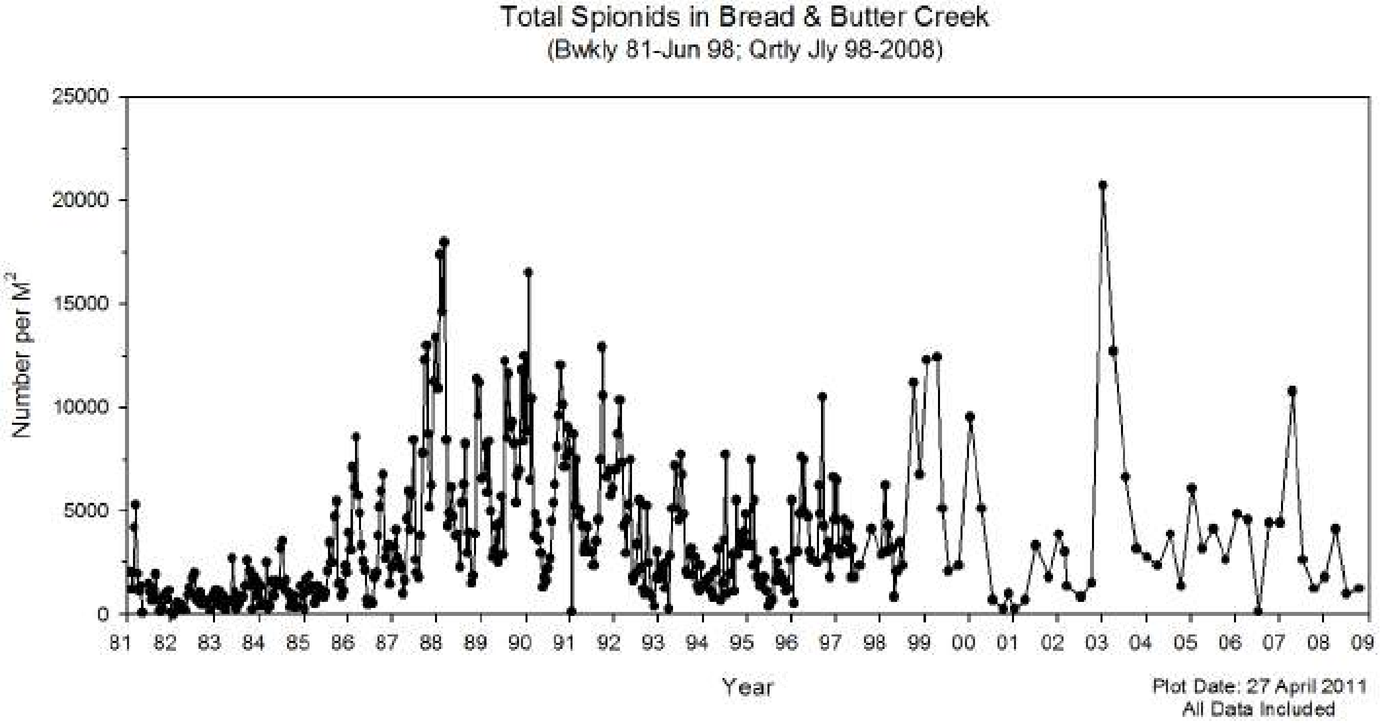


Figure 71. Total spionids in Bread and Butter Creek.

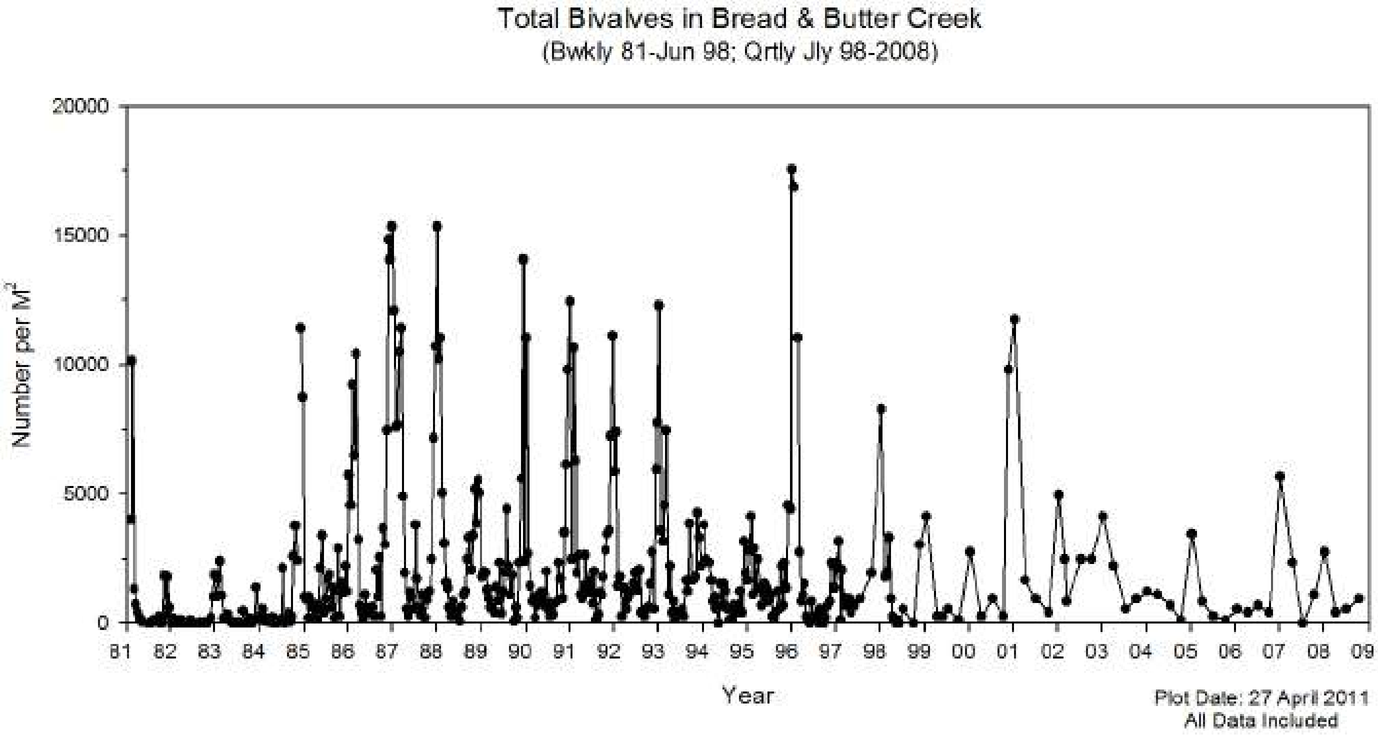


Figure 72. Total bivalves in Bread and Butter Creek.

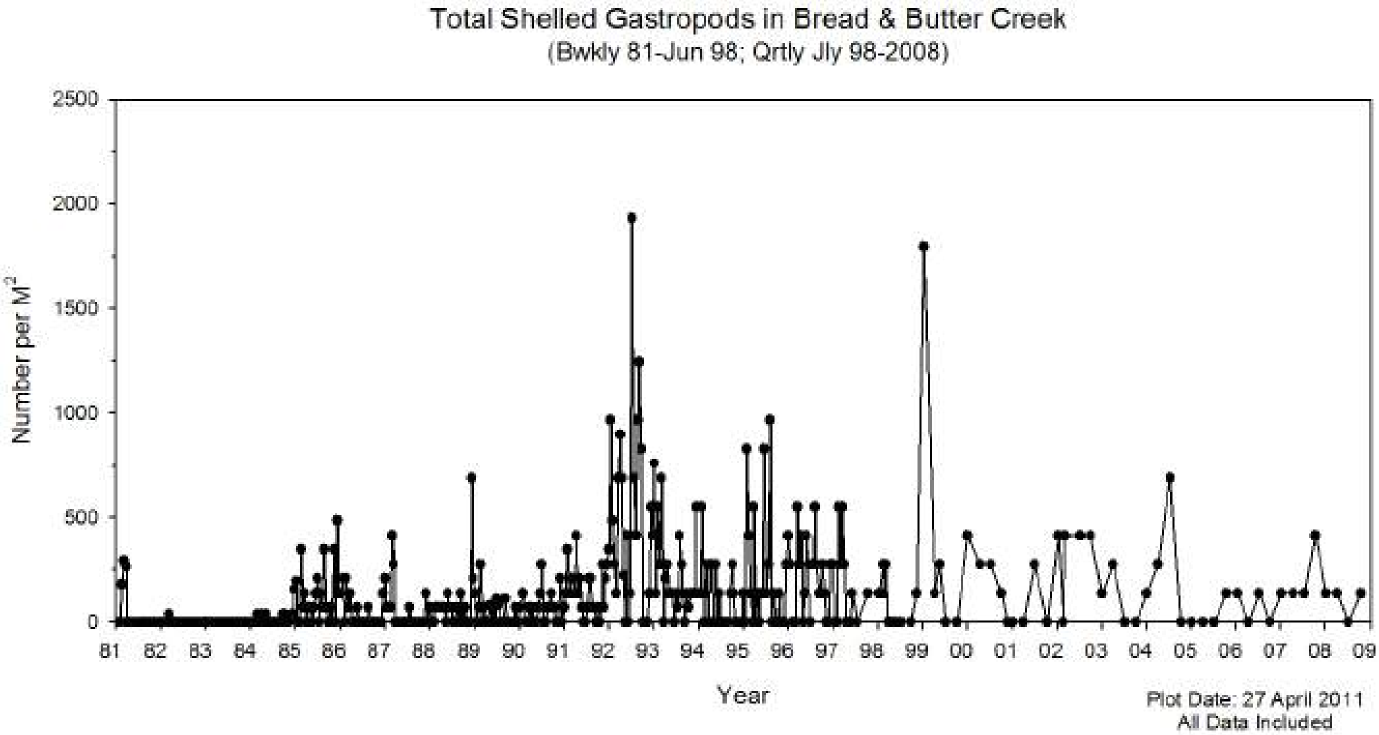


Figure 73. Total shelled gastropods in Bread and Butter Creek.

- Annelids, effects of organic enrichment on assemblages (Kihslinger and Woodin, 2000), ecology of a capitellid (Schaffer, 1979), intraspecific reproductive polymorphism in *Streblospio benedicti* (Pernet and McArthur, 2006)
- Amphipod competition and disturbance in sandflat populations (Grant, 1981a,b)
- Grass shrimp life-history and development patterns (Alon and Stancyk, 1982), production and feeding ecology (Sikora, 1977)
- Nudibranch taxonomy and new species (Shoemaker et al., 1978; Eyster, 1980) and life history and development (Eyster, 1979; Eyster and Stancyk, 1981)
- Mud snail freezing tolerance (Hilbish, 1981)
- Mud crab fatty acid incorporation (Lunetta and Vernberg, 1971), osmoregulation (Boone and Claybrook, 1977), distribution and behavior (McDonald, 1982), genetics and growth (Hilbish and Vernberg, 1987)
- Ribbed mussel reproduction in intertidal populations (Borrero, 1987), temperature effects on metabolic rates (Hilbish, 1987), growth (Borrero and Hilbish, 1988), and energy budget (Wilbur and Hilbish, 1989)
- Hard clam genetics (Rawson and Hilbish, 1991)
- Invasive species, green porcelain crab (Hartman and Stancyk, 2000; Hartman et al., 2002)
- Fiddler crab respiration rate (Dame and Vernberg, 1978), hatching rhythms (Bergin, 1981), sediment reworking (bioturbation, McCraith et al., 2003), and herd behavior (Viscido et al., 2001, 2002; Viscido and Wethey, 2002)
- Barnacle larval settlement patterns and post-settlement mortality (Young, 1991)
- Brittlestars: salinity tolerance (Stancyk and Schaffer, 1977), reproduction and morphology (Heatwole and Stancyk, 1982), regeneration and autotomy (Donachy and Watabe, 1986; Clements et al., 1988, 1993; Dobson et al. 1991), particle selection trophic dynamics (Clements and Stancyk, 1984), habitat preferences (Zimmerman et al., 1987), and browsing activity and partial (sub-lethal) predation (Stancyk et al., 1994; Pape-Lindstrom et al., 1997), subsurface feeding capabilities (Gielazyn et al., 1999), characterization of food resources (Hoskins et al., 2003)
- Odor plumes as signals emanating from the benthos (Moore et al., 1993; Zimmer-Faust et al., 1995; Finelli et al., 1999, 2000)
- Immunochemically-defined taxonomic relationships among soft-bottom benthic fauna (Feller and Gallagher, 1982; Feller, 1984b)
- Habitat modification and ecosystem engineering (McRae and Woodin, 1984; Woodin and Marinelli, 1991; Woodin et al., 2010), and hydrodynamics of animal tubes in the sediment (Luckenbach, 1986)
- Predator-prey interactions involving macrobenthos and penaeid shrimp (Beseres-Pollack et al., 2008), mud snails (Feller, 1984a), hard clams (Feller 1986)
- Crypsis (decorating) behavior and energetics of an onuphid polychaete, *Diopatra cuprea* (Berke, 2006; Berke and Woodin, 2008)
- Parasitic crabs (Bell, 1988; Bell and Stancyk, 1983)
- Gorgonian growth and development (Kingsley and Watabe, 1984)

There have also been several studies of the microbial ecology of sediments containing biogenic bromophenols (Steward and Lovell, 1997; Lovell et al., 1999) and the effects of these organic compounds as deterrents of predation (Woodin et al., 1987). Brominated compounds have also been found to serve as signals of the suitability of sediments for colonization and settlement (Woodin et al., 1993, 1997). Otherwise, recruitment of various benthic species to the substrate has been examined by Woodin (2007) and Woodin et al. (1998). Interestingly, as pointed out by Fielman et al. (1999, 2001), these naturally-occurring brominated compounds could easily interfere with assessments of toxic chemicals found in marine sediments that might be considered anthropogenic in origin rather than natural. Cowart et al. (2000) found that two types of polychaete larvae, those with and without egg yolk, also contained halogenated compounds that are parentally-derived secondary defense mechanisms, the first report of these compounds in polychaete larvae. Because these compounds have been found in species from a variety of polychaete families, it is possible that chemically-mediated traits themselves may be important for structuring benthic communities in soft-sediments. On the other side of the equation are mechanisms for dealing with the toxic properties of halogenated compounds, and there have been several interdisciplinary biochemical/genetic studies of these detoxifying enzymes in polychaetes in North Inlet (e.g., Chen et al., 1991; Yoon et al., 1994; Zhang et al., 1996; Chen et al., 1996; Roach et al., 1997; Lebioda et al., 1999; Han et al., 2001; LaCount et al.,2000; Lincoln et al., 2005).

There have also been several studies of symbiotic and commensal relationships involving crabs and polychaetes, especially for a rather large burrow-dwelling polychaete (*Chaetopterus*) (Grove and Woodin, 1996; Grove et al., 2000). Many other studies conducted by students doing independent research or senior thesis projects also provide valuable insights into the ecology of benthic animals in North Inlet and often serve as preliminary work that later evolves into full research projects funded by federal, state, and private organizations.

Building on the pioneering studies of how the huge populations of fiddler crabs in North Inlet and Winyah Bay maintain themselves reproductively (Christy, 1982; Christy and Stancyk, 1982; Christy, 1989; Christy and Morgan, 1998), more recent fiddler crab studies concern habitat choice by juveniles using molecular methods to identify which species settles where (Behum et al., 2005) and the survival capacities of their planktonic larval stages in low-salinity waters (Brodie et al., 2007; Godley and Brodie, 2007). With concerns for how organisms might adapt to climate change, Jost and Helmuth (2007) measured the mortality imposed by thermal stresses experienced by ribbed mussels (*Geukensia demissa*) that bury themselves in the salt marsh. Iacarella and Helmuth (2011) performed laboratory experiments on the ubiquitous periwinkle snail, *Littoraria irrorata*, that explored how this species manages to keep from over-heating and suffering from dessication as it inhabits the salt marsh. An interesting interplay between the shading and cooling effects of *Spartina* and how the plant simultaneously reduces cooling around it by impeding air flow and its evaporative cooling effects were at play in both of these studies.

Recently, research on the adaptive value of various types of fiddler crab behavior has been conducted by Decker and Griffen (2012). These investigators measured boldness exhibited by female sand fiddlers (*Uca pugilator*) as certain behaviors are (or are not) influenced by physiological aspects of their feeding biology. The gut morphology of fiddler and other brachyuran crabs was measured by Griffen and Mosblack (2011) to see whether they could predict the types of diets, as percent herbivory, and the relative consumption rates in a suite of 15 species in this group of crustaceans. Another aspect of animal behavior was studied by Griffen et al. (2012) who experimentally demonstrated how foraging behavior by the xanthid mud crab, *Panopeus herbstii*, upon their bivalve prey was influenced (or not) in the presence of a predator, the toadfish *Opsanus tau*, that eats the mud crab. Such indirect effects are difficult to measure, but they have been found to exist among other species in many other habitats besides the oyster reefs where this particular type of indirect trophic interaction is most likely to occur.

In a manipulative study by Toscano and Griffen (2012), various sizes of the mud crab, *P. herbstii*, were placed into subtidal cages containing bivalve prey that they normally consume in the oyster reefs. They found that large crabs ate the most bivalves, suggesting that oyster harvesting practices that remove living space for larger mud crabs have the potential to greatly alter trophic relationships that normally occur in unharvested reefs. Evidence for such a possible effect was provided by a field study of the sizes of mud crabs present in oyster reefs having a range of harvest pressure. Harvested reefs contained smaller mud crabs than unharvested reefs.

In summary, macrobenthic research has revealed a highly diverse community of organisms in all habitats sampled in North Inlet. Community dynamics have changed regularly each year in Bread and Butter Creek as wintertime high abundances decline rapidly in spring and early summer when numerous epibenthic predators enter the estuary. Although experimental evidence suggests that predators negatively impact macrobenthic populations, predation alone cannot explain the magnitude of the rates of decline and increase measured. Physical factors and biotic interactions like competition likely play a strong role in structuring macrobenthic communities as well. Polychaete and oligochaete worms and bivalves are the most common members of the soft-bottom macrobenthos, and total community abundances reach maximum values of 50,000 individuals m^{-2} in winter most years. Recruitment processes, both pre- and post-settlement, greatly impact the structure of both soft- and hard-bottom communities as well. The macrobenthos of hard substrates like oyster reefs is understudied. Ophiuroid studies have included a wide variety of topics. Burrowing fiddler crabs and worms play an important role in biogeochemical cycles when they are most active in warmer times of year. Macrobenthic fauna attract a variety of avian predators to the salt marsh each year, and numerous species of fish and invertebrates prey upon macrobenthos throughout the year. Studies of physiological and morphological adaptations to temperature in intertidal bivalves have shown that the effects of climate change and sea level rise can have large impacts on the community. Chemical defensive compounds in several taxa also impact community interactions. Studies of macrobenthos in a variety of habitats within North Inlet have encompassed numerous marine ecological subjects and processes (e.g., competition, trophic interactions, food selection, biodiversity, taxonomy, energetics, population dynamics, spatial distribution, recruitment, seasonality, secondary production, bioturbation, physiology, parasitism, autotomy, etc.). Despite this large body of work, many questions remain concerning the relative importance of biotic and abiotic forces that structure the macrobenthic community.

MEIOBENTHOS

Most of the practicing meiobenthologists in the United States and in many foreign countries have academic ties to the University of South Carolina's interdisciplinary Marine Science Program and the Belle W. Baruch Institute for Marine and Coastal Science. Many researchers from all over the world have visited the Baruch Marine Field Laboratory facilities to study the species-rich meiofauna of North Inlet. It is recognized, both nationally and internationally, that probably more is known about the ecology of meiofauna in North Inlet than at any other place in North America.

The long-term meiobenthos sampling program at North Inlet, 1972-1995, has involved core sampling from two subtidal sites: muddy Bread and Butter Creek, and sandy Debidue Creek. The abundant meiofaunal community at both locations is dominated numerically by nematode worms, with harpacticoid copepods, gastrotrichs, and turbellarians also being prominent. Other taxa (e.g., meiobenthic polychaetes) may increase rapidly in abundance at various times of the year, but the same annual decline seen in macrobenthos also takes place in the meiobenthos – high abundances in winter with springtime declines to summer lows and autumnal recovery back to the winter peak. The seasonal signal is more clearly seen in the Bread and Butter data (Figure 74) than at the Debidue Creek site where fluctuations in abundance are less marked (Figure 75). In contrast to the muddy-bottom meiofauna, changes in the meiobenthic community at the more wave-energetic sandy site are probably influenced primarily by physical or abiotic rather than by biotic factors. Hints of cyclical changes in abundance are visible in the record, but sampling would need to take place over a considerably longer period to establish whether they are regular phenomena. As is the case for macrobenthos, the only driver of changes in abundance that has been experimentally and quantitatively investigated on meiofauna is predation, mostly by transient juvenile fishes (the spot) and various shrimps. Several other potential drivers of changes in meiofaunal abundance over time have been examined (see below). Predation

Images of benthos commonly found in North Inlet: gastrotrich *left*, harpacticoid copepod *center*, polychaete *right*.

alone cannot explain the observed regular seasonal peaks and valleys of abundance or their amplitudes.

There are several hundred publications based on meiofauna research in North Inlet. The following review/synthesis papers provide context and have been among the most influential with regard to stimulating new research and leading this field of study forward nationally and internationally:

- Trophic relationships involving meiobenthic organisms (Coull, 1973);
- A call for hypothesis testing in meiofaunal studies (Coull and Bell, 1979);
- Harpacticoid copepods and their ecology, a review (Hicks and Coull, 1983);
- Field experimentation (Coull and Palmer, 1984);
- General meiofauna ecology (Coull, 1988); and
- Pollution and toxicology (Coull and Chandler, 1992).

Most of the North Inlet meiofaunal publications can be grouped into several rather broad categories (Table 6). There is considerable overlap among categories within many of the references listed in this generalized manner. Topical highlights include taxonomy of nematodes and harpacticoid copepods, centimeter-to-meter scale spatial distribution patterns, tidal transport and dispersion mechanisms, feeding of meiofauna upon bacteria and dead organic matter (detritus), their trophic role as prey in marsh/estuarine food webs involving predatory juvenile fishes, shrimps, and crabs, long-term changes in abundance and species diversity, their utility as sentinels of changes in water quality and/or presence of toxic substances, their numerical response to the impacts of human development in surrounding watersheds, their effect on juvenile members of the macrobenthos, and, most recently, the stability of their genetic make-up under various environmental stressors such as persistent pesticides and petroleum-based residues. Toxicological tests using meiofauna, particularly harpacticoid copepods, as sentinels or indicators of degraded habitat are currently under evaluation by the international Organization for Economic Cooperation and Development for eventual adoption as a mandatory screen for potential endocrine-disrupting chemicals.

Results of the meiofauna sampling effort in North Inlet have revealed a productive community dominated numerically by nematodes (70%) and harpacticoid copepods (20%) in both intertidal and subtidal sites. Taxonomy of harpacticoid copepods is well-documented, but many other taxa require additional work. Total meiofaunal abundances are somewhat higher intertidally than subtidally, always with more in muddy than in sandy sediments, and range seasonally from hundreds of animals per 10 cm^2 in mid-to-late summer to several thousands per 10 cm^2 in winter. A majority of the meiofaunal animals are usually found within the uppermost few centimeters of the sediment where dissolved oxygen concentrations remain sufficiently high above the deeper redox potential discontinuity layer. Their abundances in the sediment do not vary significantly with changes in tidal levels nor from day to night in any of the habitats. Meiofauna are patchily distributed – their abundances may vary by an order of magnitude between replicate cores taken within an area of one square meter. Therefore, high ($n > 3$) numbers of core samples must be collected

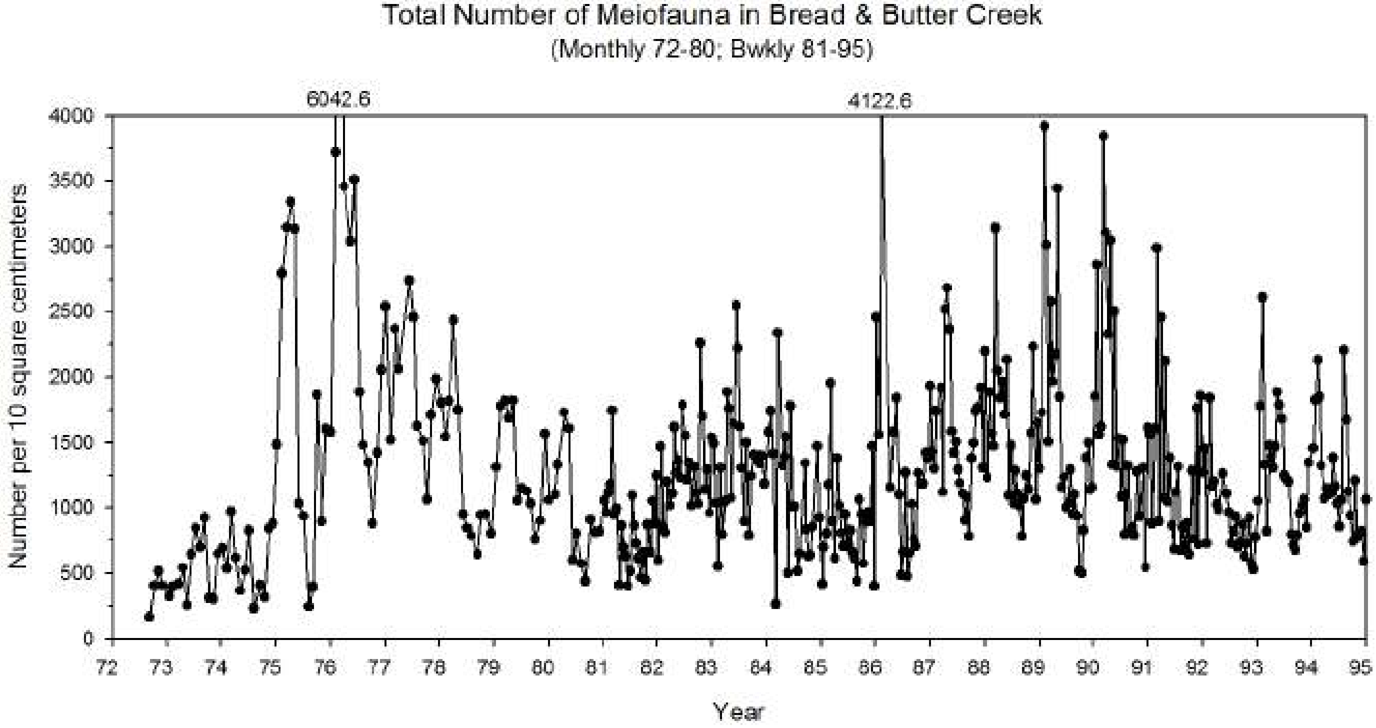


Figure 74. Total meiofauna in Bread and Butter Creek.

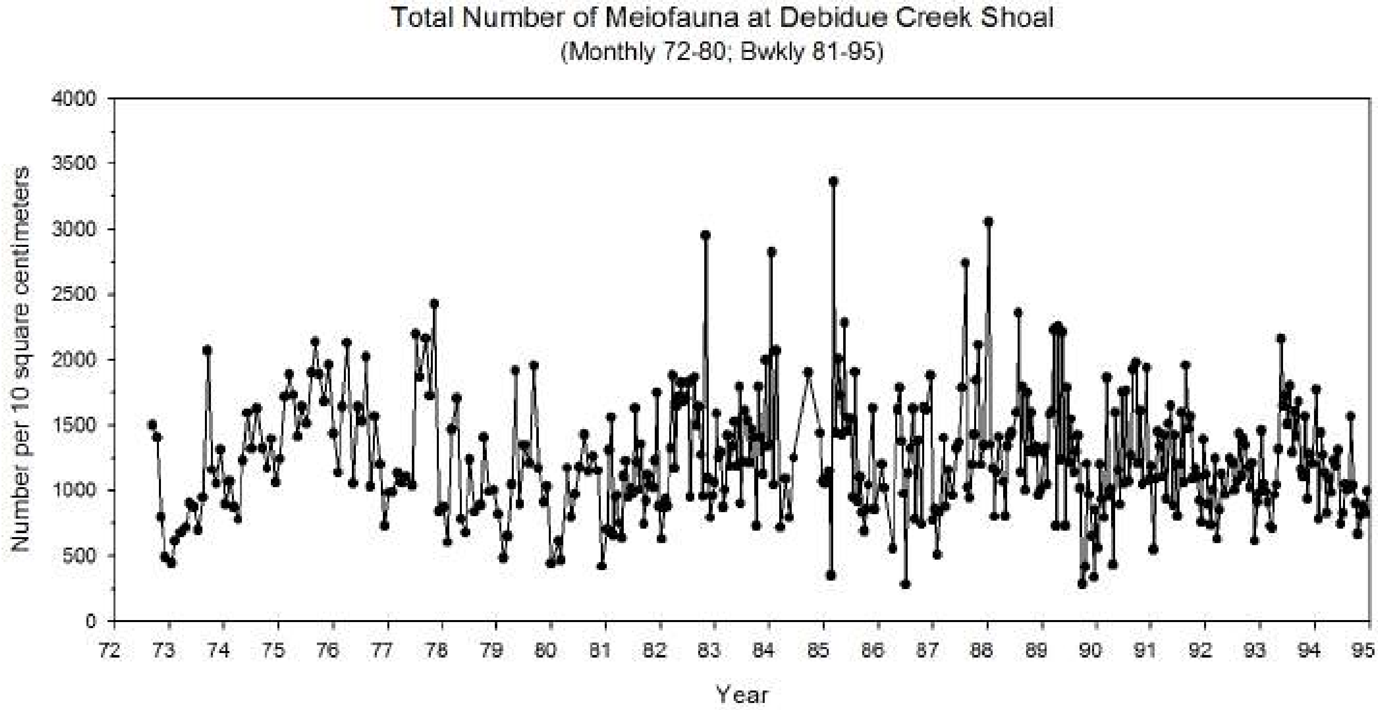


Figure 75. Total meiofauna at Debidue Creek Shoal.

Table 6. A categorized list of representative studies on North Inlet meiofauna.

Community Dynamics/ Demographics	Coull and Fleeger (1977), Hogue (1978), Bell (1979), Fleeger (1979, 1980), Montagna et al. (1983), Coull and Palmer (1984), Coull (1985a,b), Coull and Dudley (1985), Eskin and Coull (1987), Edwards and Coull (1987), Richmond et al. (2007)
Development/ Life-History	Coull and Vernberg (1975), Coull and Dudley (1976), Palmer (1980), Palmer and Coull (1980), Coull and Grant (1981), Bell (1982), Williams-Howze and Coull (1992), Williams-Howze (1996), Green et al. (1995, 1996)
Dispersal	Bell and Sherman (1980), Palmer and Brandt (1981), Eskin and Palmer (1982), Palmer (1984, 1986), Palmer and Gust (1985), Palmer and Malloy (1986), Coull et al. (1989)
Disturbance	Sherman and Coull (1980), Billheimer and Coull (1988)
Distribution/ Abundance	Bell et al. (1978), Coull et al (1979), Ivester (1980), Findlay (1981, 1982), Osenga and Coull (1983), Montagna (1982), Montagna et al. (1983), Eskin and Coull (1984), Eskin and Coull (1987), Coull and Feller (1988), Steward et al. (1992), Schizas et al. (1999)
Encystment (copepod)	Coull and Grant (1981)
Feeding By	Levy and Coull (1977), Montagna (1983, 1984a,b), Feller (1984a, b), Couch (1989), Feller et al. (1990)
Feeding On	Bell and Coull (1978), Smith and Coull (1987), Marinelli and Coull (1987), Palmer (1988), Nelson and Coull (1989), Ellis and Coull (1989), Coull (1990), Scholz et al. (1991), Feller and Coull (1995), Marshall and Coull (1996), DiPinto and Coull (1997),
Genetics	Staton et al. (2001, 2002, 2005)
Interactions	Ivester and Coull (1977), Bell (1980), Bell and Coull (1980), Creed and Coull (1984), Zobrist and Coull (1992, 1994)
Metabolism/ Physiology/ Energetics	Coull and Vernberg (1970), Vernberg and Coull (1974, 1975, 1981), Sellner (1976), Vernberg et al. (1977), Fleeger and Palmer (1982), Feller and Warwick (1988), Morris and Coull (1992)
Minor Taxa	Gastrotrichs: Hogue (1978); Kinorhynchs: Horn (1979), Higgins and Fleeger (1980); Platyhelminth flatworms: (Ax, 1995)
Models	Bell and Coull (1980), Coull (1986)
Pollution/ Toxicology	Coull et al. (1981), Strawbridge et al. (1992), Green et al. (1993), Green and Chandler (1994), Chandler et al. (1994, 1997a, b), Schizas et al. (2001, 2002), Staton et al. (2002), Klosterhaus et al. (2003)
Taxonomy	Coull (1975, 1976, 1977)

for an accurate census of the community whenever or wherever they are sampled. It is likely that nearly every juvenile form of the diverse array of estuarine fauna, both vertebrate and invertebrate, with a portion of their life cycle spent in contact with the sediment ingests meiofauna. Noted predators of meiofauna include epibenthic fauna such as bottom-feeding fishes, shrimps, and crabs. As for the macrobenthos, seasonal changes in abundance of meiobenthos cannot be explained by predation alone. Tidal current-aided dispersion of meiofaunal taxa is rapid and widespread. Meiofauna also play a prominent role in breaking down detrital products of intertidal plant growth so that these materials become available to members of the detritus-based food web in salt marsh and estuarine ecosystems. Because meiofaunal organisms reproduce so rapidly and have such short life cycles, they have been used as model organisms to document the population-level effects of several different types of pollutants, especially pesticides and herbicides, commonly used in farming in the southeastern U.S.

Benthic core sampling technique.

Researchers sample meiofauna on Debidue Creek Shoal.

» Zooplankton

Multicellular organisms collectively known as the zooplankton comprise a diverse, dynamic, and abundant component of the estuarine fauna. Most of the hundreds of zooplankton types that occur in the North Inlet waterways are microscopic, less than 5 mm in overall length. Zooplankton play important roles in aquatic food webs as they consume microscopic algae (phytoplankton), microbes, and organic material and, in turn, are eaten by larger animals.

Zooplanktonic taxa for which all developmental and adult stages occur as planktonic forms are known as holoplankton. Those with only some stages that have a planktonic existence are known as meroplankton. The majority of large invertebrates and fishes that live in North Inlet produce larvae that are planktonic for days to weeks before changing into a more recognizable juvenile form. Because the shape, size, color, and behavior of a larva changes quickly and often radically during their time in the plankton, and because many related species look very similar, their visual identification is difficult. Even the larval forms of some our most common shellfishes and worms cannot be easily identified in zooplankton samples.

A more complete introduction and description of the zooplankton of the Atlantic and Gulf of Mexico coasts, including detailed illustrations and ecological information to facilitate identifications, can be found in Johnson and Allen (2012).

HISTORY OF ZOOPLANKTON RESEARCH IN THE NORTH INLET AREA

The earliest published study of local zooplankton was by Lonsdale and Coull (1977) who used 153-micron nets to characterize the composition and seasonality of the copepod size fraction of the zooplankton at several stations in North Inlet from January 1974 to August 1975. Other early studies were on the vertical distribution of fiddler crab larvae (DeCoursey,1977), physiology of fiddler crab larvae (Vernberg, W. and Jorgensen, 1977) and energetics of various North Inlet zooplankters (Vernberg, W., 1977). Numerous other field and laboratory studies that focused on larval crustaceans and fishes were published as theses, dissertations, or as articles in the primary literature. Christy and Stancyk (1982) studied the flux of invertebrate larvae between the estuary and coastal ocean with significant imports of six of 20 taxa and a significant export of fiddler crab larvae due to the timing of larval release during spring tides. Tidal, lunar, and seasonal fluxes of small mesozooplankton were determined in the Outwelling Study in the early 1980's (Dame et al.,

Zooplankton sampling in North Inlet with a surface net (top) and an epibenthic sled (lower).

1986). Moore and Reis (1983) examined the spatial and temporal patterns of some large zooplankters. Tidal and diel (Johnson et al., 1990) and seasonal patterns (Allen et al., 1995) were described for both small and large mesozooplankton and their zooplanktivorous predators. Houser and Allen (1996) analyzed tidal and diurnal patterns of a full range of zooplankton in an intertidal creek basin. Interannual patterns of small (0.2-1.5 mm, caught in 153 micron mesh net) and large mesozooplankton (1.6-15 mm, caught in a 365 micron net) were interpreted by Allen et al. (1996). Long-term changes and responses of this size fraction to climate change from 1981-2003 were discussed in Allen et al. (2008). The most comprehensive set of data for both size fractions is in the long-term time series study which began in January 1981 and continues still. More than thirty years of biweekly collections from Town Creek probably represents the longest time series for these two size fractions of zooplankton in any ocean-dominated estuary. Results from this study, combined with information from other local studies, have been used to form the descriptions of the composition and dynamics of the assemblages below.

MAJOR TAXONOMIC GROUPS

Table 7 lists the small animals that were sampled by the 153-micron nets, and Table 8 identifies the larger taxa collected in the 365-micron epibenthic sled tows. Between the two net types, more than 50 taxonomic categories representing more than 200 species of invertebrates and fishes have been enumerated in the mesozooplankton samples. Mean densities, periods of seasonal occurrences, peak periods of abundance, and numerically dominant taxa are provided for all categories. Partial processing of collections made after 2010 indicates that there have not been many changes in the composition and relative abundances of major contributors to the two assemblages, so the information in these tables is still very relevant in 2014.

- **Small Mesozooplankton: 153-µm mesh**

Copepods are small crustaceans (generally 0.5 – 2 mm length) that account for most of the organisms in 153-micron mesh collections. They are permanent members of the zooplankton (holoplankton), and they often occur in densities of thousands per cubic meter, especially in the summer season. The highest density of total copepods collected in North Inlet was greater than 119,000 individuals m^{-3} in June 1981. At least 10 copepod species regularly occur in the water column in North Inlet, with the calanoid copepod, *Acartia tonsa* (Figure 76), being especially abundant all year. From May through September, *A. tonsa* comprises about 50% (on average) of all copepod numbers. *Parvocalanus crassirostris*, *Pseudodiaptomus pelagicus*, *Oithona* spp., and *Euterpina acutifrons* are also found year-round. *Temora turbinata* is a fall-occurring species, while both *Centropages hamatus* and *Eurytemora affinis* are primarily present in winter and spring. All copepod occurrences and peak abundances are shown in Table 7.

Most copepods reproduce sexually with females either shedding or carrying eggs that hatch into the early developmental stage, the nauplius (plural = nauplii). These minute planktonic forms have five stages of development and usually give rise to five copepodid (juvenile or pre-adult) stages, the last of which closely resembles the adult. The sixth copepodite is the adult stage. Due to high fecundity and mortality rates, the naupliar and copepodid stages always outnumber the adults. Because it is difficult to identify nauplii or copepodid stages to species, they are often counted together in mixed species categories (Table 7). Copepods feed by harvesting small suspended particles, both living (as phytoplankton and microzooplankton) and dead (organic aggregates). In turn, copepods are major sources of food for larger zooplankton (e.g., larval shrimps, chaetognaths, jellyfishes) and fishes (e.g., larval fishes, adult anchovies, herrings, and silversides).

Barnacle nauplii are among the most common of the local zooplankton types. These early developmental stages originate from the adults of several species of barnacles that grow on oyster

Table 7. Composition of small mesozooplankton in North Inlet, SC, 1981-2003 collected in 153-µm mesh nets. Taxonomic category name (A = Adult, C = Copepodid life stage), primary annual period of occurrence (POC), average density for the POC based on biweekly 1981-1992, quarterly 1993-2003 samples, maximum density during the study (same data as previous), months of peak abundance, and the primary taxa comprising the counting category.

Taxon or Category	POC	Mean (No./m³)	Max (No./m³)	Peak Month	Primary Taxa
hydromedusae	Jan 1 - Dec 31	37.6	448.8	May - Oct	mostly *Clytia*, *Bougainvillia*, *Nemopsis* spp.
gastropod veligers	Mar 1 - Sep 30	281.6	2,042.4	Mar - Sep	*Nassarius* spp., *Boonea* spp., *Melampus pominate*
bivalve larvae	Jan 1 - Dec 31	199.9	6,146.1	Jun - Sep	*Mercenaria* spp., *Crassostrea* spp. dominate in summer
polychaete larvae	Jan 1 - Dec 31	479.5	12,044.5	May - Dec	dozens of contributors; see macrobenthos list
cladocerans	Jan 1 - Dec 31	14.8	432.6	May, Oct - Nov	unidentified taxa
ostracods	Jan 1 - Oct 31	4.5	72.0	Mar - May	unidentified taxa
total copepods (A & C)	Jan 1 - Dec 31	9,086.8	119,404.4	May - Sep	All copepod taxa below plus unidentified Adults and Copepodids
Acartia tonsa (A)	Jan 1 - Dec 31	1,104.7	24,560.8	May - Sep	
(C)	Jan 1 - Dec 31	3,128.4	48,616.0	Apr - Sep	
Centropages hamatus (A)	Dec 1 - May 15	55.0	642.8	Dec - May	
(C)	Nov 1 - Apr 30	361.8	4,966.6	Dec - Apr	
Eurytemora affinis (A)	Jan 1 - May 31	11.8	918.5	Feb - Apr	
(C)	Jan 1 - May 31	61.4	3,074.9	Feb - May	
Labidocera aestiva (A)	May 16 - Sep 30	5.4	376.6	June	
(C)	Apr 1 - Nov 30	102.2	1,412.1	May - Nov	
Parvocalanus crassirostris (A)	Jan 1 - Dec 31	1,981.3	30,428.9	May - Oct	
Paracalanus spp. (A)	Jan 16 - Dec 31	7.7	232.9	Apr - May, Oct - Nov	
(C)	Jan 16 - Dec 31	42.0	1,516.5	Apr, Jul	
Temora turbinata (A)	Jun 16 - Nov 15	17.9	419.8	Jun, Oct	
(C)	Jly 1 - Dec	80.6	1,278.4	Oct - Nov	
Pseudodiaptomus pelagicus (A)	Apr 1 - Nov 15	97.2	2,226.6	Apr - Sep	Originally named:
(C)	Apr 1 - Sep 30	1,443.6	11,540.1	May - Aug	*P. cornatus*

Table 7 continued.

Taxon or Category	POC	Mean (No./m³)	Max (No./m³)	Peak Month	Primary Taxa
unidentified calanoid copepods (A & C)	Jan 1 - Nov 15	299.3	8,670.2	Feb, Jun	*Temora* spp., *Tortanus* spp. Primarily copepodid life stages
Euterpina acutifrons (A)	Apr 16 - Dec 15	339.4	3,065.7	May - Nov	
unidentified harpacticoid copepods (A)	Feb 1 - Nov 15	66.5	1,888.8	Apr - Jun	*Coullana* spp.
Oithona spp. (A)	Jan 1 - Dec 31	933.3	8,951.7	Apr, Dec	*Oithona colcarva* and other species
unidentified cyclopoid copepods (A)	Jan 1 - Dec 31	77.1	1,880.2	Apr, Jul, Sep	*Corycaeus* spp., *Saphirella* spp., *Oncaea venusta*
unidentified copepod nauplii	Jan 1 - Dec 31	1,014.8	16,741.6	May – Sep Nov - Feb	
barnacle nauplii	Apr 16 - Sep 30	5,327.9	44,113.8	May - Aug	
cyprids	Apr 16 - Aug 31	172.3	4,114.4	May - Jun	*Balanus eburneus, Chthamalus fragilis*
crab zoeae	Apr 16 - Oct 15	1,208.4	9,058.2	May - Sep	*Uca* spp., *Panopeus* spp., *Callinectes* spp.,& many others
bryozoan (cyphonautes) larvae	Jan 1 - Dec 31	56.6	1,049.2	May - Jul	Unidentified bryozoan taxa
bipinnaria/brachiolaria larvae	Jun 16 - Sep 15	7.5	188.3	Jun	*Luidia* spp., *Astropecten* spp., *Astarias* spp.
salps & doliolids larvae	Jun 16 - Nov 30	2.2	46.2	Sep	Unidentified salp taxa
Ophio- and echino-pluteii larvae	May 1 - Nov 15	107.6	1,858.2	Jun, Aug - Oct	*Ophiothrix* spp., *Microphiopholis* spp., *Arabacia mellita* & other brittlestars & urchins
ascidian “tadpole” larvae	Jun 1 - Nov 15	5.1	149.9	Jul	*Mogula* spp., *Stylla* spp., & other tunicates
larvacean (appendicularian) larvae	Apr 16 - Nov 15	304.3	2,655.6	Jun, Sep	*Oikopleura* spp.
other mesozooplankton	May 1 - Dec 15	150.7	1,165.2	May - Sep	Larval fish, amphipods, shrimp larvae, mysids, chaetognaths
total small mesoplankton	Jan 1 - Dec 31	15,069.1	143,383.9	May - Sep	all taxa above

reefs and other hard surfaces in the estuary. Pairs of horns on the heads of barnacle nauplii (Figure 76) distinguish them from the otherwise similar-looking copepod nauplii. Later stages can be very abundant especially from May through August. The last naupliar stage transforms into a small clam-like larva known as the cyprid (Figure 76). The cyprid attaches to a suitable hard surface and metamorphoses, becoming a more familiar looking barnacle.

From spring through fall, crab zoeae occur in almost all zooplankton collections, sometimes numbering in the thousands per cubic meter from pulsed releases during spring ebbing tides. This timing facilitates their transport to the coastal ocean for further growth and development. These larvae have unusually large heads with helmets that are usually spiked (Figure 76). Zoeae hatch from eggs carried by female crabs representing more than 15 local species. In most summer collections, fiddler crab (*Uca* spp.) zoeae are by far the most abundant, but zoeae from several species of mud crabs (e.g. *Panopeus herbstii*) and swimming crabs (e.g. *Callinectes sapidus*) also occur. After hatching, early stage fiddler crab zoeae pass through several advanced zoeal stages before transformation to the megalopa stage (Figure 77). Megalopae move with flooding tides into the marsh creeks and become small crabs in the adult habitat.

Due to different spawning times for polychaete worms (there are dozens of species), polychaete larvae are found throughout the year. Unlike crustacean larvae that grow in stages by shedding their old exoskeletons, polychaete larvae add segments and bristles and begin to resemble small adults before leaving the plankton and settling on to benthic habitats (Figure 76).

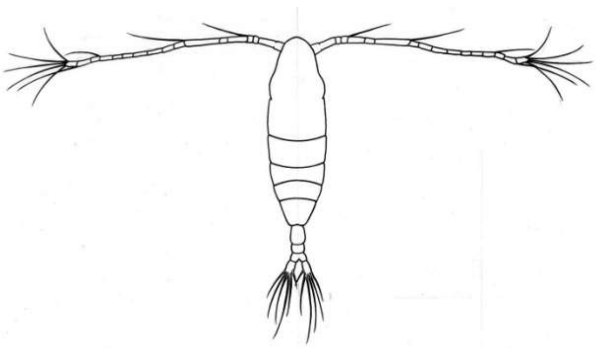

Uca pugilator. Crab zoeae occur in almost all zooplankton collections in North Inlet, sometimes numbering in the thousands per cubic meter.

Lots of other familiar estuarine invertebrates produce large numbers of zooplanktonic larvae. Bivalves (including clams and oysters) and gastropods (snails) start out as round ciliated forms known as veligers (Figure 76) that eventually develop thin shells as they settle to the bottom. Bryozoan larvae called cyphonautes are less common but uniquely triangular-shaped members of the zooplankton. Bipinnaria and brachiolaria larvae of seastars, ophiopluteii larvae of brittlestars, and echinopluteii larvae of sea urchins and sand dollars are found during the warmest period of the year. Ascidian “tadpole” larvae of tunicates are also found in summer.

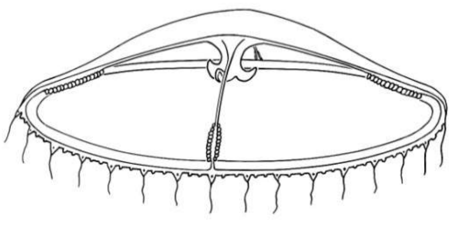
Cladocerans (Figure 76), related to the common freshwater *Daphnia* spp., are ocean-based crustaceans that sometimes occur in the estuary during summer. The larvae of other ocean-dwelling forms including salps, doliolids, and larvaceans (appendicularians) can sometimes occur at densities exceeding 1000 per cubic meter (Costello and Stancyk, 1983). Another clam-like swimming crustacean that appears in the zooplankton is the ostracod. These small adult forms live on or in the bottom but are sometimes re-suspended and/or swim into the water column, but they are never very abundant. However, other small, bottom-dwelling meiobenthic ostracods are quite abundant in the sediment.

Hydromedusae (Figure 76) are very small jellyfishes. Most originate from soft bodied, branched colonies of animals that grow on hard surfaces. Like larger, more familiar jellyfishes, hydromedusae use tentacles to collect food. If in large enough numbers, they can have a substantial impact by grazing on copepod populations and other small planktonic types. Hydromedusae are found in both sizes of collection nets, but with an order of magnitude greater abundance in 153-µm mesh samples.

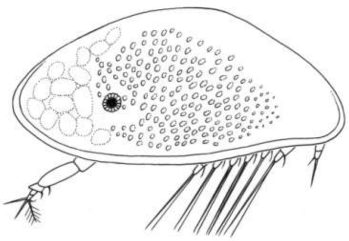
barnacle nauplius



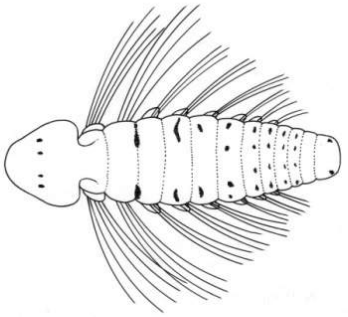
calanoid copepod (*Acartia tonsa*)



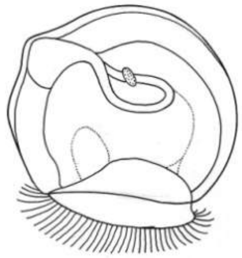
hydromedusa



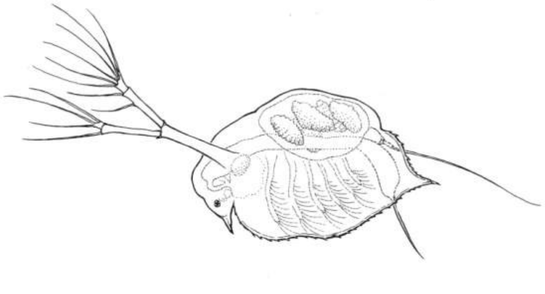
barnacle cyprid



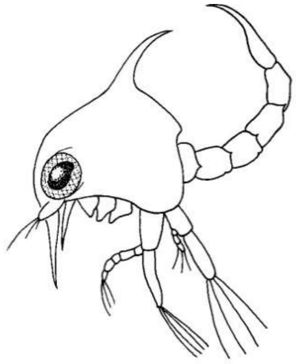
polychaete larva



bivalve (clam) veliger



cladoceran



crab zoea

Figure 76. Common small mesozooplankton taxa found in North Inlet : *Acartia tonsa* adult, crab zoea, barnacle nauplius, hydromedusa, cladoceran, polychaete larva, bivalve veliger and barnacle cyprid (illustrations by Marni Fylling; from Johnson and Allen, 2012, with permission). All are typically less than 2 mm in length except hydromedusae which range from about 2 mm to more than15 mm in diameter.

- **Large Mesozooplankton: 365-µm mesh**

The large size fraction of the mesozooplankton represents a diverse assemblage of invertebrates and larval fishes, some of which are permanent and others only temporary members. Animals comprising this assemblage are collected by both the 153 and 365 micron meshes; however, most of the animals listed as large zooplankton are not enumerated in the 153 micron samples. Larger, faster swimming zooplankton can sense the pressure wave of the small mesh net and avoid being captured by small mesh nets. Animals listed as small zooplankton are generally not well retained by the 365 micron mesh and are not enumerated in these collections. Accordingly, quantitative data for each taxonomic category comes from only one of the mesh sizes with the exception of the hydromedusae which span a wide range of sizes.

The constituents counted in the 365-micron epibenthic sled collections in North Inlet are characterized in Table 8 (Allen et al., 2008). These summary data are based on the first 22 years of biweekly collections, ending in 2003. Since then, only samples taken on certain quarterly dates have been processed; however, no major changes have been observed in the composition or relative abundances of these taxa, so the following information is applicable through 2014.

Chaetognaths (arrow worms) are among the largest of the holoplanktonic forms (Figure 77). These very abundant coastal ocean species occur in the high salinity creeks of North Inlet where they consume smaller zooplankton including copepods and larval fishes.

Larval shrimps are among the more conspicuous members of the large mesozooplankton. Grass shrimp (*Palaemonetes* spp.) larvae (Figure 77) are typically the most abundant from spring through fall, but snapping shrimp (*Alpheus* spp.), mud shrimp (*Upogebia affinis*), and penaeid shrimp (*Litopenaeus setiferus*, *Farfantepenaeus aztecus*, *Farfantepenaeus duorarum*, *Rimapenaeus constrictus*) larvae are also present during the warmest months (Table 8). Larvae of several species of ghost or callianassid shrimps occur in the estuary. Each shrimp species passes through a series of larval stages before transforming into a postlarva which precedes settlement into the adult habitat on the bottom. The adults of some shrimps are very small (typically < 20 mm) and can only be collected with plankton nets. *Lucifer faxoni* is a thin, unusual-looking shrimp of oceanic origin that swims high in the water column. The related sergestid shrimp, *Acetes americanus carolinae*, is slightly larger and more oriented to the lower or deeper levels of the water column. *Urocaris longicaudata* (formerly *Periclimenes longicaudatus*), *Latreutes*, and several other small adult shrimps found in North Inlet are closely associated with the bottom.

The late larval stages of crabs, known as megalopae, are also common constituents of the large mesozooplankton. Fiddler crab (*Uca* spp.) far outnumber all others in North Inlet, but xanthid (mud), portunid (swimming), and hermit crabs are also present during the warmest period of the year. Large porcellanid crab zoeae (including *Petrolisthes armatus*) are counted among the 365 micron-caught crab larvae. Less common mantis (stomatopod) shrimp larvae are also included in the 365 micron sample counts.

A common group of small crustaceans that brood their young are collectively known as the peracaridians. Mysid shrimps, also known as opossum shrimps (Figure 77), generally resemble some of the small adults of the true (decapod) shrimps, but incubate their young in ventral pouches. *Neomysis americana* is the most abundant mysid shrimp during the cold season when decapod shrimps are uncommon. Mysids sometimes move together in large schools or shoals, and densities of many hundreds per cubic meter are common in these aggregations. During summer, at least six other species become more numerous in collections made close to the bottom (Heard et al., 2006). Two distinct groups of amphipods, the gammarids (Figure 77) and caprellids, are year-round residents that live mostly near the bottom, especially on structure such as soft corals, sponges, and bryozoans. Cumaceans and isopods also occur near the bottom, but many species of all of these groups move into the water column to mate and feed.

Table 8. Composition of large mesozooplankton in North Inlet, SC, 1981-2003 collected in the 365 µm mesh sled net. Taxonomic category name, primary annual period of occurrence (POC), mean density for the POC based on biweekly 1981-2003 collections, maximum density during the study (based on same data as previous), months of peak occurrence, and primary taxa and/or life stages comprising the counting category (Allen et al., 2008).

Taxon or Category	POC	Mean (No./m³)	Max (No./m³)	Peak Month	Primary Taxa
chaetognaths	Jan 1 – Dec 31	8.02	167.44	Jun - Aug	mostly *Sagitta hispida*, *S. tenuis*
hydromedusae	Jan 1 – Dec 31	1.36	49.43	May - Jul	mostly *Clytia*, *Bougainvillia*, *Nemopsis*
mysids	Jan 1 – Dec 31	8.84	986.74	Jan - Jun	mostly *Neomysis americana* juveniles and adults
gammarid amphipods	Jan 1 – Dec 31	3.63	131.83	May - Aug	*Gammarus*, *Ampelisca*, *Cerapus* juveniles and adults
caprellid amphipods	Jan 1 – Dec 31	0.95	20.86	Feb - Aug	*Caprella* juveniles and adults
cumaceans	Jan 1 – Dec 31	0.46	37.29	Mar - May	*Diastylis*, *Oxyurostylis*, *Leucon* juveniles and adults
isopods	Jan 1 – Dec 31	0.11	3.94	May - Jly	*Edotia*, *Livoneca* juveniles and adults
others	Jan 1 – Dec 31	0.60	20.55	May - Sep	polychaete larvae, porcellanid crab zoeae, pagurid crab megalopae, pychnogonids, leeches, nudibranchs
adult shrimps	Jan 1 – Dec 31	0.56	16.18	May - Aug	*Palaemonetes*, *Hippolyte*, *Neopontonides*, *Rimapenaeus* and other adult shrimps, except the four taxa listed below
Urocaris	Jan 1 – Dec 31	0.44	10.29	Sep - Oct	*U. longicaudata*
Acetes	May 16 – Nov 15	1.90	206.70	Jly - Aug	*A. americanus* juveniles and adults
Lucifer	Apr 16 – Dec 15	0.58	9.77	Jun - Oct	*L. faxoni* juveniles and adults
Latreutes	Apr 1 – Sept 30	0.12	4.05	May - Aug	*L. parvulus* juveniles and adults

Table 8 continued.

Taxon or Category	POC	Mean (No./m³)	Max (No./m³)	Peak Month	Primary Taxa
total shrimp larvae	Jan 1 – Dec 31	3.97	65.64	Apr - Oct	All shrimp larvae, including the taxa below
Palaemonetes	Apr 1 – Nov 30	3.30	29.77	May – Sep	*P. pugio* and *P. vulgaris*
Alpheus	Apr 16 – Nov 15	1.72	31.41	May – Sep	mostly *A. heterochaelis*
callianassids	Apr 16 – Oct 31	0.29	8.49	May – Sep	*Callichirus*, *Biffarius*, *Gilvossius*
Upogebia	Apr 1 – Nov 15	0.34	7.33	May– Sep	*U. affinis*
penaeid shrimps	Jan 16 – Oct 31	0.28	4.82	Mar - Sep	*Farfantepenaeus aztecus*, mostly *Litopenaeus setiferus*, some *F. duorarum*
total fish larvae	Jan 1 – Dec 31	6.20	214.34	Feb - Sep	All fish larvae, including the taxa below
Gobiosoma	Apr 16 – Sept 30	11.49	206.48	May – Sep	mostly *G. bosc*
Anchoa	Apr 16 – Sept 15	0.59	9.33	May –Jul	*A. mitchilli* and *A. hepsetus*
Leiostomus	Dec 1 – May 15	0.49	12.27	Jan – Apr	*L. xanthurus*
Lagodon	Dec 1 – May 15	0.22	6.94	Jan - Mar	*L. rhomboides*
pinnotherid crab	May 16 – Oct 31	1.59	39.93	Jun – Aug	mostly *Zaops* (Pinnotheres) ostreum first crab
crab megalopae & juvenile	Feb 1 – Nov 30	3.83	145.74	May – Sep	mostly *Uca pugnax* and *U. pugilator,* some *Callinectes* and xanthids
stomatopod larvae	May 16 – Sep 30	0.08	1.45	Jun – Aug	*Squilla empusa*
fish eggs	Apr 1 – Oct 31	0.63	10.82	Apr - Jun	mostly *Anchoa*
total large mesoplankton	Jan 1 – Dec 31	40.84	1054.36	May - Sep	all taxa above

Hydromedusae are collected in both the 153 and 365 micron collections. Because there is such a wide range in size among hydromedusae only large individuals are counted in the 365 micron collections.

Larval fishes can be very abundant in summer samples (Table 8). More than 45 species have been identified in North Inlet zooplankton collections. During summer, diversity is highest with goby (*Gobiosoma* spp.) (Figure 76) and anchovy (*Anchoa* spp.) dominating most larval fish collections. During the coldest part of the year, larval spot (*Leiostomus*) (Figure 76), pinfish (*Lagodon*), southern/summer flounder, Atlantic menhaden, speckled worm eel, and American eel larvae dominate.

Dozens of wormlike animals such as oligochaetes and nematodes that usually live on the bottom can be found in both small- and large-mesh mesoplankton collections. Sediment-dwelling copepods can also become resuspended and are captured by nets. Free swimming leeches, crawling sea spiders (pycnogonids), mites, branchiurans (fish lice), and sea slugs (nudibranchs and pteropods) are among the many unusual small invertebrates that are occasionally collected.

SPATIAL PATTERNS

Comparisons of small mesozooplankton (153-µm mesh) densities at four locations within the North Inlet system were conducted by Lonsdale and Coull (1977). They showed, based on 20-month means, that total zooplankton and most taxa densities were highest in the mouth of the inlet and at the Town Creek/Old Man Creek confluence. Densities near the middle of Bly Creek were somewhat lower, and they were lowest in the southern end of South Jones Creek. Allen et al. (1982) found that densities and the diversity of small and large zooplankton in South Jones and No Man's Friend Creeks were more similar to those in North Inlet and lower Winyah Bay than to the upper portion of Winyah Bay during most of the year. In a study of larval fishes in North Inlet, Allen and Barker (1990) found very similar seasonal and interannual patterns between two sampling sites (near the inlet mouth and at the confluence of Town Creek/Clambank Creek). Moore and Reis (1983) did not observe significant differences in large zooplankton collected from a bank-to-bank transect across Town Creek. Occasional collections outside of the inlet have shown higher densities of chaetognaths, cladocerans, sergestid shrimps, and intermediate developmental stages of estuarine shrimps and crabs than those within the estuary. Especially high densities of larval decapods, fishes, and mysids have been found in summertime collections in the surf zone within hundreds of meters of the beach.

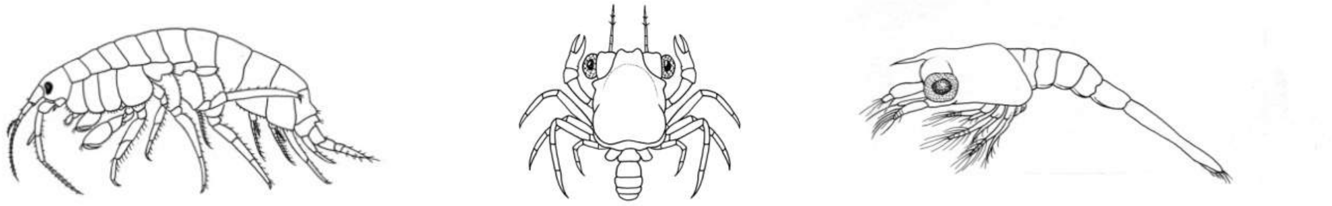
TIDAL AND DIEL PATTERNS

Several short-term studies at the long-term site in Town Creek indicate that although the composition of the small and large zooplankton assemblages does not change much between tidal stages, the highest densities of most taxa occur near high tide and lowest densities occur near low tide. Time-of-day also affects densities of many taxa; densities of the larger, more motile forms tend to be higher at night than in daytime, probably because of a lower ability to detect and avoid nets than during the day. Vertical stratification of zooplankton is not commonly observed in the shallow creeks, especially with the small mesozooplankton. However, in a summertime 48-hr study in Town Creek, surface – bottom comparisons of large zooplankton revealed several taxa that vertically segregate; hydromedusae, *Upogebia* larvae, and fish eggs were more abundant in surface collections, whereas callianassid shrimp larvae and crab megalopae preferred the bottom. Some small zooplankton, including *Acartia tonsa*, showed a tendency to remain near the bottom during the day and dispersed throughout the water column at night.

SEASONAL PATTERNS

The abundances of both small (Figure 78) and large (Figure 79) zooplankton indicated similar patterns with minimum densities during the coldest months, sharp increases in spring, high but irregular patterns in summer, and sharp drops in the fall. Water temperature and day-length are often mentioned as the primary determining factors for seasonal fluctuations in abundance and composition of zooplankton.

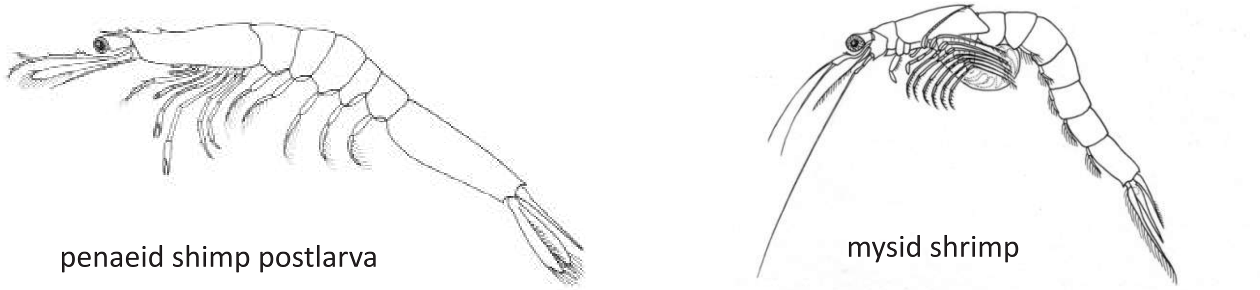
Seasonal changes in the composition of each of the two size fractions of North Inlet zooplankton follow a regular pattern with the highest diversity occurring during the warmest period. In the small mesozooplankton assemblage, copepods dominated during every season, comprising 64-73% of the average catch. Figure 80 shows the proportions of the non-copepod categories each season, and barnacles were by far the most abundant taxon all four seasons. Polychaete larvae, larvaceans, bivalve veligers, and gastropod veligers accounted for smaller proportions year round, and crab zoeae accounted for less than 10% in spring and summer. The periods of occurrence for all small taxa are found in Table 7. In 2012, the general patterns of seasonal occurrence for dominant taxa shown in



gammarid amphipod

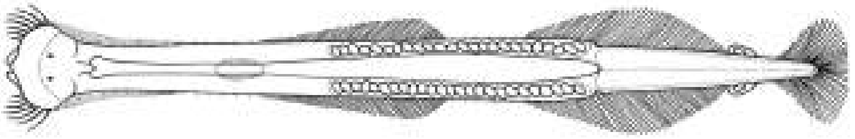
crab megalopa

Palaemonetes shrimp larva (stage 1)

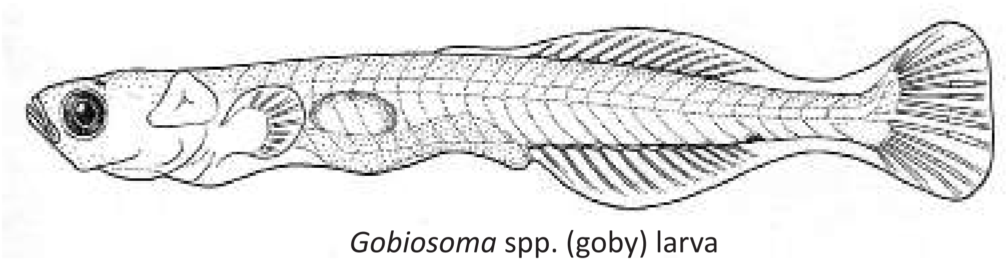


penaeid shimp postlarva

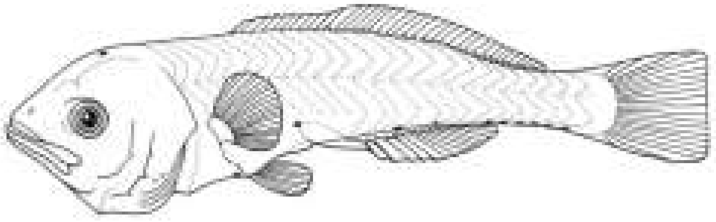
mysid shrimp



chaetognath



Gobiosoma spp. (goby) larva



Leiostomus xanthurus (spot) larva

Figure 77. Common large mesozooplankton taxa found in North Inlet: mysid, *Palaemonetes* spp. shrimp larva, penaeid shrimp postlarva, crab megalopae, chaetognath, goby larva, *Leiostomus xanthurus* larva, gammarid amphipod. (illustrations by Marni Fylling; from Johnson and Allen, 2012, with permission). These animals may reach sizes of up to almost 10 mm length.

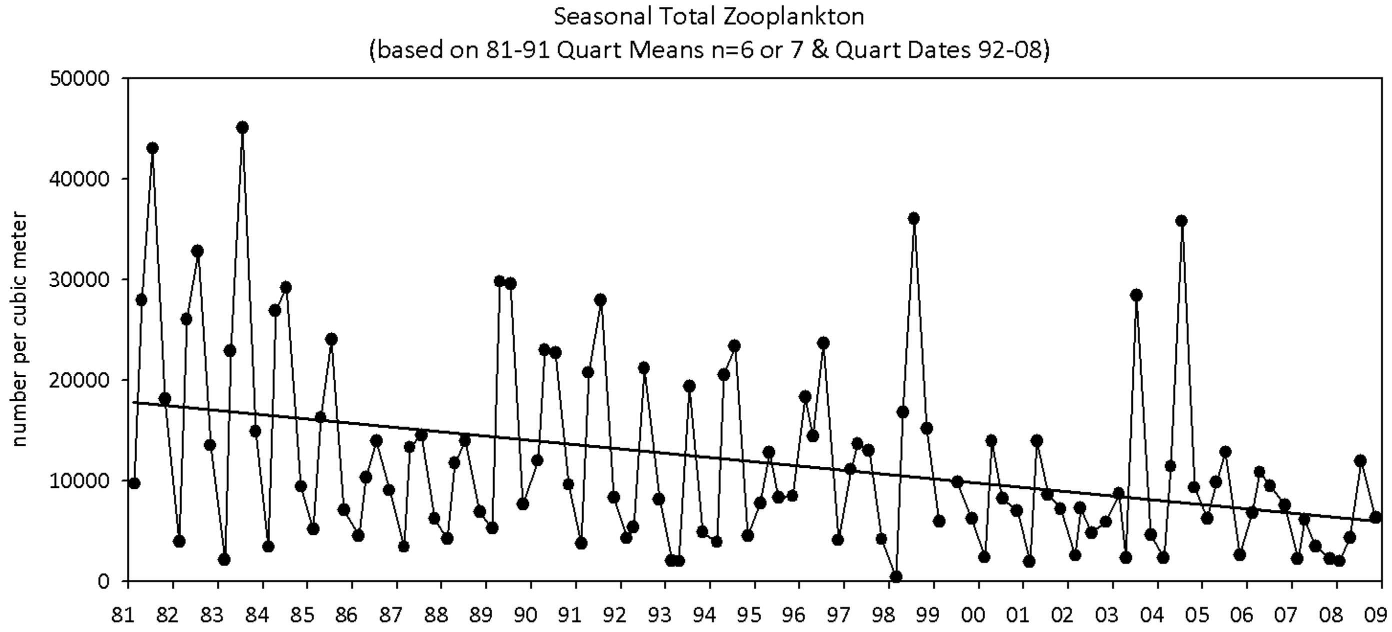


Figure 78. Abundance of total small mesozooplankton in North Inlet. Quarterly mean densities are shown for January 1981 – January 1992 and quarterly values from April 1992 – December 2008. A quarterly trend line, determined with linear regression analysis, showed a significant long-term decrease in abundance.

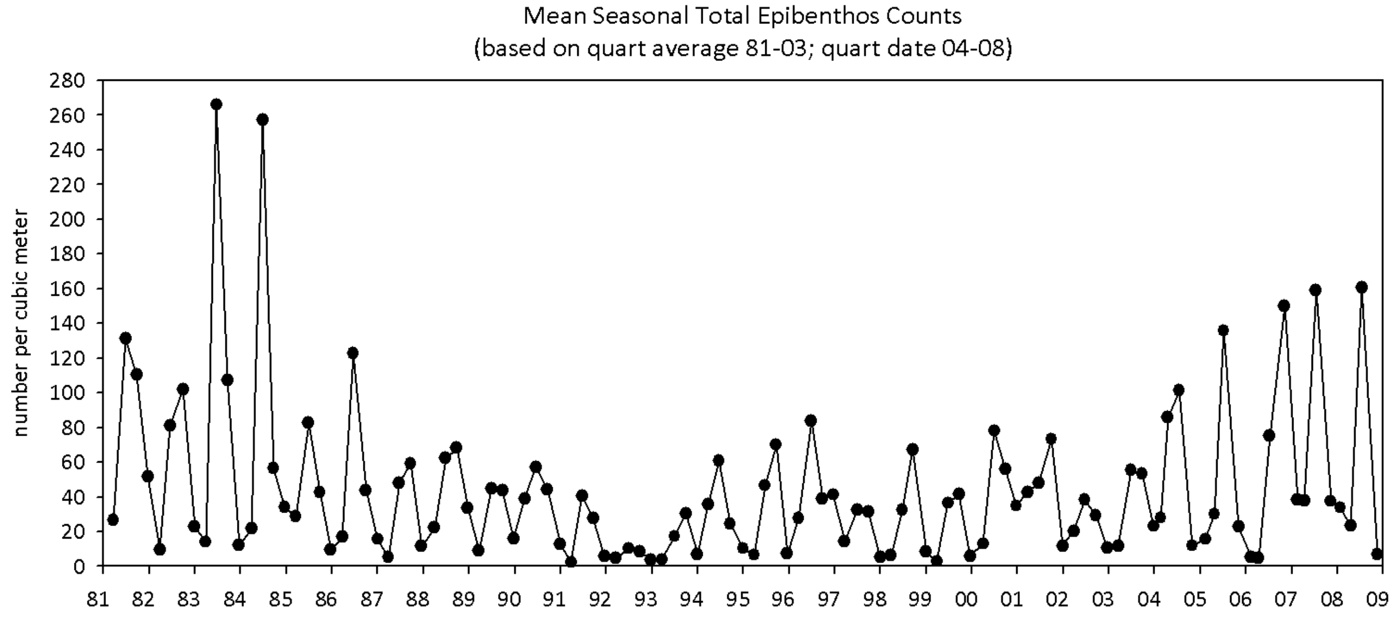


Figure 79. Abundance of total large mesozooplankton in North Inlet. Mean densities are shown from January 1981 - December 2008 (based on quarterly means 1981-2003, quarterly values 2004-2008).

this table were very similar.

The average seasonal proportions of large mesozooplankton taxa from 1981-2003 are shown in Figure 81. Mysids and amphipods were the major groups in the winter and spring, making up ~65% and ~45%, collectively and respectively. Fish larvae and chaetognaths also contributed in spring, when densities of large mesozooplankton were the highest for the year. These two groups, plus adult and larval shrimps and crab megalopae, dominated in summer. Seasonal changes in the composition of larval fishes were large with the highest proportions occurring in the spring and summer. In the fall chaetognaths numerically accounted for over 50% of the total catch.

YEAR-TO-YEAR PATTERNS AND LONG-TERM TRENDS

Large variations in zooplankton abundance have been observed between years. Seasonal mean densities from 1981-2008 are shown for the small and large size fractions of the zooplankton in Figure 78 and Figure 79, respectively. Three- to ten-fold differences in mean abundances for the same season are not unusual between consecutive years. Peak summer abundances of the small zooplankton were in excess of 50,000 individuals m^{-3}, and the long-term average for all seasons combined was about 15,000 m^{-3}. Highest abundances of large mesozooplankton were 100-300 m^{-3}, and the overall average was about 41 m^{-3}.

Long-term trend analysis for the small mesozooplankton

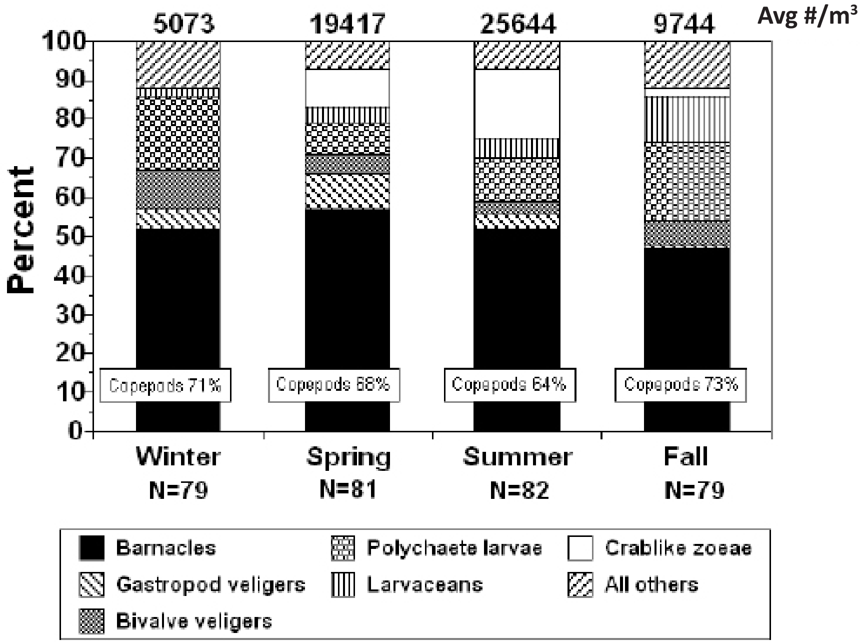


Figure 80. Seasonal composition of small zooplankton in North Inlet. Proportions of the total catch are based on the biweekly and quarterly long-term average density for each season (n = 23 years). Seasonal average numbers (per cubic meter) of total small mesozooplankton from the biweekly and quarterly database are denoted above each seasonal bar; sample size (N) is listed below. Bars represent percent of total catch for each category comprised AFTER removing copepods from the database.

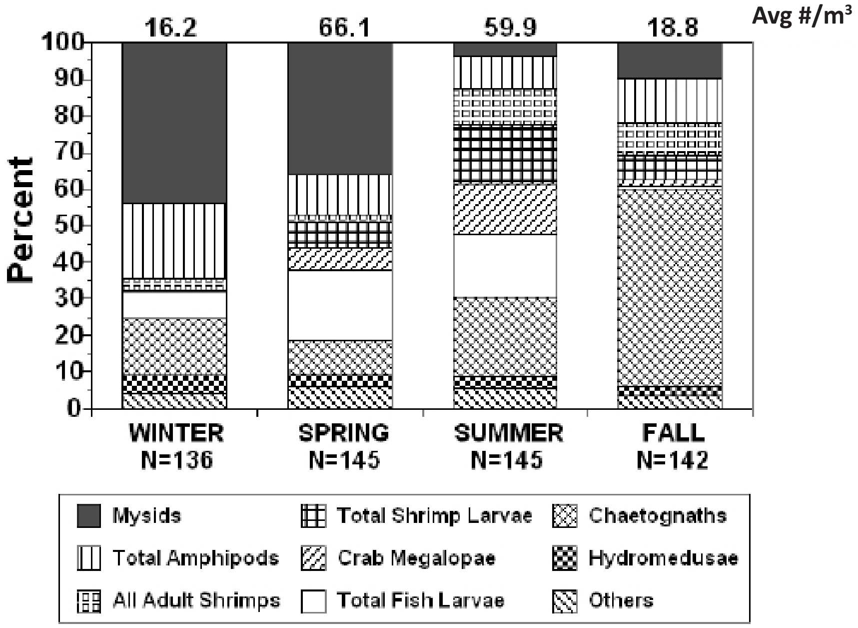


Figure 81. Seasonal composition of large mesozooplankton in North Inlet. Proportions of the total catch are based on the biweekly long-term average density for each season (n = 23 years). The average seasonal total catch is denoted above each bar in numbers per cubic meter; sample size (N) is listed below.

indicated a significant decrease in the densities of total organisms between 1981 and 2008 (Figure 78). No long term-trend was observed for the large mesozooplankton which went from high levels in the 1980s to very low densities in the 1990s, then increased through 2010 (Figure 79). Although abundance varied widely among years, the composition of these assemblages did not change much over the period. Understanding how the many interacting environmental and biological factors influence zooplankton abundances is a difficult challenge.

Salinity is thought to be a major factor influencing the abundance of zooplankton within estuaries. Figure 82 shows the long-term biweekly pattern for salinity at the Town Creek sampling site over the 32-year time series. The long-term mean salinity is 32, not much less than typical ocean salinities of 35. Long-term trend analysis did not show an overall change in salinity. The most depressed salinities in North Inlet almost always occurred in winter and spring and usually coincided with the incursion of brackish water from Winyah Bay into North Inlet during periods of high Pee Dee River discharge and winter rains. High winter rainfall in South Carolina and in North Inlet corresponded well with the occurrences of El Niño climatic events (Allen et al., 2008). Salinity directly affects the zooplankton with lower densities of oceanic forms such as chaetognaths occurring during these periods. The long-term decrease in small zooplankton may be related to a significant long-term decrease in river discharge into Winyah Bay and the associated reduction in nutrients and phytoplankton in this section of the coast. Check for recent publications for updated analyses of trends and factors affecting zooplankton abundances in North Inlet.

Changes in water temperature can be expected to affect zooplankton abundances. Although water temperature and total large zooplankton abundances were not correlated, the overall increase of 1.0 °C and winter increase of 1.7 °C from 1979 - 2011 could be expected to affect the population dynamics of estuarine zooplankton. Other factors including tidal and ocean current patterns, dissolved oxygen, incident light and penetration, food availability, predation pressure, and human activities in the watersheds also affect zooplankton dynamics. We have begun to identify relationships between changes in the local, regional, and global climate change/variability and zooplankton community structure. Continued collections, measurements, and data analyses in the years to come will enable important insights into possible relationships between estuarine zooplankton and climate change.

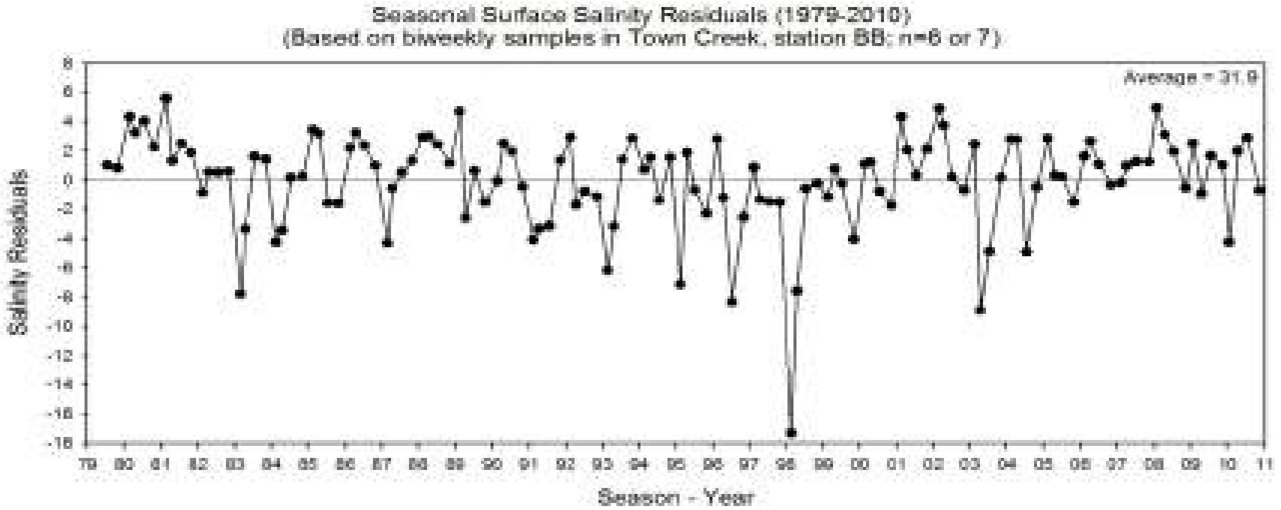


Figure 82. Salinity measured at the surface of Town Creek (near the confluence of Town and Clambank Creeks) at the time of the biweekly zooplankton collections near mid ebb tide, 1981-2011. The extended periods of winter-spring low salinities corresponds well to the occurrence of moderate or strong El Niño (EL) events. Salinity values are represented on the plot as residuals, or deviations from the long-term means for each season.

» Nekton

Fishes, shrimps, crabs, squids, and other macroscopic invertebrates abound in the waters of North Inlet and Winyah Bay. Collectively these motile animals are known as the nekton. Unlike zooplankton (an assemblage of weakly swimming forms or drifters) and benthos (an assemblage of sedentary or slow moving animals that live on or in the sediment), the nektonic organisms are generally capable of directed movements in tidal systems. This diverse and dynamic group includes many species which play key roles in coastal ecosystems and fisheries. More than 180 species of fishes and about 30 shrimps, swimming crabs, and squids have been identified within North Inlet. In this section, the focus is on the patterns of distribution for the 15 or 20 species that account for more than 90% of the individuals collected. More than 95% of all of the fish species known from North Inlet are represented by larval or juvenile life stages, which is why estuaries are often characterized as nurseries.

Because so many fishes are referred to by different common names in different locations, scientists and fishery managers have had to agree on the use of single common names for each species of fish. Throughout this document, we use the common names accepted by the American Fisheries Society. Scientific (Latin) names and additional information about all species known from both estuaries are provided in **Appendix E**.

NEKTON RESEARCH IN THE NORTH INLET AREA

Researchers working in local estuaries over the past 30 years have generated a lot of information about the distribution, life cycles, physiology, and behavior of fishes, shrimps, and crabs. The characterization of the nekton that we present here is based primarily on results from several long-term surveys, but information from other studies was used to provide additional facts and perspectives. The first surveys of fishes in North Inlet were conducted by scientists in the 1960s as part of the Belle W. Baruch Foundation's effort to establish a baseline understanding of the fauna associated with the tidal waters of Hobcaw Barony (Freeman 1970). Since the early 1970s, much of the research on North Inlet fishes has been focused on their distribution and behavior in intertidal creeks. Burns (1974) characterized the larval fish assemblages and Cain and Dean (1976) conducted a comprehensive study on seasonal changes in the abundances of resident and transient fishes in an intertidal creek. Information on the uses of shallow creeks by early life stages of fishes were contributed by Shenker and Dean (1979), Bozeman and Dean (1980), Reis and Dean (1981), and Crabtree and Middaugh (1982).

Moore and Reis (1983) characterized the nekton in the tidally dominated channel inside of the inlet. Ogburn and Allen (1993) studied relationships among shore-zone species adjacent to subtidal channels. Lehnert and Allen (2002) demonstrated the diversity and abundance of fishes using shelly bottoms adjacent to intertidal oyster reefs. Bretsch and Allen (2006) described patterns of tidal migrations of nekton into and out of intertidal creeks. Allen et al. (2007) demonstrated considerable spatial variations in the extent of nekton use among neighboring intertidal creeks and showed that these could be attributed to differences in hydrogeomorphological features of the habitat. Christian and Allen (2014) followed up on that study by developing an ecological network analysis of food web structure using data from the eight creeks; the model indicated differences in food web attributes with wide creeks having greater carbon cycling, higher trophic efficiency, and greater export in the form of nekton than narrow creeks. In another study, Allen et al. (2013) demonstrated that nekton feeding and excreting in intertidal creeks contributed dissolved nutrients to the water, potentially nourishing benthic microalgae that provide food for the small invertebrates that the fish consume while using the creeks. In 2010 and 2012, collaborating visiting scientists used new multibeam sonar technology to study the behavior of fishes moving between subtidal channels and intertidal creeks.

Some researchers have focused on single species. Middaugh (1981) studied the reproductive ecology of the Atlantic silverside. Chestnut (1983) studied the feeding behavior of spot. Potthoff and Allen (2003) demonstrated high site fidelity for young-of-the-year pinfish. Johnson et al. (1990) showed tidal and diel patterns in the feeding of the bay anchovy on zooplankton, and a companion study showed spatial and seasonal partitioning of the zooplankton prey field by the two species of anchovies and two species of silversides in subtidal channels (Allen et al. 1995). Smith (2012) conducted a one year study of the occurrences of large, trammel-net susceptible nekton in North Inlet creeks. Moore (2012) characterized the distributions of sharks and rays in subtidal creeks, and Maxwell (2008) studied the movements of the young-of-the-year Atlantic sharpnose sharks in the estuary.

With the establishment of the North Inlet Long-Term Ecological Research (LTER) site in 1980, scientists were able to initiate a four-year seine and trawl study to investigate seasonal, interannual, and spatial patterns of nekton occurrence in the lower estuary (Ogburn et al., 1988). In 1984, the nekton research program shifted emphasis to understand the shallow intertidal habitats where diversity and densities are highest. The Oyster Landing nekton study was initiated to document interannual and interdecadal changes in nekton use of an intertidal creek basin and to relate them to changes in environmental conditions. Analyses of data collected from 1984-2011 were used to develop the descriptions of nekton distributions presented below. Another study of fishes conducted in the early 1980s in creeks connecting North Inlet and Winyah Bay added to our understanding of the nursery function of the estuary (Allen et al., 1982). Information about larval fishes has been generated by the long-term zooplankton program (see section on North Inlet zooplankton) and other studies (Beckman and Dean, 1984; Allen and Barker, 1990, Allen et al., 2008; Able, et al., 2011). The NI-WB NERR began supporting the long-term monitoring programs for nekton and zooplankton in 1994, continuing the effort that began with NSF-LTER support in 1981.

This rich history of studies on the nekton of North Inlet forms the basis for the general descriptions that follow.

COMMON FISHES, SHRIMPS, AND CRABS

Of the more than 180 species of fishes and dozens of motile macroinvertebrates known from the area, few are very abundant, widely distributed, and regularly observed. Studies have shown that <10% of the species account for >90% of the individuals. Most species can be classified as either residents or transients of the estuary. Resident species reproduce, grow and die within the estuary. Examples of common residents are mummichog, striped killifish, sheepshead minnow, gobies, blennies, and grass shrimps. Transient nekton species occur only during certain periods of the year. They spawn in the ocean or in rivers and rely on the estuary during at least some stage of their life cycle. Examples of common transients are spot, pinfish, striped mullet, white mullet, brown shrimp, white shrimp, Atlantic menhaden, silver perch, and the mojarras. Many more transient than resident species occur in North Inlet, but most transient species are represented by young of tropical species that appear in low numbers during summer. Some species are difficult to classify as residents or transients. For example, juvenile red drum, black drum, and southern flounder occur year-round for one to several years before leaving the estuary to spawn in other places. Some other fish species, such as sheepshead and bay anchovy, leave only for short periods during the coldest part of the year. General distributions and life history patterns are described for some of the most common fishes and macroinvertebrates below.

‘Fishes of North Inlet: an Identification Guide’ by Simpson et al. (2006) provides more detailed information about the identification, life cycles, spatial and temporal distributions, and behavior of about 100 of the most commonly encountered species in the estuary.

The mummichog, *Fundulus heteroclitus*, is probably the most conspicuous and familiar of the resident fishes. It occupies flooded intertidal salt marshes and flats and retreats to adjacent creek edges and pools around low tide. The mummichog lays eggs at the bases of *Spartina* plants during spring tides. This small predator of marsh invertebrates plays an important ecological step in the transfer of energy to larger fishes and birds. Because mummichogs are hardy and readily trapped, 'mud minnows' are favored baits used by flounder fisherman. Other resident salt marsh killifishes have similar distributions and life cycles.

The mummichog, *Fundulus heteroclitus*, is probably the most conspicuous and familiar of the resident fishes.

The grass shrimps, *Palaemonetes pugio* and *P. vulgaris*, are very abundant in flooded intertidal areas and adjacent shallows. Adults of these almost transparent and very active crustaceans are about one half inch in size and often form large groups in water less than a few inches deep. During the warmest six months, females release microscopic larvae from eggs that they carry. After about two weeks of development in the plankton, miniature shrimp settle into adult habitats. Grass shrimps consume small benthic animals, algae, and decomposing plant material and in turn serve as an important food source for many fishes and birds.

Atlantic silverside (*Menidia menidia*) is a common year-round resident that inhabits shorelines and shallow creeks where it often occurs in schools of similarly-sized individuals. Adults 2-3 inches in length demonstrate lunar periodicity in their spawning and small silversides of three species are common throughout the summer and fall. The rough silverside (*Membras martinica*) remains near the surface of major creeks, and the inland silverside (*Menidia beryllina*) is mostly found in shallow fringing habitats where salinities are somewhat lower. Atlantic silversides are most conspicuous from fall to spring when similar-sized anchovies and mullets are absent. Silversides consume zooplankton, but larger individuals also prey on epibenthic invertebrates and large larval fishes.

There are probably more anchovies (bay anchovy, *Anchoa mitchilli*, and striped anchovy, *Anchoa hepsetus*) in local estuaries during the warmest months than any other kind of fish. Schools are found in subtidal creeks, open waterways, and along shorelines, with many moving into intertidal creeks at high tide. Small mesh nets are necessary to demonstrate the presence of what are usually enormous numbers of juvenile anchovies. Larvae, juveniles, and adults all consume zooplankton, including the developmental stages of other fishes, shrimps, and crabs. Fast swimming predators such as bluefish, mackerels, seatrouts, and ladyfish often scatter anchovy schools at the surface and terns dive on them from above. The bay anchovy spawns near inlets, especially in early summer. The striped anchovy appears to be mostly a coastal ocean spawner, but juveniles are abundant in the estuary. Anchovies overwinter in the ocean, and they are one of the first fishes to repopulate the creeks once temperatures reach about 15^{o} C.

The commercial (penaeid) shrimps (the brown, white, and pink shrimps) are not residents of the estuary. Juvenile penaeid shrimps found in the creeks originate from larvae produced in the ocean. The smallest juvenile penaeids resemble grass shrimps, and they co-occur in the same marsh fringe habitat from late spring through fall. However, most juvenile penaeids are much larger than the largest grass shrimps. The brown shrimp, *Farfantepenaeus aztecus*, arrives in early spring and grows to sub-adult size (3-4 inches) before leaving the estuary in mid-summer. White shrimp, *Litopenaeus setiferus*, juveniles arrive starting in early summer and move to coastal waters as they reach pre-harvestable size in late summer and fall. White shrimp continue to recruit to the estuary throughout the warm months, and some juveniles overwinter in deeper portions of the system. Penaeid shrimps consume small benthos while foraging in the creeks and also during excursions across the flooded marsh. The pink shrimp (*Farfantepenaeus duorarum*) is much less abundant, but, together, these three penaeid shrimps play a major role in estuaries by exporting locally produced biomass to the ocean. Penaeid shrimps comprise the most valuable fishery in SC.

Spot, *Leiostomus xanthurus*, is by far the most abundant demersal (bottom dwelling/feeding) fish occupying the estuary from March through November. Adults produce larvae in deep coastal waters, and planktonic postlarvae settle into the creeks from December through March. Spot consume meiobenthos and increasingly larger macrobenthos through the summer. They leave for more thermally stable and warm waters when they are 3-4 inches long in the fall. Some second year juveniles return, and adults (2+ years) comprise a short-lived fall fishery in the deeper channels and beaches before migrating to offshore spawning areas. Juvenile spot are one of the most widely distributed and abundant of the small silvery fish, and schools in intertidal creeks and open waters can be very large. Silver perch (*Bairdiella chrysoura*) is a less common drum which varies greatly in abundance between years. Silver perch feed on shrimps and fishes, with juveniles occurring in intertidal creeks and larger individuals (up to about 8 inches) in subtidal channels. The Atlantic croaker (*Micropogonias undulatus*) is another small local member of the drum family. It is more abundant along the salinity gradient of Winyah Bay but juveniles are present in North Inlet creeks throughout the warm season.

Pinfish, *Lagodon rhomboides*, juveniles are common in the creeks of North Inlet. Like spot, they recruit as postlarvae from the ocean in the winter-spring and grow to a few inches in size before leaving in the fall. Second and third year pinfish also occur in the deeper channels, especially near oyster reefs and other structure during the warm seasons. Pinfish of all sizes consume small swimming and crawling epibenthic invertebrates but, unlike spot, do not generally gulp sediment to obtain food. They are perhaps the most aggressive of the common fishes and annoy recreational anglers by stealing bait from their fish hooks.

Spotfin mojarra, *Eucinostomus argenteus*, juveniles are regularly collected in creeks, shore zones, and channels from mid-summer through fall. Small juveniles of this common sub-tropical fish arrive from the coastal ocean and grow rapidly during their stay in the estuary. The bright silvery spotfin mojarra is readily distinguished from the spot, pinfish and silver perch by having a small mouth located on an extendible base, but these four small silvery fishes are often confused with one another. This unique mouth of the mojarras presumably facilitates feeding on small invertebrates near or in the bottom. Several other very closely related species include the silver jenny and Irish pompano, which also occur during the warmest months.

Striped mullet, *Mugil cephalus*, is especially conspicuous in the estuary during the warm seasons when schools of juveniles travel close to the surface, both in flooded intertidal areas and open waters. Several year classes of these cylindrical, fast-swimming fishes can be observed during the summer and fall, but only mid-age and older individuals occur through the winter. Adults spawn in the ocean in the fall, and half-inch young-of-the- year move into the creeks in winter. Juveniles grow to 4 or 5 inches before leaving with cooling temperatures in the fall. White mullet, *Mugil curema*, juveniles co-occupy the estuary during the summer, but adults do not occur inside the inlet. Both species consume living and decomposing plant material and small benthos. Small mullets are consumed by many fish predators, but, locally, adults also constitute important food sources for

Common fishes found in North Inlet (top to bottom): juvenile white mullet , flounder, and spot bottlenose dolphins and osprey. Another abundant but unrelated schooling fish in summer, is the flat-sided Atlantic menhaden (*Brevoortia tyrannus*). Like the striped mullet, ocean-spawned juveniles recruit to the creeks and grow before leaving in the fall. Menhaden feed by filtering plankton from the water column.

The blennies and gobies, especially the naked goby (*Gobiosoma bosc*), are small, abundant demersal fishes that are largely unnoticed by anybody but fishery scientists who recognize them as playing key roles in the ecology of tidal creeks. Blennies and gobies are year-round residents and cryptic occupants of bottoms with shell or other structure. Most live in permanently flooded channels, but some make excursions into the intertidal. They produce large eggs which adhere to bottom material, and an adult usually tends the nest until hatching occurs. Gobies are by far the most abundant larval fish in early summer, an indication that we greatly underestimate their abundance in the estuary. Juveniles and adults of about eight species of gobies and blennies occur incidentally in nets and other standard collection gear. They consume a variety of small motile invertebrates. Other cryptic residents with similar life cycles and habits include the oyster toadfish and skilletfish.

The southern flounder (*Paralichthys lethostigma*) is the largest of the ten or more local flatfish species. The closely related and generally smaller summer flounder (*Paralichthys dentatus*) has a similar life cycle. Adults of both species reproduce offshore in the late fall, and postlarvae recruit to estuaries in winter. Juveniles occupy creeks and flats and many appear to remain in or close to the estuary for their first two years of life. Reproductive age adults return to estuaries in the spring and spend their summers feeding in estuaries. The southern flounder prefers muddy areas in the creeks, whereas the summer flounder is more likely to be found near inlets and beaches. Both are ambush predators on other nekton. Other species of flounders are also transients, but adults are much smaller than flounders targeted by anglers. The bay whiff (*Citharichthys spilopterus*) and fringed flounder (*Etropus crossotus*) are especially common small flatfishes in North Inlet during summer.

Blue crab, *Callinectes sapidus*, is the most familiar of the large crabs. It is considered a resident species with all life stages occurring within the estuary except the intermediate larval stages. Female blue crabs typically mate with males in lower salinity areas and then move to inlets to release early stage planktonic larvae (zoeae) which are transported offshore by coastal currents. Development occurs on the continental shelf and planktonic megalopa larvae enter the estuary weeks later. Blue crabs from a fraction of an inch to the largest adults may be found in any intertidal or subtidal habitat during all but the coldest months during which they become inactive and less conspicuous. Juveniles are particularly abundant on flooded marshes in summer. All stages are voracious predators on slow-swimming fishes, benthic invertebrates, and carrion. After at least two years of age, the blue crab becomes an important commercial and recreational resource. Blue crab comprises the second most valuable fishery in SC.

Red drum (*Sciaenops ocellatus*), Atlantic croaker (*Micropogonias undulatus*) and the kingfishes (mostly *Menticirrhus saxatilis*) are bottom-feeding members of the drum family that, like the spot, are sought by recreational anglers in North Inlet. Spotted seatrout (*Cynoscion nebulosus*) and weakfish (*Cynoscion regalis*) are also drums but tend to feed on shrimps and fishes in the water column. Small juvenile stages of these members of the drum family are not frequently collected in nets. Red drum spawns around inlets and beaches in August- September. Very small juveniles settle into shallow salt marsh areas and most red drum

Red drum *Sciaenops ocellatus* are sought by recreational anglers in North Inlet.

spend their first 3 to 4 years living in the same system. They grow to about 12 inches at age one year, 22 inches at age two, 27 inches at age three, and 31 inches at age four. After about 4 years of age, most red drum leave the estuary and live in the coastal ocean. Females do not spawn until they are 33 inches long (about 5 years old), and they may live more than 40 years. Anglers should consult state regulations regarding size and catch limits and should also use careful catch-and-release techniques to preserve viable populations of these recreational fishing favorites.

Other large fishes that anglers target in North Inlet include the sheepshead (*Archosargus probatocephalus*) and black drum (*Pogonias cromis*). Both have vertical bands but very different mouths. The sheepshead has a prominent terminal mouth with conspicuous teeth for scraping and biting, whereas the black drum has a subterminal (under-slung) mouth with whiskers and no large teeth. Bluefish (*Pomatomus saltatrix*) is another favorite of local anglers. Juvenile (to 2 or 3 lbs) bluefishes are voracious, toothy, fast swimming predators that chase schools of small bait fishes in open waters, including inlets, sandbars, and beaches.

Tarpon, permit, Florida pompano, ladyfish, planehead filefish, striped burrfish, and lookdown are among the regular and sometimes abundant warm-water species that are represented by juveniles during the summer. Adults of most of these species spawn in warmer southern waters, and larvae or small juveniles sometimes find their way into the estuary from spring to fall. Several species of jacks, groupers, snappers, puffers, butterflyfishes, and others known from the tropics have been found in North Inlet creeks, especially in late summer and fall. More information on the less common species of bony fishes appears in **Appendix E**. Twelve species of sharks and eight species of rays and skates have been documented in North Inlet. Juvenile Atlantic sharpnose (*Rhizoprionodon terraenovae*) sharks are commonly encountered by anglers in the creeks especially from May to August. Most species of sharks including the large and sometimes free-jumping blacktip shark (*Carcharinus limbatus*) are found during the summer. The fairly small, reddish, long-tailed Atlantic stingray (*Dasyatis sabina*) is the most common of the rays known from North Inlet. The Southern stingray (*Dasyatis americana*), weighing up to 100 lbs or more, and the somewhat smaller but increasingly abundant bluntnose ray (*Dasyatis sayi*) are found in the estuary during summer and early fall.

SEASONAL PATTERNS

Dynamic and predictable are good words to describe the seasonal occurrences of nekton in North Inlet. The patterns documented in our long-term study at Oyster Landing Basin (OLB) are representative of the timing and movements of fishes, large shrimps and crabs throughout the estuary. Figure 83 shows the Oyster Landing Basin and the location of collections in the intertidal pool (OL) and at the enclosure on the intertidal marsh (OI).

The Oyster Landing nekton study documented interannual and interdecadal changes in nekton use of an intertidal creek basin.

Nekton abundance peaks from April to October, with much lower abundances occurring during the colder months. Patterns for three different nekton categories are shown in Figure 84. The "primary transient" category includes a group of nine common transient taxa represented by first year juveniles that recruited from ocean spawning areas. This group of fishes and shrimps accounted for the majority of individuals caught at OLB each year, averaging about 84% of the total catch from April through October. The "other" category includes dozens of much less common transients plus later life stages of those taxa identified in the transient category; they never accounted for more than a few percent of the total catch each year. The "resident" category includes species that occur year round. Residents accounted for 5 – 30% of the total catch each year; their average contribution to the total catch was 13%. Taxa comprising all three categories are identified in Table 9, and their relative abundances are discussed below. For the primary transients, abrupt increases in abundance in the spring were followed by irregular levels through the summer and rapid declines in the fall each year. Other transients exhibited similar patterns. For residents, seasonal patterns were less regular from year to year, but residents were often more abundant than transients and even dominated the catch during the coolest period.

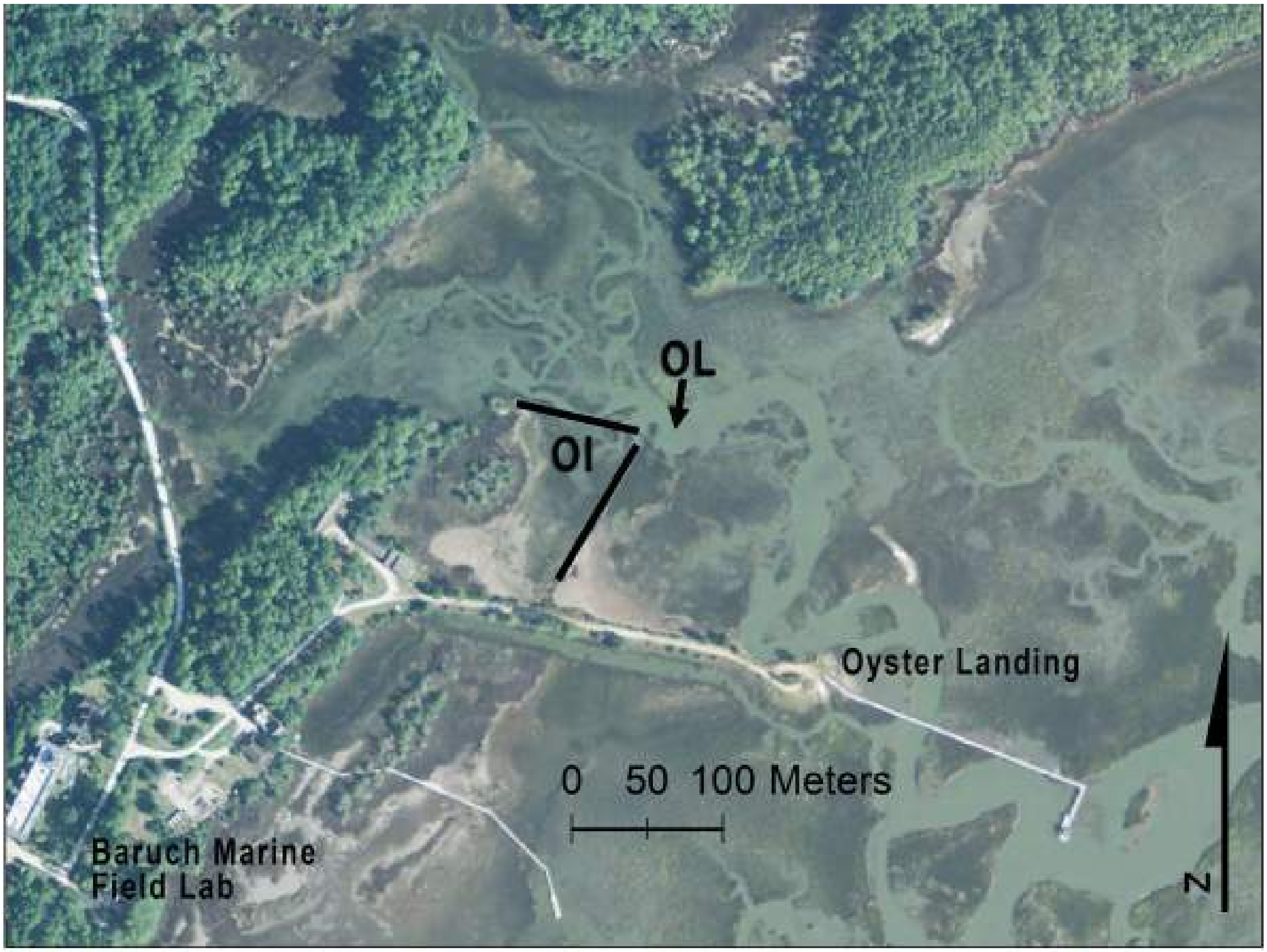


Figure 83. Map of Oyster Landing nekton study area, North Inlet, SC. Seine collections were made from an intertidal pool (OL) isolated within the creek bed at low tide every two weeks from Spring 1984 to Fall 2007. In 1995, collections were also made from the marsh at high tide by enclosing an area (OI) of about one acre with removable panels (black bars); nekton were collected in a block net as they retreated with the ebbing tide.

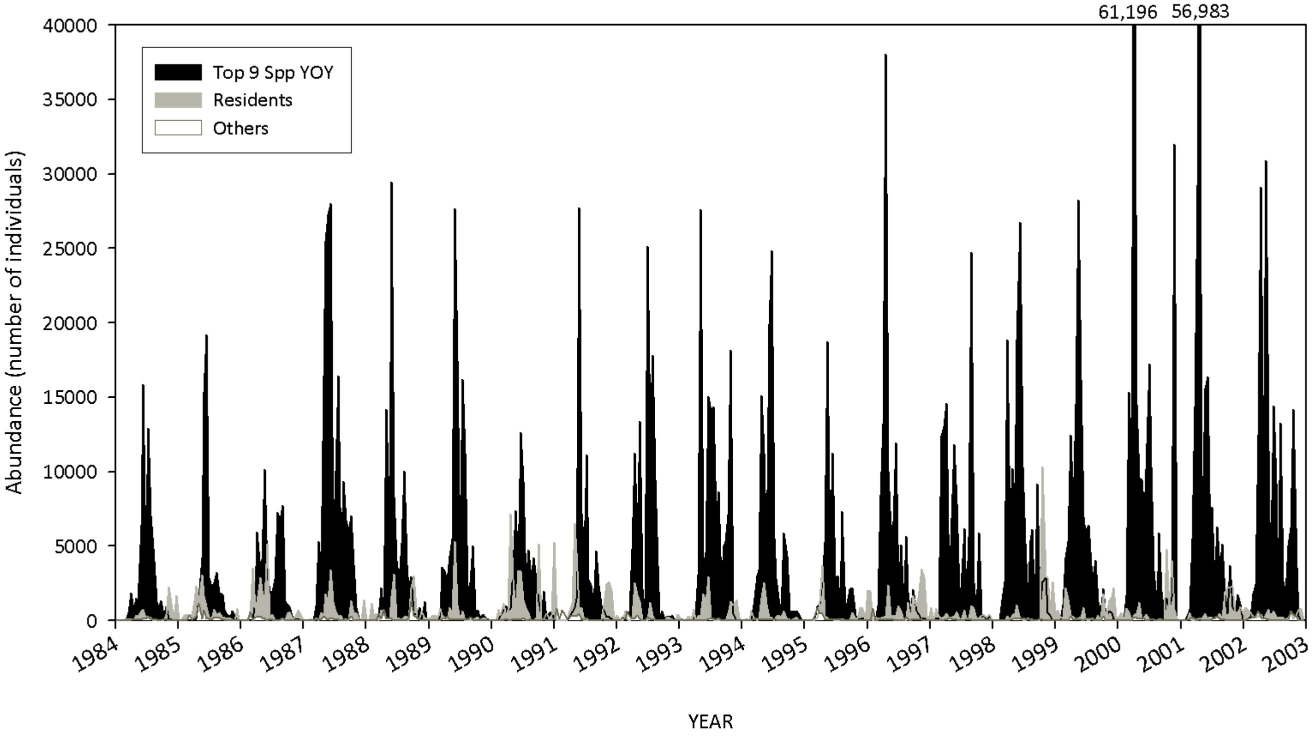


Figure 84. Biweekly abundance of nekton at the long-term monitoring site at Oyster Landing Basin, North Inlet, SC, from January 1984 – December 2003. Catches were made with a single seine haul at low tide in an isolated pool within the intertidal creek bed. Three nekton categories are shown. 'Transients' represent young-of-the-year of the 9 taxa that consistently dominated the catch. 'Residents' represent the assemblage of small fishes that occurred year round. 'Others' is composed of all other transients plus later life stages of the taxa clumped in the Transient category. The taxonomic composition of each group is given in Table 9.

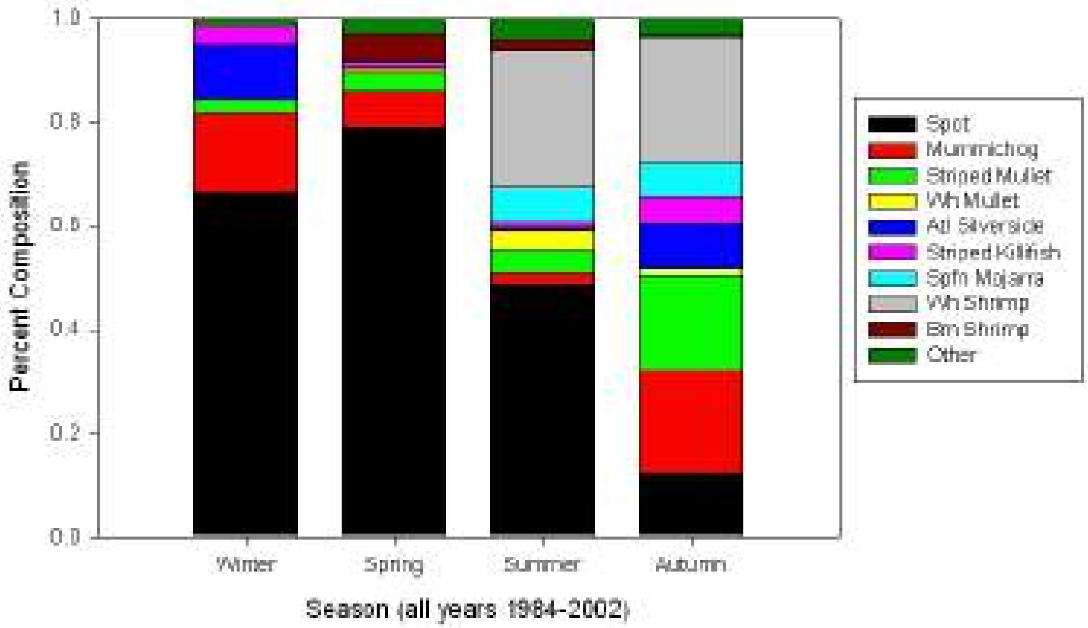


Figure 85. Proportions of the total catch that each of the most abundant taxa comprise during each season. The values are averages based on biweekly collections made from 1984- 2002 at the Oyster Landing Basin (OL).

Table 9. Species composition of the three nekton categories comprising the biweekly seine catch at Oyster Landing Basin from 1984 – 2003. Within each list, the taxa (common names) are ranked from most to least abundant according to total catches over the 20 year period. See **Appendix E** for other species. Note that grass shrimps were not included in these analyses.

Primary transients	Other transients	Residents
spot	treadfin shad	mummichog
white shrimp	ladyfish	striped killifish
striped mullet	crevalle jack	Atlantic silverside
brown shrimp	pink shrimp	sheepshead minnow
mojarras	bay anchovy	inland silverside
white mullet	gizzard shad	blue crab
Atlantic menhaden	Irish pomano	blackcheek tonguefish
pinfish	Atlantic croaker	red drum
silver perch	southern flounder	mosquitofish
	other jacks, flounders, seatrouts	black drum
	1+ age mullets, spot, pinfish	American eel
		all gobies and blennies

Very large increases in the abundance and diversity of nekton from winter to summer can be attributed to the immigration of fishes and shrimps from the ocean. As indicated in Figure 85, one species, spot, is by far the most abundant of the transients that arrive in the salt marsh as advanced larval stages every winter. Young-of-the-year pinfish, southern and summer flounder, Atlantic menhaden, striped mullet, and brown shrimp also arrive during the coldest months. In the late spring and early summer, white mullet, white shrimp, and mojarras recruit to the shallows of North Inlet. The arrival of anchovies and other year classes of spot, mullets, flounders, rays and sharks add to the diversity and abundance of transients during the summer. Water temperature and day length are thought to control the timing of seasonal migrations of many taxa. Peak migrations into and out of the estuary can be influenced by changes in weather patterns, especially in fall when the first cold fronts trigger large migrations to the more thermally stable and warmer coastal ocean areas.

HABITATS AND DISTRIBUTIONS

Even though it is possible to encounter any species of fish in any habitat or location within the estuary, the composition of nekton in specific habitats is fairly predictable. Information from the literature and from supplemental collections with seines, trawls, gill, nets, and hook and line fishing has provided a general understanding of the occurrences of common species in the primary aquatic habitats in the North Inlet area.

- **Surf zone on the beachfronts:** Striped killifish and Atlantic silversides occur year- round. Striped mullet, white mullet, and Atlantic menhaden account for major increases in fish abundance during the summer. Southern kingfish, northern kingfish, red drum, Florida pompano, pinfish, spot, bluefish, southern stingrays, and Atlantic sharpnose sharks, blacktip sharks, blacknose sharks, bonnetheads, and, more rarely, tarpon, Spanish mackerel, and king mackerel are caught by anglers in the surf.

- **Shore zone along major creeks and sounds near the inlet:** In addition to the striped killifish and Atlantic silverside, pipefish, searobins, flounders, and puffers can be found through most of the year. With warming temperatures, anchovies, mullets, and Atlantic menhaden become abundant. Juvenile spot, pinfish, mojarras, jacks (especially crevalle), planehead filefish, stargazers, inshore lizardfish, tonguefish, penaeid shimps, and a variety of crabs also add to the biomass and diversity during summer. Except for southern and bluntnose stingrays, most of the large fishes that frequent the beachfront surf do not commonly occur along lower wave energy shorelines. The composition of nekton in shore zones changes from the barrier islands to the forest edge with an increasing presence of mummichogs, grass shrimps, blue crabs, and penaeid shrimps.
- **Channel bottoms:** Larger fishes tend to occur in deeper water, so the largest spot, pinfish, Atlantic croaker, black drum, flounders, and sharks may be found in subtidal creeks. Some fishes occur almost exclusively in association with structure (e.g., shell accumulations, pilings) in permanently flooded waters. These include oyster toadfish, black seabass, snappers, groupers, Atlantic spadefish, sheepshead, and American eels. Numerous species of gobies and blennies and the skilletfish are found more in shallow subtidal than in intertidal habitats, though they occur in flooded oyster reefs. Other large fish that are caught by anglers in deeper waterways include spotted seatrout, bluefish, weakfish, Atlantic cutlassfish, and hardhead catfish. During winter and spring, the spotted hake, southern hake, clearnose skate, smooth dogfish, ocellated flounder, and windowpane can be found in deeper channels. Even accounting for differences in the sampling techniques, major differences exist between the nekton occupying subtidal channels and shore zones/intertidal creeks.
- **Open waters of large creeks and sounds:** Anchovies (bay anchovy and striped anchovy), silversides (Atlantic silverside, rough silverside), mullets (striped mullet, white mullet), squids, and Atlantic menhaden are especially common in the water column during the warm months. Other herrings (and shads), Atlantic needlefish, bluefish, ladyfish, sharks, halfbeaks and mackerels also occur here during warm periods. Atlantic silversides are by far the most commonly encountered open water fishes during winter. In studies comparing nekton catches near the bottom to those near the surface, patterns of separation in depth and diet were apparent for the various zooplanktivorous fishes (anchovies and silversides) (Johnson et al. 1990; Allen et al. 1995).
- **Intertidal creeks and mudflats:** More than 60 species of nekton regularly migrate through flooded intertidal creeks. Many, but not all, of the fishes and shrimps that move into flooding intertidal creeks and edges of channels also move onto the flooded marsh surface. Mummichog, striped killifish, sheepshead minnows, and grass shrimps move up and down the long axes of intertidal creeks with the tide, but most seek refuge in pools during low tide. Striped mullet, white mullet, spot, pinfish, mojarras, Atlantic silverside, brown shrimp, white shrimp, blue crab and anchovies move in with the flooding tide and back to adjacent subtidal areas with the ebb; however, some individuals remain in intertidal pools (Bretsch and Allen, 2006). Large southern flounders, stingrays, and red drum use well-flooded, large intertidal creeks. Although there is a general relationship with larger fish occurring at deeper depths, some large fishes including striped mullet and red drum routinely move into water only slightly deeper than their body height. Almost all of the species found in intertidal creeks also occur on flooded flats, with higher abundances and diversity occurring on muddy than on sandy flats.
- **Flooded marsh:** Mummichogs and grass shrimps account for most of the small nekton that occur in the flooded grass year round, but

other residents include the striped killifish, sheepshead minnow, silversides, and blue crabs. Large striped mullet and red drum also occur all year. Juvenile striped mullet and white mullet rove in large schools from spring to fall. Spot, penaeid shrimps, and ladyfish forage on the marsh surface during the warm period. Less commonly encountered on the marsh are the sailfin molly, mosquitofish, spotfin killifish, sleepers, lyre goby, and rainwater killifish which appear to favor low salinity areas near the forest edge.

TIDAL MOVEMENTS OF NEKTON

The use of several sampling strategies has provided insights into movements of common fishes, shrimps, and crabs during different stages of the tide. In general, ebbing tides force animals off the intertidal marsh, flats, and creeks into the deeper channels. During summer low tides, shallow subtidal channels often appear to be boiling with fishes and shrimps as schools of small, active nekton become concentrated there. Many of these tidal migrants remain close to the water's edge, perhaps maximizing their avoidance of predators and placing them in the best position to occupy intertidal areas as they become covered with the rising or advancing flood tide.

From 1995 – 2002, collections were made from the flooded marsh surface at high tide (OI) on the same date that collections were made from the adjacent pool at low tide (OL) (Figure 83). Posts were set around a section of marsh (approximately one acre) located adjacent to the pool. On dates scheduled for sampling the flooded marsh, the area was enclosed by setting fiberglass panels between the posts at high tide. A ¼ inch mesh stop net was set at the lower end to collect animals retreating with the ebbing tide. At low tide, the stop net was emptied and then a nearby pool was seined with a ¼ inch mesh net before the tide started to re-flood the area.

Comparison of the two catches (high tide flooded marsh surface vs low tide pool) showed that the same species used the marsh at high tide and remained in the pool at low tide. The same resident and transient ranked highest in both the high and low tide collections. Mummichog was clearly the most abundant resident taxon in both the high and low tide catches, and spot was by far the most common transient in both areas. But there were important differences in relative abundances of some common taxa as well as in the occurrence of some less common taxa. Young-of-the-year transients accounted for the largest proportion of the catches in both the pool and flooded marsh, but residents tended to be more abundant on the marsh than in the pool.

Community members assist with sorting the catch from the Oyster Landing survey.

Mummichogs, spot, and striped mullet caught retreating from the marsh were significantly smaller that those seined from the low tide pool. White shrimp, brown shrimp, white mullet, and blue crab were larger on the marsh. Differences in the collection efficiencies of the stop net and seine could account for some of these size differences, but these results in large part reflected ontogenetic differences in patterns of tidal movement within and among life stages of the species. For instance, large white shrimp move onto the flooded marsh and then leave the intertidal creek basin rather than remaining in the pool at low tide. Higher species richness in the high tide collections also indicates that many species leave the basin with the ebbing tide.

Because small adult grass shrimps are not retained by ¼ inch mesh nets, they were not quantified in the OLB study. Field observations have revealed

Nekton caught in the Oyster Landing surveys were measured using an electronic system.

that grass shrimps are among the first to move into the intertidal and last to leave it. This "first in – last out" pattern was demonstrated in a supplemental study that employed an array of lift nets located across an elevation gradient extending from the edge of a shallow subtidal creek to the high marsh. Predictable and sequential movements of different species and life stages of nekton into intertidal creeks were also demonstrated in a study by Bretsch and Allen (2006) using sweep flumes. Together these studies have revealed patterns of habitat use by nekton that probably reflect behavioral adaptations that minimize competition for space and food while maximizing use of the available resources.

FACTORS INFLUENCING THE DISTRIBUTION OF NEKTON

One of the most difficult challenges for scientists interested in the distributions and biology of nekton is identifying factors that influence changes in these parameters. The description above of nekton distributions among habitats indicates that physical structure is important, with some species preferring shallow over deep areas, or the sandy surf over muddy creeks. Within subtidal channels, gobies and blennies are abundant in areas with accumulations of shell and almost absent in flat sandy areas nearby. In one study comparing the use of eight intertidal creeks by nekton, large differences were related to the geomorphology of the creeks with more nekton using shallow, gently sloped creeks with slow rates of flooding and ebbing. This preferential use of creeks with certain characteristics continued season after season (Allen et al., 2007).

Seasonal patterns of nekton occurrence in the estuary, and even in certain habitats, are generally related to varying physical conditions in the water. Measurements of environmental conditions made at the time nekton are sampled are useful in establishing such relationships, especially when made over weeks, months, and years. Water temperature is clearly a primary factor in the timing of migrations, metabolism, growth, reproduction, and other aspects of the biology and behavior of both fishes and motile macroinvertebrates. Total abundance and total number of species (often referred to as species richness or diversity) were highest during the warm months. Other physical (e.g., dissolved oxygen concentration, water clarity) and biological (e.g., availability of food, predators) factors which are closely related to water temperature cannot be easily separated and thus confound our understanding of which factors most strongly influence nekton behavior.

Salinity is another important controlling factor for estuarine nekton, but it too was significantly related to water temperature in the Oyster Landing Basin. Increased rainfall during the spring and summer reduces characteristically high salinities in North Inlet creeks, especially near the edge of the forest. There were no significant relationships between the abundances of common nekton species in OLB and salinity, but major and extended depressions in salinity at OLB resulted in temporary reductions. During wet winters, brackish water from Winyah Bay can move into North Inlet via Town and South Jones Creeks. Some fishes typical of low salinity including Atlantic sturgeon, American shad and longnose gar have been captured in the system, but these are uncommon and occur over short periods of time. Major tropical disturbances have temporarily affected fish distributions in OLB. The retreat of the surge of Hurricane Hugo (September 1989) scoured accumulated organic materials off the marsh and out of the creek beds near the forest. Displaced fish returned after several weeks that fall, but the altered habitat might have been responsible for the low level of transient production observed in 1990. The introduction of some unusual tropical fishes, invertebrates, and sargassum weed occurs after periods of sustained winds from the east.

Biotic factors also play important roles in the distribution and biology of nekton. Studies have shown that fish move into intertidal areas to consume prey and that some species and life stages have fairly specific diets. For instance, adult red drum forage for fiddler crabs on the marsh surface, the only habitat in which this crab occurs. The availability and quality of food resources influences the behavior and movement of nekton and can affect growth rates and other physiological functions. Competition among individuals of the same and different species affects their distributions and growth, while predation affects survival. Fish are responsive both to changing biotic and physical conditions.

LONG-TERM TRENDS

The large week-to-week variations in total nekton abundance shown in Figure 84 are typical as different age groups of different species occupy the basin on different tides, months, and seasons. On any given tide during spring, a large school of young-of-the-year spot might remain in the pool, only to spend the next tide somewhere else. Accordingly, we tend to use seasonal averages in interpreting trends over years and decades. In Figure 86, seasonal means for the entire OL (low tide seine) and OI (high tide block net) time series are shown. Long-term trend analyses have shown that there was a significant increase in nekton abundance in the OL Basin from 1984 to 2002. This could have been influenced by the generally lower salinity during the 1990s when a series of El Niño events created increased rainfall and runoff into the OL Basin and area in general. From 1995 to 2010, the trend indicated a significant decrease in total nekton with only about half as many fishes and shrimps occurring in recent years compared to the mid-1990s. A series of extended droughts and high salinity started in about 2001. No doubt, other factors influenced the trends and additional analyses are being conducted to better

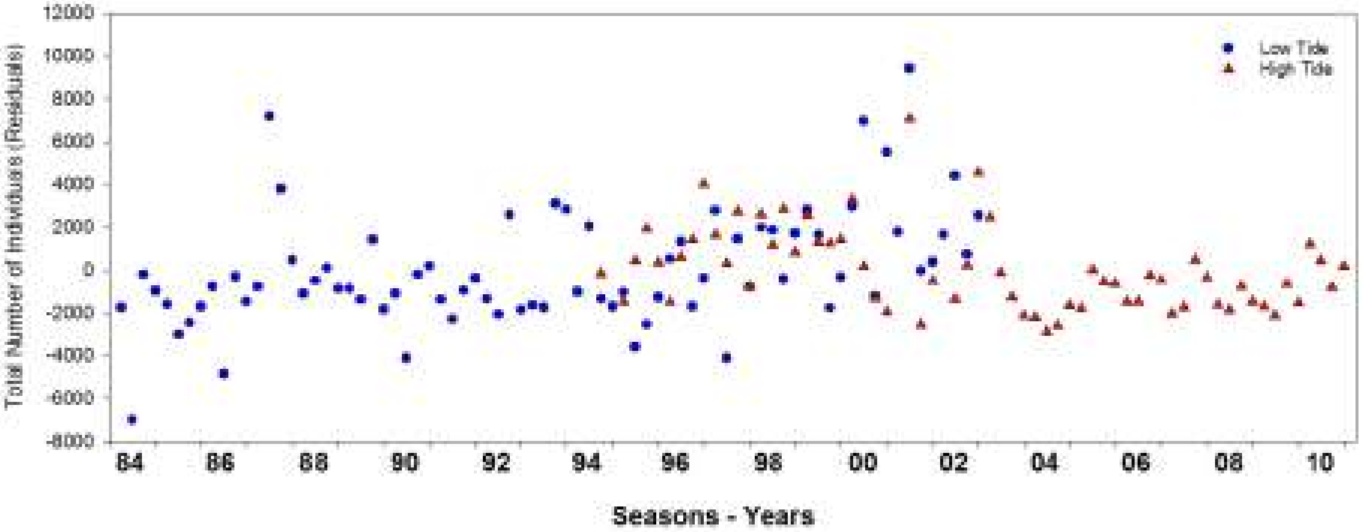


Figure 86. Total numbers of nekton caught in the low tide pool (circles, seine, 1984-2002) and on high tide flooded marsh (triangles, enclosure-blocknet, 1994-2010). These are seasonal values shown as residuals or deviations from the long-term means for each season in each of the time series. The two series overlapped from 1995-2007 with the high and low tide samples being collected on the same day.

understand the effects of long-term changes in environmental conditions on the composition, abundance and growth rates of nekton in the nursery habitats of the estuary.

During the 7 year period when collections were made from both the flooded marsh and low tide pool (total of 64 paired collection dates), there was a strong correlation between the catches. For the total catch, the numbers of nekton using the basin when flooded was a good predictor of how many would be in the pool at low tide. This demonstrated relationship enabled us to compare the trends for the independent time series over the decades.

FISHERIES

South Carolina's largest inshore fisheries, the penaeid shrimps and blue crab, are absolutely dependent on estuaries. White, brown, and pink shrimps require marshes to complete their life cycles, and there are relationships between the amount of habitat (and perhaps the quality of that habitat) and the amount of adult shrimps that are available to the ocean-based fishery. Blue crabs are harvested with baited traps within the estuaries, and this is the only commercial fishery that is allowed in the North Inlet system. This small traditional trap fishery occurs mostly during the winter season.

The vast majority of fishes known from North Inlet are not recognized as commercially or recreationally important species. In fact, since red drum and spotted seatrout were designated gamefish in the 1980s and because gill nets were banned from inshore waters, estuarine finfish species are not allowed to be harvested for commercial markets. However, incidental catches of flounders, whitings, spot, Atlantic croakers and a few other species in shrimp fishery trawls in the ocean are sold in small quantities. The recreational harvest of red drum, southern/summer flounder, seatrouts, sheepshead, bluefish, sharks, and some additional species comprises a valuable economic asset to the coastal counties. The other more than 100 species of small fishes that occur in SC estuaries are not of any direct economic value but they play critical roles in the ecology of these productive systems, often serving as food sources of larger and more familiar local fishes.

A nekton sampling crew heading out to the Oyster Landing site.

» Reptiles, Amphibians, and Mammals

Herpetofauna (reptiles and amphibians) occur in a wide-variety of habitats across the North Inlet–Winyah Bay area. Their distribution and abundance are determined by water regime, salinity, and vegetative community (Sandifer et al., 1980) which vary greatly from the upland pine-forest to the marshes and tidal creeks. Reptiles and amphibians are not abundant in saltwater environments and adjacent areas. Their distribution is patchy in space and time. Compared to other animal assemblages in the North Inlet area, research on the herpetofauna has been sparse; however, observations made over the long-term and a few limited, directed surveys, especially in the uplands, have revealed the presence of over 65 species and detailed information on some of the more widely-distributed species.

Among the most abundant and conspicuous reptiles within the NERR boundaries are turtles found in the marine environment, on barrier islands, in tidal creeks, and at the marsh–upland interface. A different group of reptiles and amphibians occurs in the adjacent watershed including non-tidal, forested wetlands.

Turtles are the most widely-distributed and well-studied of the herpetofauna in the NI-WB NERR. Of these, loggerhead (*Caretta caretta*) and green sea turtles (*Chelonia mydas*) occur in the coastal marine habitat and are considered mostly transient. The loggerhead, the most abundant of the sea turtle species in South Carolina, is often observed in tidal creeks and open waters in North Inlet. It is listed as Threatened under the U.S. Endangered Species Act. Small green turtles, usually with a carapace width around 30 cm, have been fairly commonly observed in shallow tidal creeks. The leatherback sea turtle (*Dermochelys coriacea*) has not been recorded within North Inlet, but adults are frequently reported from the ocean during their northern migration up the coast.

Loggerhead and green turtles are typically not residents of local waters during the coldest months. Both species live exclusively in the water except when they come on shore to lay eggs. Loggerheads and rarely green sea turtles nest on area beaches from mid-May through August, with individual females returning to nest 3-7 times over the course of a season. Loggerhead sea turtles are primarily carnivorous and feed mostly on shellfish that live on the ocean floor and in the tidal creeks of the estuary.

Populations of loggerhead sea turtles have declined over the past decades. Loss of nesting habitat, incidental capture in recreational and commercial fisheries, and predation pressure from nest raiders including raccoons, foxes, coyotes, and feral hogs are some of the threats to sea turtles. The South Carolina Department of Natural Resources (SCDNR) oversees a very successful network of sea turtle volunteers who monitor and protect nests on several of the state's beaches during the nesting season. Members of a local volunteer organization (South Carolina United Turtle Enthusiasts) are part of this network and have been monitoring sea turtle nesting on Debidue Island for more than 20 years. The southern two mile (3.2 km) undeveloped stretch of Debidue Island (Hobcaw Beach) is within the NI-WB NERR boundary and provides important nesting habitat for the loggerhead sea turtle. Additional information about the status of sea turtles in South Carolina can be found on the SCDNR website: www.dnr.sc.gov/seaturtle/.

The loggerhead, the most abundant of the sea turtle species in South Carolina, is often observed in tidal creeks and open waters in North Inlet. It is listed as Threatened under the U.S. Endangered Species Act.

The diamondback terrapin (*Malaclemys terrapin*) is a small, long-lived estuarine turtle that is relatively common in salt marsh creeks. This is the only turtle species in North America endemic to brackish coastal marshes and it is an important component of the salt marsh ecosystem where it feeds on mollusks and crustaceans. The diamondback is considered a commercial species in South Carolina. The South Carolina Department of Natural Resources has the authority to issue collection permits, but has not done so recently given the unknown population status of this species across the state and elsewhere (Gibbons et al., 2001).

Genetic studies on diamondbacks have revealed that populations in South Carolina are not distinct from each other or from those in North Carolina. Intentional transplants of terrapin for the commercial industry have disrupted the natural population's genetic structure, and some populations in South Carolina are genetically more like those found in Texas (Hauswaldt and Glenn, 2005).

Diamondback terrapins are present in the intertidal creeks of North Inlet throughout the year.

Terrapins are present in the intertidal creeks throughout the year, but are most often observed during the summer months between May and August when nesting in the dry soft sand/soil above mean high tide levels. During the winter months, they dig into the soft bottoms and banks of intertidal creeks where they remain relatively dormant until spring. The habitat needs of juvenile terrapins are poorly understood. Investigators from Francis Marion University and Coastal Carolina University have been radio-tagging adult terrapins to determine site fidelity, home ranges, and nesting sites in the North Inlet system.

Major terrestrial threats to terrapins include loss of nesting habitat from coastal development and predation by raccoons and fire ants. In the marine environment, threats include abandoned crab pots. Other threats include boat and propeller mortality and habitat and water quality degradation. High site fidelity of this species indicates that once a population is extirpated, it is unlikely to return naturally.

Several other turtles have been observed in the watershed surrounding North Inlet, especially the eastern mud turtle (*Kinosternon subrubrum*) and the eastern box turtle (*Terrapene carolina*). Also found in the swamps adjacent to North Inlet salt marshes are snapping turtles (*Chelydra serpentina*), yellowbelly slider (*Chrysemys scripta*), and spotted turtle (*Clemmys guttata*).

American alligators (*Alligator mississippiensis*) are relatively common in the North Inlet area. They are generally limited to freshwater areas but can be seen in estuarine waters especially close to the edge of the forest after major periods of rainfall. These tend to be small and medium sized individuals and they rarely stay in salty waters for very long. Occasionally, alligators are seen in the surf on the barrier islands.

American alligators, such as this small one in a drainage ditch near the BMFL, visit the estuarine waters in North Inlet, but must return to fresh water.

Twenty-two species of snakes can be found in the Hobcaw Barony uplands, but none frequents the salt marsh or tidal creeks. Occasionally, canebrake rattlesnakes (*Crotalis horridus*) and cottonmouths (*Agkistrodon piscivorous*) have been observed on the upper reaches of the salt marsh, but most local snakes have specific upland habitat requirements. Among the more commonly seen snakes in the pine forests are the corn snake (*Elaphe guttata*), rat snake (*Elaphe obsoleta*), and king snakes (*Lampropeltis* spp.). The black racer (*Coluber constrictor*) is likely to reside in open areas and wetland margins. Water snakes (e.g., *Nerodia* spp.) are found in freshwater marshes and ponds. Venomous snakes such as the copperhead (*Agkistrodon contortrix*) are more likely seen in drier habitats, whereas the pygmy rattlesnake (*Sistrurus milliarius*) is likely to be found from upland forest to wetland and swamp habitat. The Eastern coral snake (*Micrurus fulvius*) is seen only rarely. This elusive species, found in the pine forest and on sandy soil, is a SC State Species of Concern.

Frogs and toads comprise the majority of the amphibian species. These are all freshwater dwelling animals, and none occurs in the salt marsh or tidal creeks of North Inlet. Thirteen species are distributed across habitats ranging from relatively dry regions with brushy undergrowth, including the Eastern spadefoot (*Scaphiopus holbrooki*) and oak (*Bufo quercicus*) toads. Freshwater wetlands are preferred by the tree frogs including spring peeper (*Pseudacris crucifer*) and the southern cricket frog (*Acris gryllus*). Among the several species of frogs of the genus *Rana* in local wetlands, only the southern leopard frog (*Rana spenocephala*) is sometimes observed in low-salinity tidal marshes.

Sirens, skinks, newts, lizards, salamanders and freshwater turtles constitute the remainder of the amphibians and reptiles. These too occupy a variety of freshwater habitats, well away from the edge of the salt marsh (Martof et al. 1980). A list of amphibians and reptiles for Hobcaw Barony and adjacent estuaries is provided in **Appendix F**.

Reptiles and amphibians occur in a wide-variety of habitats across the North Inlet–Winyah Bay area. Occasionally, canebrake rattlesnakes (top left) and cornsnakes (top right) are observed on the upper reaches of the salt marsh. Green anoles (bottom left) are commonly seen, but glass lizards (bottom right) are more secretive.

In the NI-WB NERR, mammals include both aquatic and terrestrial species and are distributed across a variety of habitats including salt marsh, cypress-tupelo wetlands, pine-hardwood forest, and mixed and longleaf pine forest (**Appendix G**). Small terrestrial mammals dominate the local species distribution. Most are in the Family Muridae which includes the marsh rice rat (*Oryzomys palustris*), eastern harvest mouse (*Reithrodontomys humulis*), cotton mouse (*Peromyscus gossypinus*), and southern red-backed vole (*Clethrionomys gapperi*). Cotton mice and voles are typically woodland dwellers and occur along water courses where stumps, down logs, and tangles of brush and vines offer suitable retreats; they also occur frequently in woodland areas bordering open fields. Marsh rice rats typically inhabit marshy, including upper salt marsh, areas,but they may be found in almost any place where grasses and sedges offer an adequate food supply and protective cover (Webster et al., 1985).

The marsh rabbit (*Sylvilagus palustris*) is present in the forest, fields, and lawns around the North Inlet salt marsh. Although known to be an excellent swimmer, it has not been observed in the intertidal marsh or tidal creeks.

Three species of squirrel can be found here and include the gray (*Sciurus carolinensis*), southern fox (*Sciurus niger*), and the southern flying squirrel (*Glaucomys volans*). All eat nuts, acorns and insects. These species overlap in their distribution but have some differences in preferred habitat. The gray squirrel prefers hardwood forests and forested wetlands, whereas fox squirrels are more abundant in mature oak-hickory forests. The southern flying squirrel is the only carnivorous member of the squirrel family. It is also almost completely arboreal. Its omnivorous diet includes acorns, nuts, berries, fruits, seeds, buds, blossoms, insects, birds, nestlings, eggs and, occasionally, carrion.

The only bat species commonly observed in the area is the little brown bat (*Myotis lucifugus*). This species is one of the most common bats in the U.S. and Canada. It feeds primarily on aquatic insects and can be found foraging along forest edges, streams and small cultivated areas. Bats can be found during the day in hollow trees or under the bark of dead trees. Standing dead trees may also be used as maternity colonies.


The southern fox squirrel occurs in the upland forests adjacent to North Inlet.

Larger semi-aquatic species include river otter (*Lontra canidensis*), beaver (*Castor canidensis*), and mink (*Mustela vison*). River otters are occasionally observed in salt marsh creeks as well as in freshwater streams around the border of North Inlet. They occur throughout the year and are usually seen in small groups. Historical statewide data are limited for mink, but they are known to be susceptible to threats including harvest, loss of habitat, and contaminants (Baker, 1999). Minks were extirpated by hunters in the 1800s and re-introduced by the SC Dept. of Natural Resources in recent decades. Individuals are occasionally seen in salt marsh creeks in North Inlet.

The beaver is a freshwater species that occurs throughout the watershed adjacent to North Inlet, but it occasionally wanders to the edge of salt marsh creeks. Because of its habit of damming drainage ditches and culverts, the beaver is often considered a nuisance to forest managers.


Mink were re-introduced to the area in recent decades after being extirpated by hunters in the 1800s.

Historically, there have been sightings of black bear in the Hobcaw Barony forest and at least a few reports have been made over the past several decades; however, no fully documented occurrences are available. Their occasional occurrence should not be a surprise because they are well established in the local river basins and individuals show up in neighborhoods in Georgetown and the Waccamaw Neck.

Some uplands mammals including white-tailed deer and feral hog are actively managed. Although Bernard Baruch and guests actively hunted the property for deer in the early 1900s, harvest restrictions limited hunting in the 1960s. Unrestricted growth in the deer population has affected deer health. An outbreak of Hemorrhagic Disease occurred around 1980, resulting in a major die-off.

Feral hogs may have been on the Hobcaw Barony since the arrival of the European settlers. Clemson University wildlife researchers conducted many studies from 1970-1990. Trapping initiated in the 1970s resulted in the capture of about 1000 hogs, leaving an estimated 300 to 400 animals. A total of 1,672 hogs were harvested in 2000, and several hundred were harvested additionally as a part of a USDA Brucellosis study. Feral hogs cause extensive damage when rooting, an activity that alters sensitive sand dunes and wetland habitats. Hogs may also impede longleaf pine regeneration and provide an opening in habitat for invasive plant species such as *Phragmites*.

Many years without harvesting of deer and feral hogs on the property led the Baruch Foundation to suggest that populations of both white-tailed deer and feral hogs are over-abundant. To this end, the Hobcaw Barony Wildlife Management Plan (Bruce 2003) was developed. The purpose of this plan was to estimate population size of white-tailed deer and feral hogs along with eastern wild turkey (*Meleagris gallopavo silvestris*) and bobwhite quail (*Colinus virginianus*), and to subsequently develop appropriate management recommendations. Estimates of 95 deer per square mile and a total of 600-1500 feral hogs were determined. Management recommendations for these species included a 50 percent reduction in deer and an intensive trapping/shooting schedule for feral hogs in an attempt to eliminate as much of the population as possible.

Little predator control has been practiced on the property. Raccoons (*Procyon lotor*) are considered in high abundance on the property. Sightings of opossums (*Didelphis virginiana*) are numerous. Bobcats (*Lynx rufus*), gray fox (*Urocyon cinereoargenteus*), red fox (*Vulpes vulpes*), and coyotes (*Canis latrans*) occur but little is known about their ecology and behavior.

The only completely aquatic mammal in the North Inlet estuary is the bottlenose dolphin (*Tursiops truncatus*). They feed on fish, including mullet, sea trout, red drum, and flounder. Bottlenose dolphins are both a coastal and an oceanic species, with the coastal ecotype preferring waters less than 30

White-tailed deer (left) and feral hogs (right) are actively managed under the Hobcaw Barony Wildlife Management Plan.

meters (~98 feet) in depth. The habitats they occupy range from rocky reefs to calm lagoons and open waters. The coastal ecotype is adapted for shallow waters. Its smaller body and larger flippers suggest increased maneuverability and heat dissipation. These dolphins occur along the outer coastline and in bays, sounds, inlets, estuaries and other inland waters (Hersh and Duffield, 1990).

Although the bottlenose dolphin is the most common marine mammal along the southeastern coast, certain coastal stocks appear to be depleted based on the most recent stock assessments (Waring et al., 2002; MMC 2004). Threats to this species include natural predation, disease, parasites and natural biotoxins and human-caused factors such as incompatible coastal development practices, pollutants, vessel strikes, and debris entanglement.

A dozen or so dolphins are residents of North Inlet. Local surveys by Coastal Carolina University researchers have recognized some of the same individuals for more than 15 years, with at least one female, "Eve", producing young in the estuary multiple times. Calculations have shown that these resident dolphins consume a significant proportion of the large fish population in North Inlet (Young and Phillips, 2002). Ongoing studies of this species will provide more detailed information on their bioenergetics, social structure and behavior.

SPECIAL STATUS SPECIES

The eastern woodrat or "packrat" is a SC State Species of Concern. It can be found in wooded areas with dense understories and its dens are often occupied by a succession of individuals, each one adding more sticks and other material to the collection. Dens average 61-91 cm (24-36 inches) in height and offer protection from many predators. Woodrats store edible and non-edible material in their dens, and it is not known why the inedible materials are kept. Threats to this species likely include loss of habitat. However, only limited information is available on their status and additional potential threats.


A dozen or so dolphins are residents of North Inlet each year, including this female, Eve, and her calf.


Bobcats are documented in the uplands and marshes surrounding North Inlet, but no conclusive evidence of a jaguarundi or mountain lion has been found.

The Gulf Coast jaguarundi (*Puma yagouaroundi cacomitli*) is currently designated as endangered in its entire range. It is a native of Mexico and Texas. The presence of this ever-elusive species continues to be the catalyst for many animated debates throughout the Southeast. Many reports of a medium-sized, long-tailed cat that resembles this species have been made on Hobcaw Barony over the years , especially along roads close to the salt marsh, but except for footprints photographed at the locations of observations, the presence of this cat has yet to be fully documented. The jaguarundi is also found in Florida, although these are descendants of a small population introduced to that area in the 1940s.

Despite reports of the occurrence of the large, long-tailed Eastern mountain lion (also known as cougar or panther) throughout coastal South Carolina, its presence remains debated and denied by the SC Dept. of Natural Resources. Carcasses of cougars examined by wildlife officials have been clawless indicating the animal was likely an escapee or released by a private pet owner.

» Birds

It could be argued that the 16,000 acre Hobcaw Barony property is protected in perpetuity and that there is a National Estuarine Research Reserve here today because of birds – namely the ducks that attracted Bernard Baruch to the area and resulted in his purchasing the property in 1905 as a hunting retreat. Baruch in his autobiography (Baruch, 1957) writes:

"…I naturally grasped the opportunity that came to me in 1905 to acquire a veritable Shangri-La in my native South Carolina – famed Hobcaw Barony, whose sandy beaches and salt marshes once offered the finest duck hunting in the United States…"

Later in the chapter on Hobcaw Barony, Baruch describes a typical duck hunting experience:

"To the eastward, as the sun rose, one could see tens of thousands of ducks. At times they appeared like bees pouring out of a huge bottle. Their numbers were so great that you had to blink your eyes to be sure that you were not suffering from some illusion. As the sun mounted above the horizon, flock after flock would break away from the swamps and rice fields and come down to the marshes, flying in V formation. Nearing the marsh or hearing the call of the hunter, they would circle around and come down to the decoys. I have seen outlined in the sky the patterns of the very creeks from which the ducks rose."

Birds thus hold a special place in Hobcaw's history and have been subjects of study since the creation of the Belle W. Baruch Foundation in 1964.

Some of the first bird work conducted on the property was informal in nature – day counts, modeled a bit like Audubon Christmas Bird Counts, but much smaller in geographic scope, focusing just on the Hobcaw Barony property. Birders from around the state looked forward to the "Bellefield Annual Bird Count" where they spent the morning birding in different regions of the property and gathered for lunch and refreshments at Bellefield House at the invitation of host Ella Severin, Belle Baruch's trusted friend and resident trustee of the Belle W. Baruch Foundation. These counts, initiated in the late 60s by Dr. Harry Freeman, Professor of Biology at the College of Charleston and later picked up for a few years by the Waccamaw Audubon Society, continued into the 1980s. These once a year efforts provided snapshots of what birds were present on Hobcaw in the fall. However, to our knowledge, no attempt was made to organize and analyze the information systematically, and the count was discontinued in the late 1980s. Based on these counts, breeding bird surveys, Winyah Bay Christmas Bird Counts, and other surveys and observations made by individuals over the years, 276 species of birds have been observed in or adjacent to the boundaries of the North Inlet – Winyah Bay NERR (**Appendix H**). Rare and unusual avian visitors to North Inlet have also been documented including Sabine's Gull (Sutton et al., 1986) and Snowy Plover (Pulliam et al., 1996.)

Birds classified as endangered or threatened that breed and/or feed in or near the reserve include Wood Stork, Red-cockaded Woodpecker,

Bernard Baruch purchased the Hobcaw Barony property as a duck hunting retreat in 1905. Photo courtesy of the B.W. Baruch Foundation.

Piping Plover, Least Tern, and Bald Eagle. The entire Hobcaw Barony property is designated an "Important Bird Area" by the National Audubon Society. In addition to providing important habitat to several endangered and threatened species, Hobcaw Barony and the reserve serve as breeding habitat for many species of neotropical migratory birds, including warblers, painted buntings and shorebirds.

The first effort to systematically record bird species utilizing North Inlet occurred during the NSF-funded Outwelling Study, covered in greater detail in the water quality section for North Inlet. In the bird sub-study of the Outwelling Study, investigators designed a plan to identify and quantify birds in the estuary and calculate their contributions to energy flow in the system. Christy et al. (1981) used four methods to census bird populations in the North Inlet study area: aerial surveys twice a month along eight transects; twice a month high tide counts of communally resting shorebirds; nearly daily spot checks to monitor arrival and departure of low-density transient species; and airboat surveys to estimate clapper rail numbers. A total of 94 species of birds were recorded feeding on or over the North Inlet marsh during the period October 15, 1978 – October 15, 1979. Species numbers and numbers of individuals were greatest in spring (March-early May) and fall (July-early September.) Wading birds (Ciconiiforms) comprised more than 25% of the population in spring and made up over 60% of the spring avian biomass. In terms of energy flow, wading birds were calculated to contribute more than half of the avian-based flow in spring and summer, with the White Ibis population responsible for most of this. The contribution of wading birds to energy flow in the fall and winter was considerably less (15%) and was attributed to fewer wading birds present in the marsh in fall and greater numbers of non-wading birds, particularly shorebirds (Charadriiformes) and passerines, including migrating swallows. The authors also noted that the impact of waders on the North Inlet marsh is greatest during the breeding season when several species, including White Ibis, nest on the nearby Pumpkinseed Island in Winyah Bay.

Airboat surveys were used to estimate numbers of clapper rails as part of the Outwelling Study.

Clapper rails are one of the most abundant bird species in North Inlet marshes.

Bird surveys were continued through a second year of the Outwelling Study and yielded additional insights into the avian communities in North Inlet. Bildstein et al. (1982a) recorded 95 species of birds foraging on or over the North Inlet marsh over the two year period, October 15, 1978 – October 15, 1980. Three species, Clapper Rail, Short-billed Dowitcher, and White Ibis, comprised over half of the birds sighted on an annual basis. Species richness was greatest in the spring (March – early April) and lowest in early summer (June - early July) and late autumn (October). Clapper Rail, White Ibis and Great Egret comprised over half the avian biomass. Clapper Rails were the most abundant species in all four seasons and the largest component of the avian biomass for all seasons except spring when White Ibis contributed more. The authors indicated that these results point to the need to concentrate future efforts on the primary contributors to the North Inlet avian community, particularly Clapper Rails and White Ibis. One question presented was whether the observed 100% increase in the rail population between April and late September is due to reproductive success of breeding birds in the region, an influx of birds from the north, or both. Another future area for research identified by the authors is the role of large breeding colonies in structuring salt marsh bird communities. They concluded by saying that although they documented the size and structure of the North Inlet marsh avian community, their study does not provide structural mechanisms. In other words, how is the community affected by neighboring avian communities and how might disturbances of these neighboring populations impact the North Inlet community? These were insightful questions that led to additional research on many aspects of the avian populations in and surrounding the reserve, particularly feeding and breeding behavior of wading birds, especially White Ibis, in future years.

Additional analysis of the shorebird component of the North Inlet avian community censused during the two-year period, 1978-1980, was conducted (Bildstein et al., 1982b.) Twenty-one species of shorebirds were sighted during the period. Seventeen of the 21 species were observed during all four seasons and five species bred on or near the study site including American Oystercatchers and Willets. Most of the species were more abundant in spring and only Sanderling and Lesser Yellowlegs were most common in winter. Dowitchers, primarily Short-billed Dowitchers, comprised 43% of all shorebirds sighted. Calculated average energy flow for the entire avian community was 9.9 kcal $m^{-2}yr^{-1}$. Shorebird calorie consumption averaged 1.3 kcal $m^{-2}yr^{-1}$ with dowitchers accounting for 41% of all shorebird caloric consumption.

These early avian community studies were incorporated into an analysis and synthesis of all parameters examined during the Outwelling Study in order to assess net material and water fluxes for North Inlet (Dame et al., 1986.) Bird census data were used to estimate density at 2.6 birds ha^{-1} and a biomass of 0.7 kg ha^{-1} dry weight. The avian community was also estimated to consume 8.1 x 10^5 kcal of food annually. It was noted that although the bird contribution to carbon export in the system (estimated at 0.05 g m^{-2} yr^{-1}) was comparatively lower than other biological components examined, birds removed quantities of material and coupled the marsh-estuarine system to other environments where they can increase nutrients around breeding and roosting colonies. They may also play a role in regulating the distribution and abundance of benthic and fish populations in the marsh-estuarine system.

Shorebird foraging and predation on benthic communities has been explored by graduate students working in North Inlet. Grant (1981c) used a bioenergetic model to examine the potential effects of predation by shorebirds (Charadrii) on a population of the burrowing amphipod *Acathohaustorius millsi* on an intertidal flat on Debidue Beach near the mouth of North Inlet. Predator and prey abundances were determined August – November 1977. Amphipods were collected in 12 cores taken monthly. Shorebirds were censused bi-weekly in a defined area on Debidue Flat where the cores were taken. Recorded species included Dowitcher, Sanderling/Peep, Semipalmated Plover, Dunlin, Black-bellied Plover, Knot and Willet. Results of the model indicated that *A. millsi* accounted for 10.4% of the caloric intake of the shorebirds at the location studied. Grant suggested that the small contribution of the amphipod to shorebird diets was related to the availability of its prey, including burrow depth, and shorebird behavior. He suggested that further prey availability studies are needed to better understand predator-prey interactions. In another study, Grant (1984) examined the relationship between sediment microtopography and shorebird predation. Dowitchers, which are tactile feeders that use their bills to probe for prey, were observed foraging on Debidue Flat on a low tide in September 1980. Dowitcher probe holes were randomly sampled on ripple crests and troughs and the depths of the probes were measured. Sediment penetrability was measured at a later date in both ripple crests and troughs. The number of dowitcher probe marks on crests was found to be significantly higher than in adjacent troughs. Semipalmated Sandpipers which spent most of their time pecking versus probing were also observed foraging in these areas and showed no preference for crests or troughs. Penetrability tests showed that ripple troughs were significantly less penetrable than crests. Grant suggested that tactile foraging birds respond to microscale foraging cues.

Luckenbach (1984b) investigated the foraging behavior of five species of shorebirds in relation to tubes of the polychaete worm *Diopatra cuprea* on Debidue Flat in North Inlet during the summer of 1982. Benthic macrofauna composition and abundance around tubes and in tube-free areas were also determined. Of 102 foraging episodes noted, only 4 were in the vicinity of high densities of worm tubes, even though the greatest densities of prey items were around the tubes. These results supported the hypothesis that worm tubes serve as a refuge to infauna from shorebird foraging, at least for the species observed that included Willet, Least Sandpiper, Lesser Yellowlegs and two species of Dowitchers.

As mentioned earlier, Clapper Rails and waders, particularly White Ibis, were identified in the early census work to be significant avian components of the North Inlet system in terms of numbers, biomass and energy flow (Christy et al., 1981, Bildstein et al., 1982a.) Additional investigations were subsequently conducted to learn more about age and sex-related differences in foraging and flight patterns of White Ibis as well as mechanisms controlling the seasonal periods when ibises were observed feeding in the North Inlet marsh. A similar set of protocols was used in a variety of studies of White Ibis conducted in the 1980's, with observations made from a 18.5 m tower that overlooks the North Inlet marsh. Bildstein (1983) investigated age-related differences in both flocking and foraging behavior of White Ibises in North Inlet during July and August, 1980-1982. Most ibises fed in flocks and 95% of the juveniles fed in the company of adults. Juveniles hunting near adults were 47% as successful as adults on a per probe basis and caught prey at 40% of the adult rate. The author noted that even though considerable age-related differences in the feeding ecology of ibises were observed, they did not explain why the differences exist. Bildstein continued to explore these relationships in June and July of 1983 (Bildstein, 1984). Paired sequential 4-minute observations of two age classes of White Ibises (2nd year and > 2nd year birds) feeding within 5 m of each other in mixed-age flocks were made from the 18.5 m tower. Number of times a bird stepped, looked up, probed into a crab burrow or captured prey was recorded. Second-year ibises were only 50% as successful on a per-probe basis as older birds and caught prey 67% as frequently. The author compared these results to an earlier study of foraging behavior of first-year ibises which were observed to only capture prey at 40% the adult rate, thus showing a gradual improvement in foraging success of 2nd year birds. Further investigations into the foraging behavior of White Ibises feeding

The foraging behavior of White Ibis adults (left) and juveniles (right) was investigated by observation from a tower that overlooks North Inlet.

in flocks was conducted June – August in 1983 and 1984 (Petit and Bildstein, 1987.) Sequential 4 minute paired observations of adult White Ibises feeding in North Inlet marsh in four different social situations were made with spotting scopes from the 18.5 tower: central adults in large flocks (≥ 15 birds); peripheral birds in large flocks; adults in small flocks (5 or fewer birds); and solitary adults. Similar to previous studies, behaviors recorded included number of steps, number of probes into burrows or at surface crabs, number of fiddler crabs captured, number of times and total amount of time bird looked up and scanned its surroundings. In large flocks, the only significant differences in foraging behavior were that peripheral ibises looked up more often and for longer periods of time than central birds. Ibises in small flocks, single birds, and to some extent, ibises on the edges of large flocks stepped quickly to capture fiddler crabs before they could get into burrows. Even though central birds spent less time being vigilant in large flocks, they did not realize any advantage in terms of greater prey capture rates, likely as a result of depressed availability of surface crabs due to the activity of surrounding birds that caused crabs to remain in their burrows.

Petit and Bildstein (1986) examined the development of formation flying in recently fledged White Ibises in a study conducted in North Inlet June 25-September 1, 1984. Over the study period, juvenile ibises showed an increased tendency to fly in formation, from 17.8% in late June up to 88.0% in late August. Foraging differences between male and female White Ibises and energetic consequences were explored in a study by Bildstein (1987) conducted in North Inlet marsh May-July 1985 and May-August 1986. As with previous ibis behavior studies, paired 4-minute observations were made, this time of males and females foraging together in mixed flocks. To control for flock effects demonstrated in previous studies, pairs of birds feeding in larger flock peripheries or small flocks were analyzed separately from pairs feeding in the centers of large flocks. Even though male ibises have significantly longer bills (27%) than female ibises, males captured prey at similar rates to females. No significant differences were observed between males and females for any of the measured foraging parameters.

Several additional investigations and discoveries on different aspects of White Ibises and other wading birds have been made, primarily through work conducted on or in connection with what was historically a large wading bird colony on Pumpkinseed Island in Winyah Bay. These studies are treated separately in the bird section of the chapter covering Winyah Bay.

Although birds were not shown to be a significant direct contributor to nutrient exchange or energy flow relative to other measured biological components (Christy et al. 1981), they can serve to link ecosystems. In order to explore this idea, Bildstein et al. (1992) compared the annual inputs of nitrogen, phosphorus, potassium and calcium from atmospheric, stream flow, and ibis sources at the colony site in Winyah Bay to North Inlet over a two year period. Total amounts of nutrients contributed by ibises varied considerably between years, largely as a result of significantly lower numbers of nesting ibises in 1985 versus 1984. Results also showed that nutrient inputs to estuaries from colonial nesting birds can be substantial compared to atmospheric sources.

Marsh harrier behavior, specifically inter- and intra-specific aggressive interaction of Northern Harriers was studied over four winters between 1979 and 1984 (Bildstein and Collopy, 1985.) Northern Harriers escort flight behavior was observed in two different locations and habitats during these winters: North Inlet salt marsh in South Carolina and the Paynes Prairie, a freshwater marsh prairie in Florida. “Escorting flight” was defined as two birds flying in tandem within 50 m of one another with the trailing bird turning at least once to follow the leading bird. The sizes of the hunting ranges were also determined for five individuals. In both SC and FL, most individuals maintained areas of exclusive use for several hours up to 15 days (maximum period of continual observations.) In SC, exclusive areas averaged 70 ha. Harriers in the North Inlet marsh spent 4.3% of their time engaged in escorting flight behavior with other harriers compared to 4.1% in the Florida freshwater prairie system. South Carolina harriers were also observed to attack Red-tailed Hawks 13 times, Peregrine Falcons twice and a Cooper's Hawk once. High-speed chasing and stooping were much more common in inter-specific interactions than intra-specific interactions. During these five winters, the same investigators also examined the foraging behavior of Northern Harriers (Collopy and Bildstein, 1987). They compared foraging behavior, hunting success and diet of harriers. They recorded the time birds spent perching, hunting in flight, soaring, carrying prey, and feeding. The method of hunting, number of pounces and prey species were also recorded. Five types of pounces were observed. Harriers in the North Inlet marsh spent 33.8% of their time hunting compared to 27.2% for the Florida birds. North Inlet harriers captured prey on 15.1% of their pounces while Paynes Prairie harriers were successful on 5.8% of their attempts. The difference in hunting success between the two populations of overwintering harriers was explained by differences in prey. Harriers in North Inlet captured small and medium sized birds exclusively (rails and sparrows) while harriers in the Paynes Prairie were observed catching cotton rats. The authors concluded that habitat and prey base influence the foraging behavior and hunting success of harriers.

Comparatively little bird research has occurred in North Inlet in the last two decades compared to the activity that occurred in the 1980s, largely as a result of principal investigators moving to other regions of the country and the lack of others filling this niche. However, the North Inlet – Winyah Bay NERR has been involved in regular surveys of some species, including annual censuses of Piping Plovers that overwinter in South Carolina and Wilson Plovers that nest on area beaches in the spring. The south end of Debidue Beach and all of North Island are within the reserve boundaries. The South Carolina Department of Natural Resources (SCDNR) coordinated state-wide surveys of Wilson's Plovers in 2009 and 2010. Three breeding pairs of Wilson Plovers were reported to nest on Debidue Beach in 2009 and zero in 2010 while 26 and 23 pairs nested on North Island in 2009 and 2010, respectively (F. Sanders, personal communication.)

The American Oystercatcher, *Haematopus palliatus*, is classified by SCDNR as a Species of Concern (SCDNR, 2005) and has been the focus of recent monitoring and conservation efforts by the agency. SCDNR conducted surveys of wintering American Oystercatchers in South Carolina (Sanders et al., 2004) and assessed breeding season abundance and distributions of American Oystercatchers in the state (Sanders et al. 2008.) Surveys conducted over three winters, 1999-2002, found oystercatcher numbers to be relatively stable ranging from 3,327-3,734. The greatest concentrations of oystercatchers were observed between the Cape Romain National Wildlife Refuge and Dewees Inlet (Cape Romain Region) and accounted for 51-57% of the state totals over the three years. North Inlet oystercatcher numbers ranged between 100 and 200 each year. Breeding season surveys of oystercatchers were conducted by SCDNR, 2001-2003. A mean of 1,105 oystercatchers were recorded each year. Breeding pairs numbered 407 and 397 in 2002 and 2003, respectively, with 57% of the birds nesting in the Cape Romain Region. Oystercatchers in North Inlet totaled 22, 41 and 63 in 2001, 2002 and 2003, respectively, with 14 nesting pairs recorded in both 2002 and 2003. Nesting areas traditionally used by American Oystercatchers and other beach nesting birds in North Inlet are posted and roped off each nesting season to discourage people (and their dogs) from walking through the area. SCDNR scientists and NERR staff also record sightings of banded, color-marked individuals. To date, observations of marked oystercatchers have demonstrated that North Inlet is used by birds banded as nestlings in Virginia, North Carolina and Georgia. American Oystercatchers with colored bands have been observed and recorded with a webcam mounted at the Oyster Landing pier near the Baruch Marine Field Laboratory.

The NI-WB NERR initiated a secretive marsh bird monitoring effort in spring 2009 to assess distribution and relative abundances of Clapper Rails, *Rallus longirostris*, in the marshes of North Inlet. Reserve staff and volunteers counted Clapper Rails along routes using a standardized call broadcast method developed by the U.S. Geological Survey, Arizona Cooperative Fish and Wildlife Research Unit

Bird nesting areas in the reserve are roped off by the SCDNR each nesting season.

Volunteers help to monitor secretive marsh birds by listening for their calls following a standardized procedure.

(Figure 87). The Reserve also serves as a banding location for Painted Buntings. This is part of a citizen science project coordinated by a researcher at the University of North Carolina-Wilmington.

Marsh sparrows have also been the focus of recent studies initiated by investigators from the University of Connecticut and Coastal Carolina University. One study is designed to examine the migration patterns, survival and condition of tidal marsh sparrows. Another is looking at the relationship of marsh sparrow abundances at different sites in the North Inlet-Winyah Bay NERR to marsh characteristics. All recently initiated bird studies that have not yet resulted in publications are more fully described in the Current Research, Monitoring, and Education Projects 2012. This publication is updated annually by the Baruch Marine Field Laboratory in cooperation with the NI-WB NERR and is available electronically on the Baruch Institute website: www.baruch.sc.edu.

Although a great deal of avian research and monitoring has occurred in North Inlet in the past, especially in the 1980s, there are many opportunities for additional studies. The North Inlet – Winyah Bay NERR provides an excellent location for survey work and investigations on birds and their roles in coastal ecosystems.

Seaside sparrows inhabit the marshes of North Inlet.

Figure 87. Secretive marsh bird census locations in the North Inlet-Winyah Bay NERR

A webcam mounted at the Oyster Landing pier provides a peek at a popular roosting spot for birds during high tide and has been used to document the appearance of banded birds, including the American Oystercatchers, L1 and M7 (right).

» Insects

Although ubiquitous, seasonally abundant, and also annoying at times, the insect population in the NI-WB NERR is poorly understood. No comprehensive surveys and only a few scientific studies have been conducted. It is likely that many of the species found in similar estuarine habitats in North Carolina and Georgia as reported by Luckett Davis in *An Annotated Checklist of the Biota of the Coastal Zone of South Carolina* (Zingmark, 1978) also occur here. Davis's species list could provide a foundation for future insect survey work in the North Inlet-Winyah Bay region.

A field entomology class from the University of Guelph in Canada visited the Hobcaw Barony property in spring of 2004. A list of species that they collected and identified during this field course is included as **Appendix I**. Most of their collections were made on the upland portions of the property, with an emphasis on acalyptrate Dipterans (a subset of flies), Hymenoptera (bugs), and certain beetles of the order Coleoptera. They reported state records of the following species: *Panagagaeus crucigerus* (Carabidae), *Dirrhagofarsus lewisi* (Eucnemidae); *Abedus immaculatus* (Belostomatidae), *Proxius gypsatus* (Aradidae), *Otiocerus degeeri* (Derbidae), *Otiocerus stolli* (Derbidae), and *Cyarda melichari* (Flatidae) found in relatively large numbers in high marsh shrubs and *Juncus*. They also reported state records for the following reduviids: *Apiomerus crassipes*, *Melanolestes picipes*, *Phirontis modesta*, *Pselliopus cinctus* and *Repipta taurus*.

North American Butterfly Association Butterfly Counts have been conducted on the Hobcaw Barony property, including the North Inlet and Winyah Bay portions of the NERR, every year since 1993. More than eighty-five species of butterflies have been observed on Hobcaw Barony during these counts and at other times (**Appendix J**). Some of these species are salt marsh dependent, laying their eggs on marsh host plants. For example, the Eastern Pygmy-Blue, the smallest butterfly in North America, uses salt marsh glasswort, *Salicornia* spp., as its host plant. Saltgrass, *Distichlis spicata,* is the caterpillar host plant for the Salt Marsh Skipper. Phaon Crescents are another special coastal species and have been observed necturing on *Lippia* plants near salt marsh and beach habitats in the Reserve.

More than 85 species of butterflies have been documented on the Hobcaw Barony property, including the Juniper Hairstreak (top), Eastern Pygmy-Blue (bottom).

Signficant herbivory of *Juncus roemerianus*, *Iva frutescens*, and *Spartina alterniflora* was observed in summer 2003 and also summer 2004 in several areas of the North Inlet salt marsh (W. Allen, pers. ob). At least three different species of grasshoppers were very abundant and were observed grazing on the marsh vegetation. Some *Iva* plants were completed stripped of their leaves and did not recover by the next year.

Several NERR sites, including the NI-WB NERR, have served as platforms for research on the latitudinal variation of herbivores and plant-herbivore interactions in salt marshes. Wason and Pennings (2008) examined the latitudinal variation in composition of tettigoniid grasshoppers in salt marshes along the Atlantic coast. Two sites in the North Inlet-Winyah Bay NERR were sampled in this study that spanned from Florida to Maine. Eight species of grasshoppers were collected and identified from the *Spartina alterniflora* zone, with *Orchelimum fidicinium* dominating the community at low latitudes and *Conocephalus spartinae* dominating at high latitudes. In another study, Pennings et al. (2009) examined latitudinal variation in herbivore pressure in Atlantic Coast salt marshes using three different approaches: herbivore counts, leaf damage assessments and transplant experiments. Herbivores were sampled in different salt marsh vegetations zones and included several species of insects, gastropods, a mite and a decapod crab. Results of herbivore counts showed that chewing herbivores and gall makers were more abundant at lower latitudes. Chewing herbivore damage to plants was also greater at low versus high latitudes. In transplant experiments, plants transplanted to low latitude sites experienced two orders of magnitude more herbivore damage than plants transplanted to high latitude sites. Although distinct latitudinal differences in herbivory were observed, results varied with herbivore feeding guild. The authors suggested that future studies would benefit from comparisons of herbivores from different feeding guilds.


Significant insect herbivory of salt marsh plants has been observed in North Inlet marshes, but research is needed to better understand the role of insects in marsh food webs.

Areas for future work on insects are wide open, given the limited extent of our knowledge not only on species composition, but on the role insects are playing in the North Inlet and Winyah Bay systems. Insects can be significant consumers of marsh primary productivity and are important links in marsh food webs. Additional research is needed to better understand these interactions.

» Invasive Species

Approximately 42% of Threatened or Endangered species are at risk due to invasive species (Pimentel et al., 2005). The National Invasive Species Management Plan defines invasive species as, "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health" (National Invasive Species Management Council, 2008). Many non-native species are non-invasive and can even be beneficial to the ecosystem and humans. This section will briefly describe species considered to be invasive, as defined above, which have either been documented as occurring in North Inlet or are considered a future threat to the area. Table 10 contains a list of invasive animal species and Table 11 lists invasive plant species that have been documented in the South Carolina coastal region.

MARINE INVERTEBRATES

There are an estimated 500 alien marine species within the coastal waters of the US. Marine species are spread beyond their native ranges though shipping related causes, such as ballast water transfer and hull fouling, and also through the transport of fishing and diving gear and recreational boat traffic. In some cases, invasions have occurred as a result of both intentional and unintentional releases of species from mariculture, aquariums, and live seafood and fish bait trades. The environmental impacts of invasive marine invertebrates include the loss of biodiversity due to preying upon native species, decreased habitat availability and increased competition for native species, the introduction of parasites and disease, and in some cases, through smothering and overgrowth of natives. Economic impacts of marine invasive species are well documented, and include the interference with fisheries through fouling or tearing of nets, damage to infrastructure through fouling of pipes, wharves, buoys etc., disruption to tourism, and the costs of clean up, control, and treatment or quarantine. To date, there has been no successful eradication of invasive marine invertebrates in the United States (Benson, 2014).

Although no major shipping or commercial fishing occurs within North Inlet, the introduction of marine invasive species is a concern due to water exchange with Winyah Bay where these activities do occur, as well as the potential for introductions through recreational uses of North Inlet. No long-term monitoring directly targeting marine invasive species has occurred within North Inlet. Settlement substrates were placed at Oyster Landing and Clambank Creek in 2007 for a DNR study of green mussel (*Perna viridis*) recruitment. Most records of marine aquatic invasive species in the area are the result of incidental catch.

The Asian tiger shrimp, *Penaeus monodon*, was reported in North Inlet in 2013 (NAS …[cited 2014]). Mature tiger shrimp can be distinguished from native penaeid shrimp by their overall rusty brown color and the distinctive black and white banding across the back and on the tail. This species, native to the Indo-West Pacific oceans, has a rapid growth rate and broad tolerance to salinity (2-30) that have contributed to the success of this species in aquaculture, however, these are also characteristics that enable it to invade new areas. (FAO, 2014; McCann et al., 1996). Tiger shrimp are currently found from North Carolina to Texas, and nearly 300 tiger shrimp were collected off the coast of South Carolina, Georgia and Florida in 1988 over three months after an accidental release of roughly 2,000 animals from an aquaculture facility in South Carolina (NAS …[cited 2014]). The impacts of this invasive shrimp on the native fauna in areas where it has been introduced are uncertain. The tiger shrimp has been shown to be a more aggressive predator on soft-bodied invertebrate benthic organisms than native shrimp, feeding primarily on small crabs, shrimp, bivalves and gastropods (Marte, 1980).

The titan acorn barnacle, *Megabalanus coccopoma*, was first collected from South Carolina waters in the Folly River, near Charleston Harbor, in the fall of 2006, and was found in a seawater intake pipe at Oyster Landing in 2011. This large, pink barnacle, native to the eastern Pacific, grows to around 5 cm in height and can attain a body mass 100 times greater than that of native species (Tibbetts, 2007). Water temperatures may prevent its permanent establishment in South Carolina, and population die offs in the winter of 2009-10 are suspected to be the result of low water temperatures. (SC DNR, 2014).

The green porcelain crab, *Petrolisthes armatus*, was first observed in South Carolina in low densities in the spring of 1995 and has been reported as far north as Murrells Inlet in 2000. Hartman (2003) found fluctuations in the population of *P. armatus* from 300 to 0 individuals/m^2 in North Inlet over a three-year study. Seasonal temperature changes appeared to be the major reason for population changes.

The Indo-Pacific Swimming Crab, also known as the spiny hands crab, *Charybdis hellerii*, was discovered by staff of the Southeastern Regional Taxonomic Center at the Marine Resources Research Institute in Charleston, SC in 2001. It was collected in 2002 in Town Creek in North Inlet (SERTC, 2014).

The green porcelain crab, *Petrolisthes armatus.*

The Asian green mussel, *Perna viridis*, has not been documented in North Inlet, but was discovered in South Carolina in 2006 on a settlement panel in the Folly River. Subsequent surveys in 2007 and 2008 by SC DNR of four sites from Murrells Inlet to Port Royal Sound only found 9 live mussels in Folly River. Mussels have been found incidentally in seawater intake pipes and vessel hulls in the Charleston area, suggesting that a much greater source of propagules is available along the South Carolina coast. The northern expansion of this tropical species is constrained by low water temperatures, although there is no consensus on where this thermal tolerance will be reached along the east coast of the United States. Initial predictions suggested it would not survive north of Georgia (Baker et al., 2002), however, Knott et al. (2008) found a population that persisted for two years in the Folly River. In addition to hull fowling and clogging intake pipes, *P. viridis* may out-compete the commercially important native eastern oyster, *Crassostrea virginica*, and little is known about the biodiversity associated with *P. viridis* patches compared to *C. virginica* (Firth et al., 2011).

INSECTS AND DISEASES

The redbay ambrosia beetle, *Xyleborus glabratus*, bores through the bark of trees and introduces a fungus that causes laurel wilt, a disease that can kill several tree species in the Lauraceae family, including the redbay, *Persea borbonia*. Redbay is the primary food source for the Palamedes Swallowtail caterpillar, and a large component of the coastal forest understory. The fungus is extremely fast-acting and trees typically die within a month after being infected. In the areas where the beetle has been found, there can be a loss of up to 90% of redbay (SCFC, 2012). The beetle is believed to have been introduced into Georgia in 2002 by infested packing materials, such as wooden crates and pallets (Thomas, 2007). In 2003, significant redbay mortality on Hilton Head Island, South Carolina, was reported to the South Carolina Forestry Commission, and by 2011 redbay mortality was confirmed in 11 South Carolina Counties (SCFC, 2012). Laurel wilt was confirmed in Georgetown County and on the Hobcaw Barony property in 2012.


The kudzu bug is considered a nuisance around buildings and structures due to its fowl odor. It is unknown what impact this species may have on agriculture.

The kudzu bug, *Megacopta cribraria*, a close relative of the stink bug, was first seen in Georgia in October of 2009 and has now spread throughout Georgia, South Carolina, and other southern states. Kudzu bugs feed on kudzu and on many other legumes such as wisteria and soybeans. The large number of kudzu bugs and the foul odor attributed to their secretions make them a nuisance around buildings and other structures. Kudzu bugs were observed in large numbers adjacent to the Reserve headquarters in 2012

VERTEBRATE ANIMALS

Feral swine may be the most destructive of the invasive species found on Hobcaw Barony. Introduced by European settles in as early as the 1600s, escaped and free ranged swine were documented to be one of the primary causes for longleaf pine regeneration failures as early as the 1930s. Swine compete with native species for forage, as well as causing extensive damage to understory plants through their rooting and feeding activity. The disturbance caused by this rooting activity may contribute to the spread of invasive plant species such as *Phragmites* and chinese tallow tree that can quickly colonize disturbed sites. Swine are also a major predator of native wildlife including ground nesting birds, amphibians, and even sea turtles through nest predation.

Coyotes first appeared in South Carolina about 30 years ago and continue to expand greatly in numbers and are currently found in every county in the state. Sea turtle nest depredation by coyote has become a concern on North Island and neighboring beaches.

AQUATIC PLANTS

The red alga, *Gracilaria vermiculophylla*, is an invasive alga native to Southeast Asia that has invaded many estuaries in North America and Europe. The presence of *G. vermiculophylla* on the east coast of the USA from Massachusetts to South Carolina has been confirmed using molecular techniques (Gulbransen et al., 2012). In North Inlet, *G. vermiculophylla* blooms and declines seasonally. *G. vermiculophylla* reaches its peak abundance in the early summer and declines in abundance through the fall. By winter, it is absent from the intertidal mudflat. During this time and into the spring, the diversity of other seaweed species increases in North Inlet. By mid spring, *G. vermiculophylla* is once again present and other seaweed species decline in abundance. By the summer, *G. vermiculophylla* is the dominant, greatly abundant seaweed in North Inlet, where it can be found covering the lower mudflat. Though negative relationships between *G. vermiculophylla* abundance and the abundance of other seaweed species has been found in seaweed communities elsewhere in the world, there has not been sufficient research at this time to suggest that the patterns of abundance observed in North Inlet are the result of direct competition between the non-native *G. vermiculophylla* and other seaweed species (Lindsay Haram, personal communication).

The common reed, *Phagmites australis*, occurs in tidal salt and fresh, non-tidal and upland habitats throughout large parts of Canada and the entire continental US. Although it has been a minor component of North American wetland plant communities for thousands of years, it has become a dominant species in the past century and both genetic and environmental arguments have been made to explain the recent range expansion. The loss of biodiversity and habitat as native plants are replaced by monotypic stands of *Phragmites* is of concern. No formal mapping effort of *Phragmites* in North Inlet has been completed, but it is known to occur in the ditches near the Reserve headquarters at the Baruch Marine Field Laboratory. In July 2012, Mozdzer and Neubauer investigated how methane emissions and net ecosystem exchange are altered with *Phragmites australis* invasion in tidal fresh and brackish marshes of North Inlet (Mozdzer, personal communication). Mozdzer worked in *Phragmites* invaded brackish marshes by Marsh Rd and in an oligohaline marsh near Barnyard Village on Hobcaw Barony. At these sites, Mozdzer and Neubauer found that methane emissions were three fold higher than adjacent native vegetation. These changes in methane emissions have important implications with respect to the carbon balance of tidal wetlands. While tidal wetlands have been described as “blue carbon” pools due to their ability to sequester disproportionately more carbon than terrestrial ecosystems, changes in species composition, like *Phragmites* invasion, can result in increased methane emissions which can potentially change the radiative forcing of the ecosystem.

VASCULAR PLANTS

In the early 1990s, the woody shrub beach vitex, *Vitex rotundifolia*, was planted for erosion control on South Carolina beaches, but by the mid-1990s plant specialists began to notice beach vitex spreading on state beaches where it was crowding out native species like sea oats. A workshop was hosted by the North Inlet-Winyah Bay National Estuarine Research Reserve in 2003 to address concerns about the spread and possible impacts of the plant on loggerhead sea turtle nesting. This workshop brought together private citizens, personnel from state and Federal agencies, and representatives from non-profit organizations, resulting in the formation of the South Carolina Beach Vitex Task Force, which later became simply the Beach Vitex Task Force after North Carolina and Virginia joined the effort. In 2004, the Task Force received a National Fish and


Beach vitex can rapidly colonize dunes, reducing plant diversity and adversly impacting sea turtle nests.

Wildlife Foundation grant to begin removal of the plants. Clemson University researchers performed experiments to determine the best herbicide and application method, and personnel began removing *Vitex* and replanting dunes with native vegetation. From 2003 to 2011, the Task Force received over $800,000 in grants from a diverse group of stakeholders including the National Fish and Wildlife Foundation, US Fish and Wildlife Service, Natural Resources Conservation Service (NRCS), Town of Pawleys Island, the Donnelley Foundation and the Bunnelle Foundation. Through the Task Force's education and outreach efforts, ordinances banning beach vitex have been passed in a number of NC and SC beach communities. A GIS data base of occurrences, reported by volunteers through a web site maintained the Reserve, and through SCDNR and NRCS survey efforts, is currently maintained by NRCS.

Chinese tallow tree, *Triadica sebifera*, was initially introduced to South Carolina in the 1700s. It commonly occurs on disturbed sites such as spoil banks, roadsides, agricultural lands, urban areas, and storm-damaged forests. It is considered a severe threat in the piedmont and coastal plain regions of South Carolina due to its displacement of native species through vigorous growth and spread. No formal mapping or eradication effort of tallow has been done adjacent to North Inlet, but tallow trees are found throughout the uplands surrounding the Reserve.

RESEARCH AND EDUCATION EFFORTS

No formal survey or mapping efforts of invasive species within the NI-WB NERR have been conducted to date. This remains an important research and management need, especially as climate change is predicted to increase the distribution and impact of many invasive species. The reserve partnered with the North Carolina, ACE Basin, and Sapelo Island NERRs on a project to work with the nursery industry to prevent the sale of invasive landscape plants. The project began in 2012 with a series of interviews with growers and nursery owners to better understand the barriers to preventing the sale of invasive plants and promoting the use of native plants in landscaping. The next step of the project will be to develop an outreach plan to educate homeowners about invasive landscape plant species and native alternatives.

Table 10. Invasive invertebrate and vertebrate animal species occurring in the South Carolina coastal region. Species that are known to occur in North Inlet, Winyah Bay, or the adjacent Hobcaw Barony uplands are in **bold**.

Marine Invertebrates

Charybdis hellerii	**spiny hands crab**	*Perna viridis*	Asian green mussel
Haplosporidium nelson	**MSX, an oyster disease**	***Petrolisthes armatus***	**green porcelain crab**
Megabalanus coccopoma	**titan acorn barnacle**	*Phyllorhiza punctata*	Aust. spotted jellyfish
Molgula manhattensis	**sea grape**	*Styela plicata*	rough sea squirt
Mytella charruana	charrua mussel	*Synidotea laevidorsalis*	Isopod
Penaeus monodon	**Asian tiger shrimp**		

Insects

Aedes albopictus	Asian tiger mosquito	*Ochlerotatus japonicus*	Asian mosquito
Megacopta cribraria	**Kudzu bug**	***Xyleborus glabratus***	**Redbay ambrosia beetle**

Vertebrate Animals

Canis latrans	**coyote**	*Pterois volitans*	Red Lionfish
Dasypus novemcinctus	Nine-banded armadillo	***Sus scrofa (feral type)***	**Feral pig**
Myocastor coypus	Nutria	*Trachemys scripta elegans*	Red-eared slider

Table 11. Invasive plant species occurring in the South Carolina coastal region. Species that are known to occur in North Inlet, Winyah Bay, or the adjacent Hobcaw Barony uplands are in **bold**.

Aquatic Plants

Alternanthera philoxeroides	**Alligatorweed**	*Ludwigia uruguayensis*	Water primrose
Gracilaria vermiculophylla	**Red algae**	***Phagmites australis***	**Common reed**
Egeria densa	Brazilian elodea	*Pistia stratiodes*	Water lettuce
Eichhornia crassipes	Water hyacinth	*Salvinia molesta*	Giant salvinia
Hydrilla verticillata	Hydrilla		

Vascular Plants

Ailanthus altissima	Tree of heaven	*Lespedeza bicolor*	Two Color Bush Clover
Albizia julibrissin	**Mimosa, Silktree**	*Lespedeza cuneata*	Sericea
Arundo donax	**Giant Reed**	***Ligustrum*** **spp.**	**Privet**
Broussonetia papyrifera	Paper Mulberry	*Lonicera fragrantissima*	Sweet Breath of Spring
Carduus nutans	Nodding Thistle	***Lonicera japonica***	**Japanese Honeysuckle**
Celastrus orbiculatus	Asian/Oriental Bittersweet	*Lygodium japonicum*	Japanese Climbing Fern
Cinnamomum camphora	**Camphortree**	***Melia azedarach***	**Chinaberry**
Cirsium vulgare	Bull Thistle	*Microstegium vimineum*	Japanese Stilt Grass
Clematis terniflora	Yam-leaved clematis	*Miscanthus sinensis*	Chinese Silvergrass
Crotalaria spectabilis	**Showy Rattlebox**	*Morus alba*	White Mulberry
Cytisus scoparius	Scotch Broom	*Murdannia keisak*	Wart Removing Herb
Daucus carota	Queen Anne’s Lace	*Panicum repens*	Torpedo Grass
Dioscorea polystachya	Chinese yam, Air potato	*Paspalum dilatatum*	Dallis Grass
Elaeagnus pungens	**Thorny-olive**	***Paspalum notatum***	**Bahia Grass**
Elaeagnus umbellata	Autumn-olive	*Paspalum urvillei*	Vasey's Grass
Eragrostis curvula	Weeping Love Grass	*Paulownia tomentosa*	Princess Tree
Festuca arundinacea	Tall Fescue	*Phyllostachys aurea*	Golden Bamboo
Firmiana simplex	Chinese Parasol Tree	*Polygonum cuspidatum*	Japanese Knotweed
Hedera helix	**English Ivy**	*Poncirus trifoliate*	Trifoliate Orange
Imperata cylindrical	Cogongrass	*Populus alba*	White Poplar
Pueraria montana	**Kudzu**	*Sorghum halepense*	Johnson Grass
Rosa bracteata	Macartney Rose	*Spiraea japonica*	Meadowsweet
Rosa laevigata	Cherokee Rose	*Tamarix ramosissima*	Saltcedar
Rosa multiflora	Multiflora Rose	***Triadica sebifera***	**Chinese Tallow Tree**
Securigera varia	Purple Crownvetch	*Vinca major*	Bigleaf Periwinkle
Sesbania punicea	Rattlebox	*Vinca minor*	Common Periwinkle
Solanum pseudocapsicum	Jerusalem Cherry	***Vitex rotundifolia***	**Beach Vitex**
Solanum viarum	Tropical Soda Apple	***Wisteria sinensis***	**Chinese Wisteria**

WINYAH BAY'S MAJOR BIOTA

» Primary Producers

Few studies pertaining to primary producers in Winyah Bay have been conducted, especially in comparison to North Inlet. Those that have been done involve phytoplankton and vascular plants and are summarized below. No studies on benthic microalgae or macroalgae were found for Winyah Bay in the literature search for this summary document.

PHYTOPLANKTON

Chlorophyll *a* has been measured in the NI-WB NERR 20 day water chemistry program at the SWMP sites since 1994. At the Thousand Acre Marsh location in Winyah Bay, chlorophyll *a* concentrations during July 3-4, 2010 were lowest during low tide and highest at high tide (Figure 88). This tidal pattern did not vary much between day and night.

Short-term variability was greatest during summer when there were up to 8-fold differences in the minimum and maximum values during single 26-hour collection periods (Figure 89). The June and August peak values of 80 to more than 100 mg L^{-1} are very high concentrations for the brackish portion of an estuary. In general, chlorophyll *a* was highest during summer and lowest from December to April, but low summer values were equivalent to high winter values.

No long-term trend was evident for chlorophyll *a* at the Thousand Acre Marsh site; however, summer and fall levels from 1994-96 and 2004-10 were generally higher than those from 1997-2003 (Figure 90). Interannual variations in chlorophyll *a* at this site did not correspond to patterns of salinity or river runoff, perhaps because of the alternating influence of the adjacent shallow marsh and creeks during ebbing tides and the exchange with the Mud Bay section of the larger estuary during flooding tides.

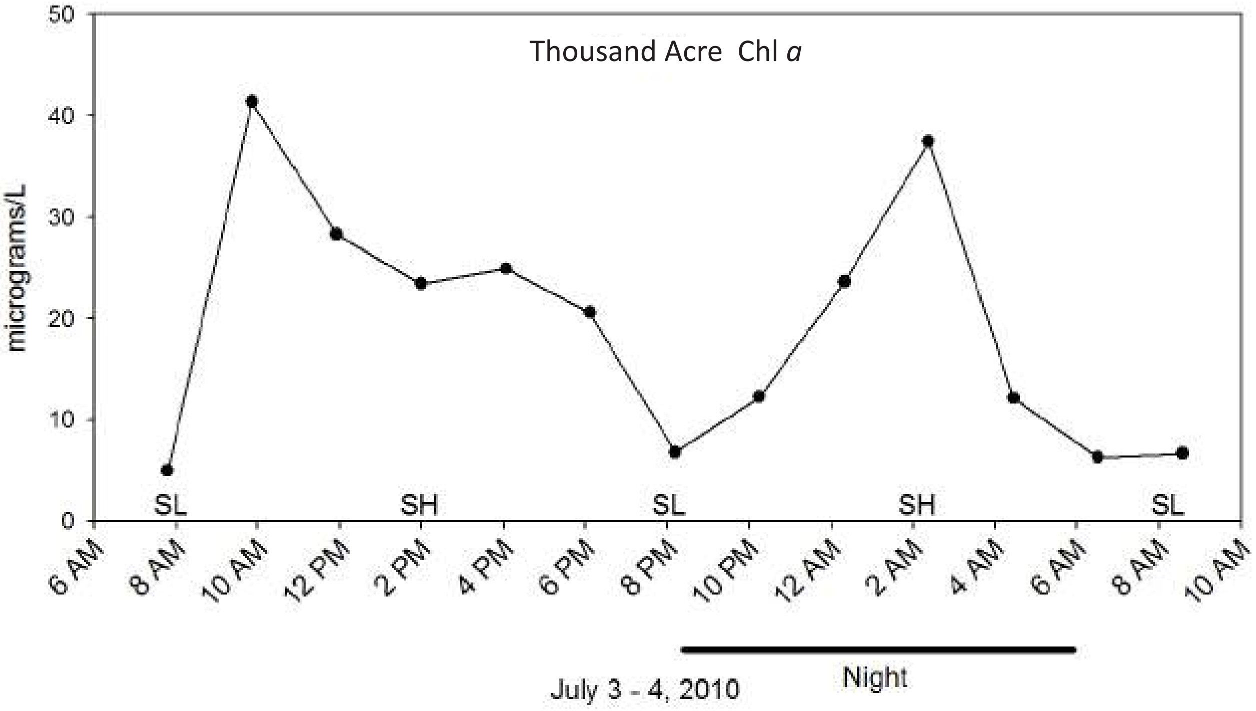


Figure 88. Chlorophyll *a* concentrations in water samples collected every hour July 3-4, 2010 at the NI-WB NERR SWMP Thousand Acre Marsh monitoring site.

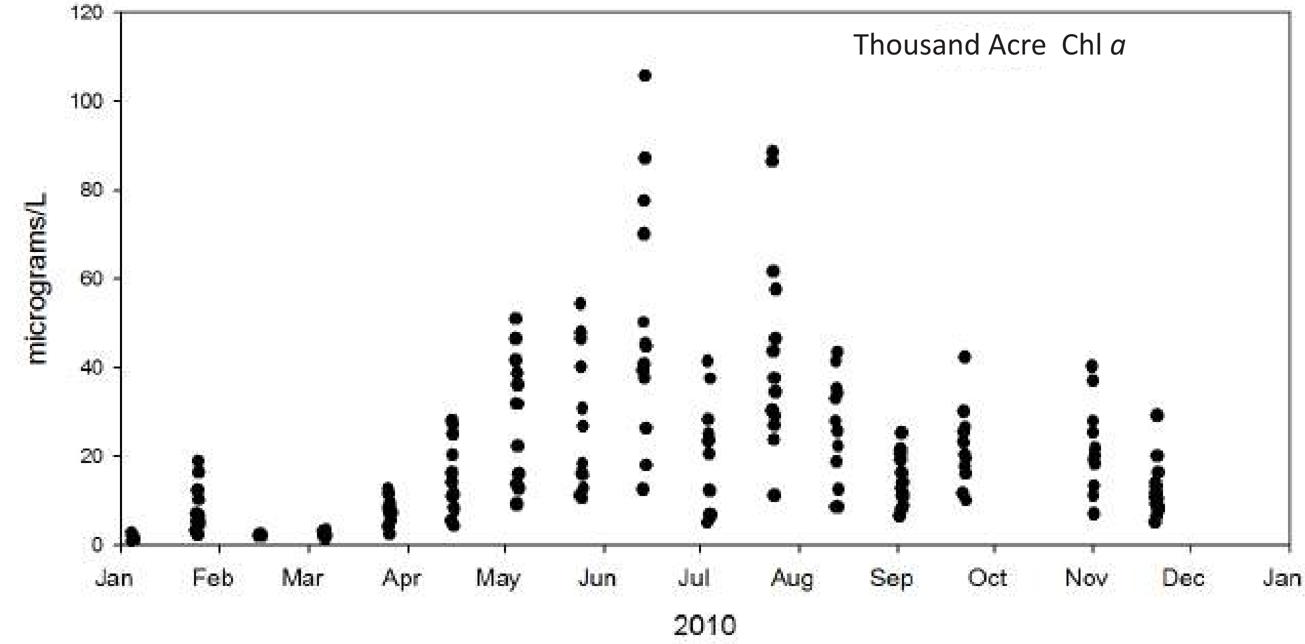


Figure 89. Chlorophyll *a* concentrations in water samples collected every hour during the 20 day samplings in 2010 at the NI-WB NERR SWMP Thousand Acre Marsh monitoring site.

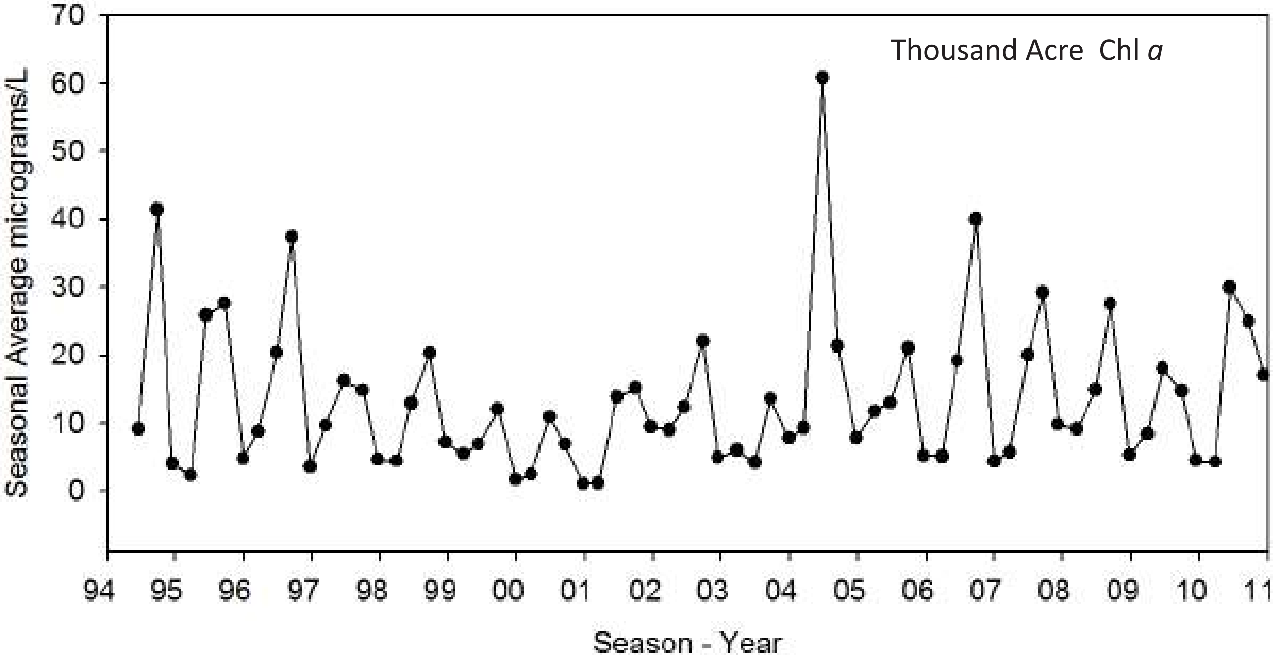


Figure 90. Mean seasonal chlorophyll *a* concentrations in water samples collected from 1994-2010 at the NI-WB NERR SWMP Thousand Acre Marsh monitoring site.

SUMMARY OF OTHER STUDIES ON PHYTOPLANKTON IN WINYAH BAY

Compared to North Inlet, the phytoplankton community in Winyah Bay is considerably less studied. As part of a state-wide study, the SCECAP program (Dept. of Natural Resources) occasionally measures chl-*a* concentrations at various stations in the bay. A volunteer water sampling effort associated with the Winyah Rivers Foundation measures chlorophyll and other water quality parameters at river parks in the upper Bay. Ranhofer (2009) and Ranhofer et al. (2009) studied the role of nutrient limitation. Lawrenz et al. (2010) and Lawrenz (2011) investigated the role of light as a control on community composition.

Ranhofer's (2009) dissertation research involved the phytoplankton's utilization of dissolved organic phosphorus via expression of alkaline phosphatase, a hydrolyzing extracellular enzyme, using a cell-specific enzyme-labeled fluorescence assay. These investigations were run using *in situ* nutrient-addition bioassays and laboratory time-series experiments with cultures representing five different taxa. Lastly, she investigated how the presence of humic acids affects the ability of the phytoplankton to utilize phosphomonoesters as a source of phosphorus.

Ranhofer et al. (2009) found that diatoms dominated both the riverine site (at the confluence of the Pee Dee, Waccamaw, and Black Rivers) and the coastal site just between the jetties at the entrance to Winyah Bay. Nitrogen limitation existed at each site: in May at the coastal station, and in August at the riverine station. Phosphate limitation was not demonstrated at either site. The expression of the enzyme occurred in a range between 30% and 1% of the cells and only in cells with low abundance. The general lack of either N or P limitation suggested that riverine input of these elements was high. Their work pointed to the need for more study of the role of the dissolved organic phosphorus pool and its utilization in Winyah Bay. Those interested in the topic of nutrient supply and pollution in Winyah Bay should consult Kucklick and Bidleman (1994a, b), Krest et al. (2000), Eddins (2001), Goni et al. (2003), Buzelli et al. (2004), and the SCECAP website.

Lawrenz's dissertation (2011) involved the study of CDOM, chromophoric or colored dissolved organic matter's effects on water color and hence on phytoplankton community composition in Winyah Bay. She found that cryptophytes dominated in upstream portions of the bay when wind-mixing was low; otherwise, diatoms dominated. Cryptophytes and cyanobacteria harvested light more efficiently than diatoms or chlorophytes in blackwaters containing high amounts of CDOM. Their earlier paper (Lawrence et al., 2010) is basically the text from Chapter 3 of her dissertation. The other chapters relate to species-specific studies of fluorescence (Lawrenz and Richardson, 2011) using natural phytoplankton populations from Winyah Bay, extraction protocols for phycobilins, underwater light fields and phytoplankton community composition in North Inlet, with a model of spectral irradiance, light absorption, and vertical mixing.

VASCULAR PLANTS

The baseline habitat map developed for the North Inlet-Winyah Bay NERR (Figure 65), presented at the beginning of this Ecological/Biological Setting chapter, indicates that much of the Winyah Bay portion of the NERR is comprised of high marsh and maritime forest vegetation in contrast to North Inlet where low marsh vegetation dominates. The description of Winyah Bay's macrophyte community provided by Blood and Vernberg (1992) is the most recent summary of what types of vascular plants can be found there. The diverse (species-rich) plant community exists because there is such a wide range of salinities occurring in Winyah Bay. Thus freshwater, brackish water, and salt marshes all exist, with freshwater marshes covering the greatest area and salt marshes the least. Nearly all of the marsh area in Winyah Bay is affected by tidal changes in water level. Tiner (1977) provided the species inventory presented by Blood and Vernberg (1992).

Unfortunately, there have been no studies of vascular plant productivity or biomass in Winyah

Bay. By all outward appearances, the *Spartina* surrounding Mud Bay looks the same as in North Inlet. It is unknown whether the more brackish environment in this part of the NERR significantly alters the growth rate and productivity of cordgrass relative to the same species growing in North Inlet. Such a difference would be very difficult to detect given the wide range of vascular plant production values reported for North Inlet.

Much of the Winyah Bay portion of the NERR is comprised of high marsh and maritime forest vegetation in contrast to North Inlet where low marsh vegetation dominates.

» Microbial Communities

The Winyah Bay portion of the NI-WB NERR has received considerably less microbiological study than North Inlet over the last four decades. It was not until the 1990s that any close examination of water quality was made on a regular basis in Winyah Bay. Earlier studies were directed at assessing human health issues that arise from industrial pollutants and agricultural runoff entering the bay from the surrounding watershed, primarily through the Pee Dee, Waccamaw, and Sampit rivers. The focus then was on fecal coliform bacteria, heavy metals, organic compounds (pesticides) and anything potentially harmful that might enter harvestable species of fish and shellfish. These data were compiled and reviewed by Blood and Vernberg (1992) who summarized what was known in the period 1970 to 1985. At that time, however, no regular, standardized sampling programs existed from which any trends in the health of the Winyah Bay estuary could be inferred. Most of the microbiological studies have been conducted by state agencies specifically to measure fecal coliforms as they relate to water quality and the need to close public shellfish beds after particularly high runoff events. Such precaution is necessary because the receiving waters of Winyah Bay likely contain more human-derived (from rural septic tank overflow) and larger quantities of animal-derived (e.g., cattle, swine, poultry) coliforms than occur in North Inlet.

The most coordinated and comprehensive coastal monitoring program to have taken place in Winyah Bay is called the South Carolina Estuarine and Coastal Assessment Program (SCECAP) that began in 1999. This program's goal is to monitor the condition of the state's estuarine habitats and associated living resources on a biannual basis. It is a collaboration between the SC Department of Natural Resources and the SC Department of Health and Environmental Control. The SCECAP samples water and sediments at 6 sites in North Inlet and 24 sites in Winyah Bay, though not all are sampled every year because they use a random, probability-based sampling regimen. The program issues a summary update covering two-year periods that compares data from many other locations in the state and by virtue of the sampling design is able to make some trend assessments of habitat and resource quality changes over time. These reports are available online (**www.dnr.sc.gov/marine/scecap/**). Van Dolah et al. (2008) provide comparative analyses of estuarine habitat quality that include fecal coliform measurements in 29 different watersheds in South Carolina, including Winyah Bay.

Ullman and Aller (1979) studied the biogeochemistry of sediments in Mud Bay, including the anaerobic decomposition of organic matter that leads to the production of iodine. Ullman and Aller (1983) found that about 90% of the dissolved iodine flux comes from the top 10 cm of the sediment in Mud Bay.

Fungal infections in fish, particularly menhaden, have been assessed by Dykstra et al. (1989) on specimens captured in Winyah Bay. Long et al. (1996) and Long (2000) utilized a 5-min microbial bioluminescence test on organic extracts from sediments in Winyah Bay as part of a larger NOAA program examining sediment toxicity in U.S. estuaries. Guentzel and Tsukamoto (2001) examined the role of microorganisms in the speciation of mercury compounds as they influence the bioaccumulation and bioconcentration of this heavy metal in the marine food web leading to fishes.

Heterotrophic bacteria release dissolved organic matter (DOM) as they grow and multiply, get grazed by microplanktonic protozoans, or die from viral lysis. The origin and composition of DOM produced by bacterioplankton in water samples from Winyah Bay was studied by Kawasaki and Benner (2006). They incubated water samples in artificial media containing glucose as the sole carbon source for several months and found that extracellular release of dissolved organic matter (e.g., amino acids and amino sugars) can result in the underestimation of bacterial carbon production rates unless these releases are taken into account.

Microbiological investigations typically require quantification of microbe abundance. Most methods for doing this are expensive and time consuming, particularly for particle surface-associated bacteria. Swenson et al. (2012) developed a fluorometric method that is relatively rapid and inexpensive using cultures of sediment bacteria collected from Winyah Bay. This high throughput method may be useful for the examination of antibiotic resistance.

Based upon the low number of studies conducted on microbial communities from or in Winyah Bay, this portion of the NI-WB NERR is severely understudied.

» Benthos

MACROBENTHOS IN WINYAH BAY

The earliest studies of macrobenthos beneath the open waters of Winyah Bay were reported by Hinde et al. (1981). The impetus for these efforts was a proposed ship channel-deepening project. Their three replicate samplings per station were collected in October 1980 along the main axis of the Bay towards the southwestern shoreline in the high-salinity portion of the estuary. They also collected some samples offshore near the mouth, but none of their study was done inside the NI-WB NERR boundary. Benthos in the collections from the 12 total sampling stations were dominated by pelecypods and polychaete worms. Amphipods and gastropods were also prominent in the collections. Some 154 taxa were identified in the collections. Species diversity was highest in the offshore stations and lowest near South Island where sediment conditions and high currents afforded habitat suitable for high densities of the mussel *Brachidontes exustus*.

Biogeochemical studies in the sediments of Mud Bay, inside the present NI-WB NERR boundary, have been done by Aller and Ullman reported earlier in the Water Quality chapter. Unfortunately, none of these particular studies was designed to assess benthic community structure there. Mud Bay is extremely shallow during low tides and many investigators have inadvertently been trapped there when their boats became grounded in soft sediments that resist walking efforts. Anecdotal observations of the Mud Bay area during such times has revealed the presence of numerous deposit- and suspension-feeding bivalves (e.g., *Mya arenaria*, *Macoma balthica*), but the sediments can be muddy one year and have a muddy-sand or sandy-mud consistency the next, making these bivalve communities ephemeral.

The soft sediment of the South Carolina coast, referred to and celebrated by locals as 'pluff mud', can make research difficult in shallow systems such as Mud Bay.

Van Dolah et al. (1984) collected benthos in the same area offshore as Hinde et al. (1981) near the mouth of Winyah Bay but focused on the dredge disposal site. The macrobenthic fauna consisted, species-wise, mostly of polychaete worms, amphipod crustaceans, pelecypod bivalves, gastropod snails, and decapod crustaceans. Numerically the community was dominated by pelecypods with polychaetes being second most abundant, then amphipods and bryozoans. Over 357 invertebrate species or taxa were found in the survey. Neither spatial (station-to-station) nor seasonal differences in abundance were significant.

Aller and Yingst (1985) studied the distribution of solutes around a capitellid polychaete and two bivalve species in Mud Bay and found that these organisms irrigate the sediments in which they live. The resultant transport of dissolved oxygen into reducing sediments makes the habitat suitable for these organisms.

The transport of the planktonic larvae of many benthic species is strongly affected by currents and tides. Stancyk and Feller (1986) provided a mini-review of what is known about larval transport mechanisms for non-decapod invertebrate larvae in estuaries such as Winyah Bay.

The South Carolina Estuarine and Coastal Assessment Program (SCECAP) was started in 1999 by the SC Department of Natural Resources in conjunction with the Department of Health and Environmental Control. It is designed to monitor the health status of the state's estuaries and other tidal waters by periodically (about every 2 years) sampling a variety of related water quality parameters, including macrobenthic fauna, at locations all along the South Carolina coastline. The most recent report by Bergquist et al. (2009) covers the period 2005-2006 and includes coarse results from benthic samples taken in the open water region near the mouth of Winyah Bay. The macrobenthic fauna were dominated by polychaetes, mollusks, and amphipods. Based on the number of species found (species richness), total faunal density (number of individuals), and mathematical measures of species diversity (H') and evenness (J'), the data were assigned a score according to the Benthic Index of Biotic Integrity (B-IBI, Van Dolah et al., 1999). The samples collected in the Bay near the mouth were assessed as Fair, while those collected just outside the Bay were Good. Samples taken in North Inlet were also scored as Good according to the B-IBI. An interesting aspect of the SCECAP is that the same stations are not sampled each time. Rather a probabilistic statistical methodology is used to determine which among the thousands of possible regionalized stations in SC will be sampled each time. For all years between 1999 and 2006 in which different open water stations were sampled farther up the Bay, upper Winyah Bay was among the locations having the most numbers of degraded (Poor) stations in the state. However, the SCECAP's benthos samples are collected outside the NERR boundary in Winyah Bay.

LaSalle et al. (1991) inventoried the flora and fauna of the low intertidal salt marsh that developed on a dredge spoil island area in Winyah Bay. Oligochaetes and polychaetes dominated the assemblages there, one that developed 8 years after unconfined sediments were placed and the other that was only 4 years old. Macrobenthos densities were high in both.

Kamermans et al. (1999) examined shell length and weight relationships for a bivalve (*Macoma balthica*) in the Mud Bay region of Winyah and compared them with those for shells from several other locations on both sides of the Atlantic Ocean. Shells from Winyah Bay were among the largest collected, suggesting that recruitment had not occurred in Mud Bay in recent years, as no small individuals were found.

MEIOBENTHOS IN WINYAH BAY

A collection of benthic foraminifera was made in Winyah Bay by Collins et al. (1995). Using a Van Veen grab sampler and taking subsamples from the 11 collections made along Winyah Bay's main axis, no live specimens were found. Upstream in the Intracoastal Waterway, outside the Bay in the nearshore, and in North Inlet, many living forams were collected. The authors ascribed the absence of living specimens in Winyah Bay to pollution there.

In summary, the benthos of Winyah Bay is undersampled, and no data on benthic communities exist within the NERR boundaries in the Bay. Given the very different hydrographic regime in Winyah Bay compared to that in North Inlet, there are many opportunities to characterize and compare the community structure of macrobenthos, meiobenthos, and microbenthos in a stressed environment (Winyah Bay) with that in an unstressed environment (North Inlet).

» Zooplankton

The spatial and temporal distributions of mesozooplankton in Winyah Bay estuary are more complex than in North Inlet. The taxonomic composition, seasonal patterns, and relative abundance of constituents of both the small- and large-mesh size fractions are largely the same in the high salinity areas of both estuaries during most seasons and years. However, when freshwater discharge from one or more of the rivers increases and the salinity gradient is shortened along the axis of Winyah Bay, there is a net seaward displacement of the typical high salinity inhabitants of the lower Bay toward the ocean with replacement by a less abundant and diverse assemblage of low-salinity forms. Even during average runoff conditions, the salinity at the jetties can vary by 20 or more between high and low tides. During periods of relatively moderate and steady riverine discharge, zooplankton with different salinity preferences vary along the axis of the Bay. General information about zooplankton composition, distribution, and behavior in river-dominated estuaries can be found in Johnson and Allen (2012).

Most of what we know about Winyah Bay zooplankton comes from studies in the early 1980s. In a one-year study (August 1980 – July 1981), collections were made at South Jones and No Man's Friends Creeks (at the connecting points between North Inlet and Winyah Bay) every three weeks. Every other cruise that year was an intensive 24-hour series of bihourly collections at each site. This was known as the Coastal Energy Impact Program (CEIP) Phase I study (Allen et al., 1982). In addition to a focused effort to characterize the zooplankton at those creeks, a companion series of collections was made at six locations extending from the jetties to the lower river every six weeks. Starting in August 1981 (CEIP Phases II & III), a more intensive sampling program provided collections from the original six stations (plus five others) along the axis of Winyah Bay (Allen et al., 1984). Towed 153-micron mesh ring nets and a 365-micron mesh epibenthic sled were used to collect samples about once each month for one year. Collections from this series of stations characterized assemblages throughout the Bay on a single day. In another series (tidal series of CEIP II & III), opening and closing nets (both 153- and 365-micron) were deployed to determine vertical distributions in the lower, middle, and upper Bay once per month. Other CEIP II & III sampling efforts included a 48-hour series which examined tidal and diel changes in abundance, composition, and vertical distributions in the lower Bay in September 1982. Below is a summary of the spatial and seasonal patterns determined in these studies. More details and results from the short-term studies are available in the cited reports.

OVERALL PATTERNS

Zooplankton concentrations varied considerably throughout Winyah Bay, both temporally and spatially. With the small mesozooplankton, the upper bay had fewer and different species present in lower numbers. Relatively few species occurred in both the upper and lower bay regions, and the lower bay more closely resembled nearshore coastal and North Inlet environments (Allen et al., 1982). Seasonal changes occurred throughout the bay, but patterns were not always similar among the upper, middle, and lower bay. Like in North Inlet, copepods dominated the small mesozooplankton community, with the calanoid copepod, *Acartia tonsa*, being the most abundant overall. *Parvocalanus crassisrostris*, *Eurytemora affinis* and *Pseudodiaptomus cornatus* were also common calanoids in Winyah Bay. Among the cyclopoid copepods, only *Oithona colcarva* and *Halicyclops* spp. were common. *Euterpina acutifrons* was the only planktonic harpacticoid copepod which was found regularly in the bay. Other holoplankton which comprised a large percentage of the total number of small mesozooplankton included medusae, rotifers, appendicularians and chaetognaths.

The temporary or meroplanktonic forms consisted mostly of the eggs and larval stages of fish and benthic invertebrates. The most common larvae found were barnacles (nauplii and cyprids), crab zoeae, polychaetes, and mollusk larvae (gastropod and bivalve veligers) (Allen et al., 1984). Many of the less abundant holoplankton and meroplankton were the same taxa found in North Inlet collections.

Mysid shrimps were perhaps the single most important group of large mesozooplankton in Winyah Bay, by comprising over half, and up to 80%, of all organisms collected overall (Allen et al., 1984). Like the North Inlet large zooplankton community, mysids along with amphipods, shrimp and fish larvae, chaetognaths, and hydromedusae were the dominant groups in Winyah Bay. However, the numbers and species of mysids and larval fishes and shrimps can be quite different. For example, a few clupeids, sciaenids, and soles which were abundant in Winyah Bay were rare or absent in North Inlet.

SEASONAL PATTERNS

Small and large zooplankton densities in Winyah Bay peaked in summer and were lowest (typically about 10 times lower) during the coldest months, in large part due to the absence or very low densities of invertebrate larvae from November to March. Copepods comprised at least 60% of the small zooplankton catch from May to November and more than 80% in January and March (Figure 91). *Acartia tonsa* was the dominant copepod throughout the Bay during the warm season.

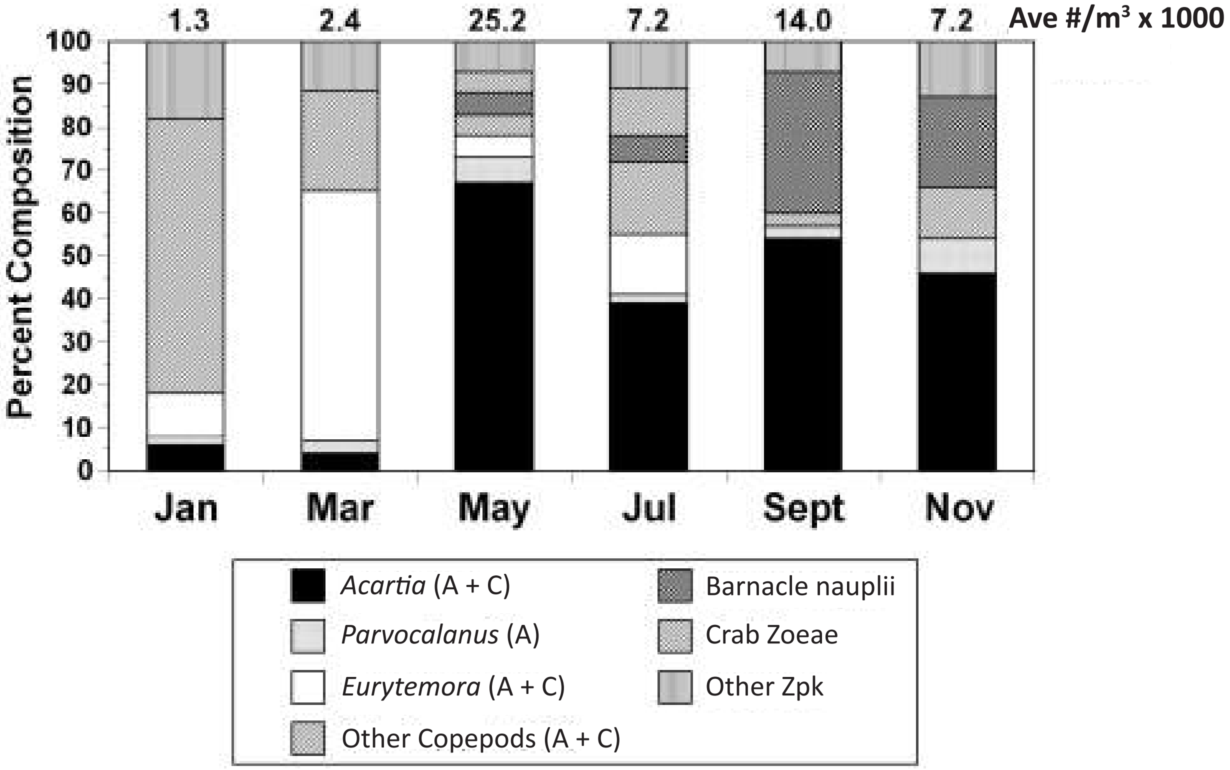


Figure 91. Mean bimonthly composition of small mesozooplankton (153-micron mesh) collected in Winyah Bay on a single date each month (November 1981 – September 1982). Each value is a mean of all 11 stations sampled on that date. Mean abundance of total organisms is located above each bar. Adapted from Fig. 5-8 in Allen et al., 1984.

Parvocalanus crassirostris was abundant in the lower Bay year round, but especially from spring to fall. Other copepods collected near the ocean included *Centropages hamatus* during winter and *Oithona colcarva*, *Pseudodiaptomus pelagicus*, *Labidocera aestiva*, and *Paracalanus parvus* during the warmest months. Other copepods were more important during the winter and spring, especially in the upper Bay where *Eurytemora affinis*, a species that favors low salinity waters, often exceeded *A. tonsa* in abundance. Crab zoeae represented the largest meroplanktonic group during summer, and barnacle nauplii comprised the most important larval group in the fall; neither taxon was collected in January or March (Figure 91).

For large mesozooplankton, mysids (almost entirely *Neomysis americana*) and gammarid amphipods accounted for about 35-95% of the catches during the year, with especially large proportions occurring from September to March (Figure 92). Shrimp larvae, crab megalopae, and fish larvae were the major meroplankters from spring to fall. 'Others' including *Lucifer*, *Acetes*, isopods, and cumaceans comprised a particularly large proportion of the catch in May. Although chaetognaths were common especially during summer in the lower bay, they were not enumerated in the CEIP studies. Hydromedusae were not enumerated, but their densities during spring and summer, particularly in channels in the mid bay, were very high, with more than one liter of jellyfish occurring in some tows.

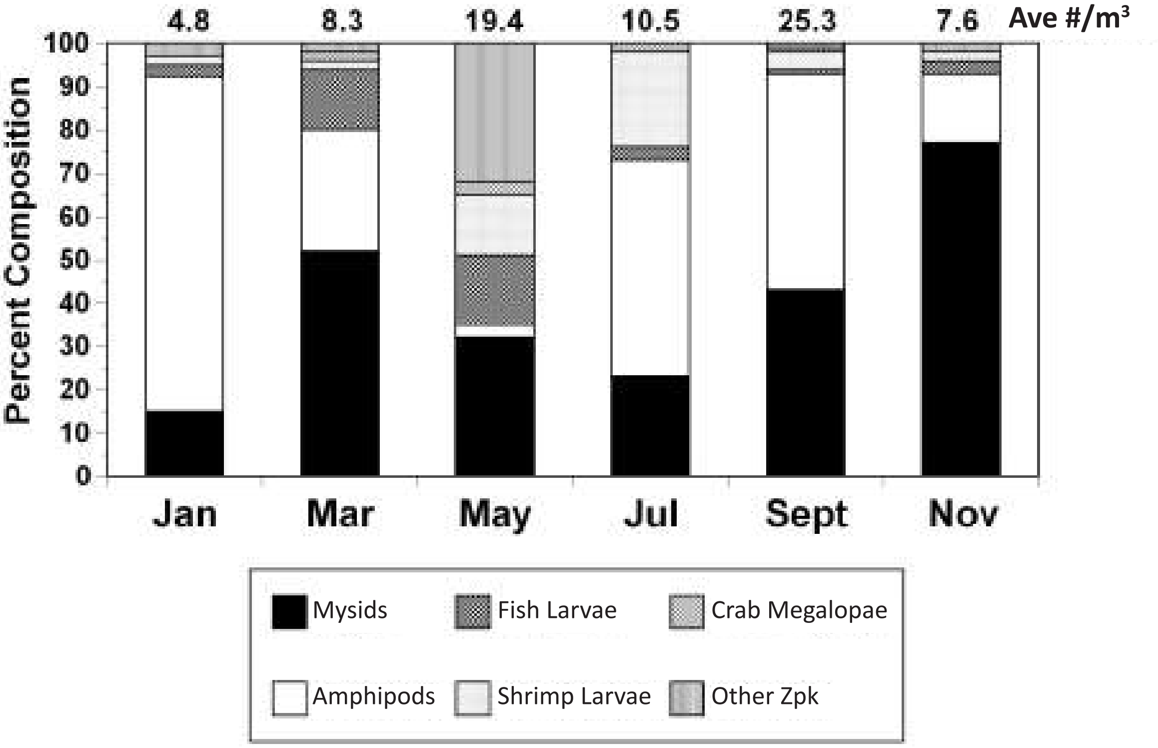


Figure 92. Bimonthly mean composition of large mesozooplankton (365-micron mesh) collected in Winyah Bay on a single date each month (November 1981 – September 1982). Each value is a mean of all 11 stations sampled on that date. Mean abundance of total organisms is located above each bar. Adapted from Fig. 6-1 in Allen et al., 1984.

SPATIAL PATTERNS IN TAXON DENSITY AND DIVERSITY

Small mesozooplankton diversity was greatest in the lower bay where 15-31 taxa occurred throughout the year. The middle bay taxon diversity was most variable with 8-28 categories, and the upper bay had the least on almost every cruise with 8-20 taxa. Total small zooplankton densities were lower in the upper bay with annual means of 6,000-9,700 m^{-3} compared to 8,000-13,000 m^{-3} for the lower bay (Figure 93). Diversity of large zooplankton was also highest near the ocean. However, total densities of large animals did not show the same decreasing pattern toward the riverine end of the gradient exhibited by total small zooplankton. Instead, rather consistent differences in density occurred among sites, with some stations in all three zones being much lower than other nearby stations (Figure 94). Based on the less complete list of enumerated taxa, most Winyah Bay densities were 2-15 m^{-3}, and the peak was 147 m^{-3}. Data in the CEIP II & III report for individual taxonomic categories makes it possible to make density comparisons for them between the estuaries.

Comparisons of average proportions of the major taxa showed that most were widely distributed throughout the Bay. *Acartia tonsa* accounted for ~ 10% at the most oceanic site and reached highest densities in the intermediate salinity areas of the middle bay, but this species often accounted for 30-70% of the total in the upper bay (Figure 93). *Parvocalanus crassirostris* was generally restricted to the lower half of the bay and *Eurytemora affinis* to the upper half during their periods of occurrence.

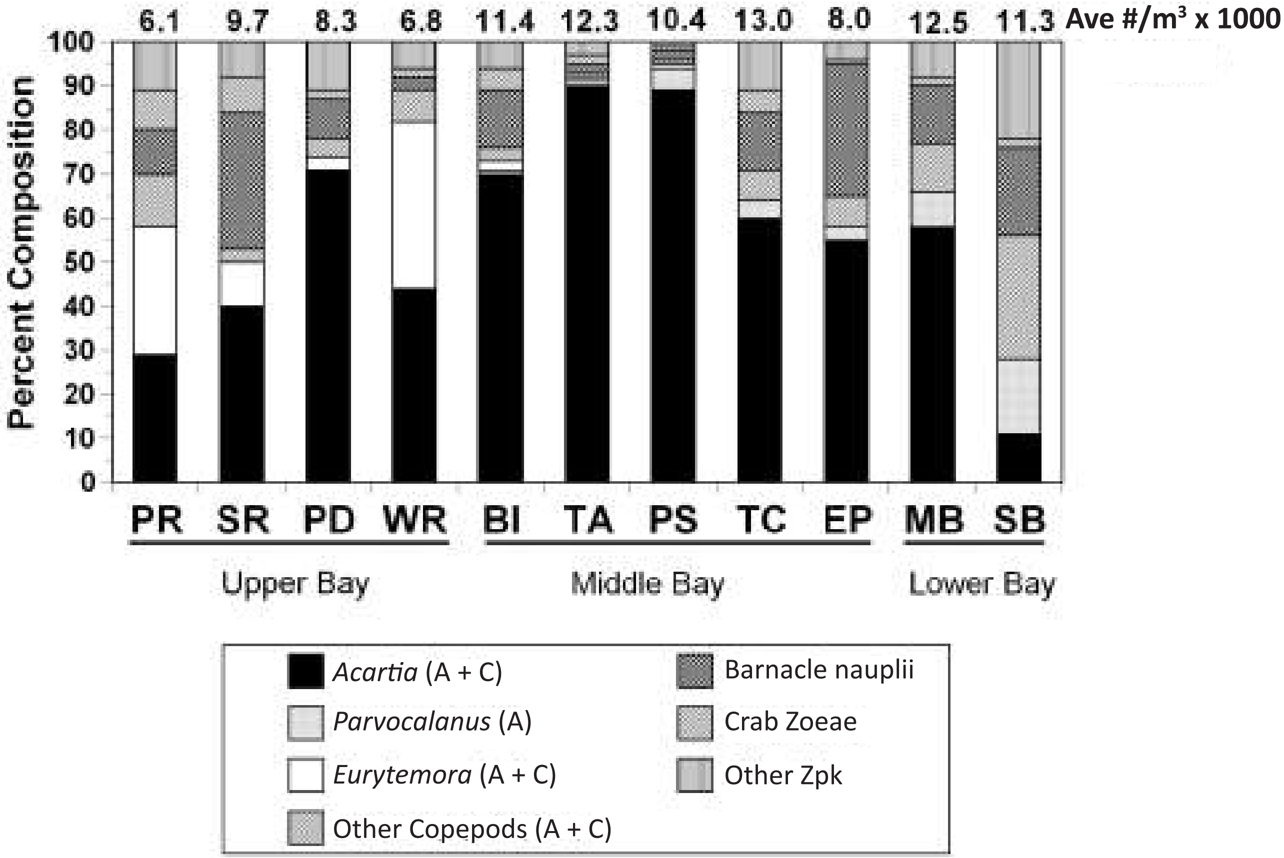


Figure 93. Mean sampling station taxon composition of small mesozooplankton (153-micron mesh) collected at 11 sites in Winyah Bay. Each value is a mean of collections made on all dates (November 1981 – September 1982). Mean abundance of total organisms for each station for all dates is located above each bar. Adapted from Fig. 5-7 in Allen et al., 1984.

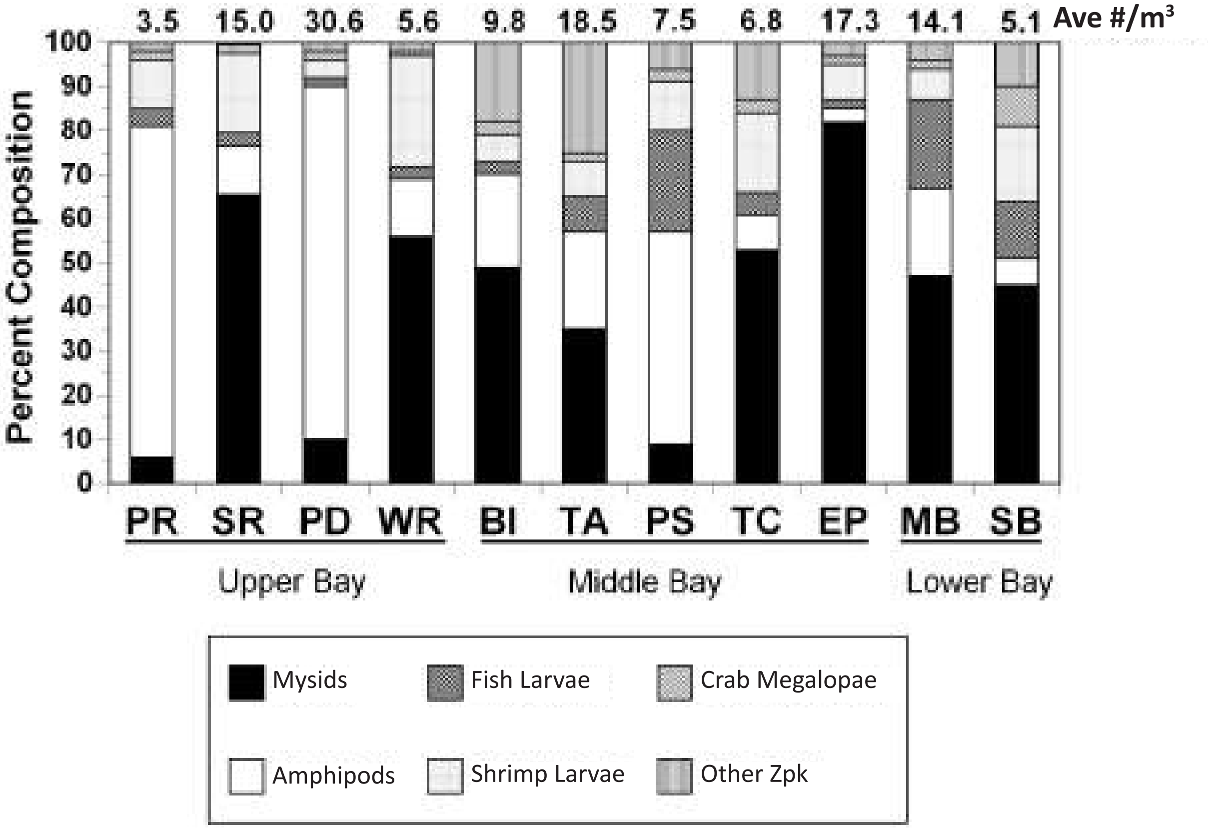


Figure 94. Mean sampling station taxon composition of large mesozooplankton (365-micron mesh) collected at 11 sites in Winyah Bay. Each station value is a mean of collections made on all dates (November 1981 – September 1982). Mean abundance of total organisms for each station for all dates is located above each bar. Adapted from Fig. 6-2 in Allen et al., 1984.

Barnacle nauplii and crab zoeae were widely distributed in the Bay. For the large zooplankton, high salinity types including chaetognaths, *Lucifer*, *Acetes*, isopods, and cumaceans did not occur in the upper bay. Many types of shrimp larvae, fish larvae, and crab megalopae were collected along the salinity gradient as various stages followed recruitment patterns into and out of the estuary (Figure 94). Recent studies by R. Brodie, R. Tankersley, R. Styles, and S. Borgianini and their students have examined behavioral and hydrographic mechanisms that enable fiddler crab megalopae to recruit in an upstream direction to upriver settling sites.

WATER COLUMN AND TIDAL PATTERNS

Bimonthly surface-bottom mesozooplankton collections were made at 3 stations, representing the 3 regions (upper, mid, and lower) of Winyah Bay in 1981-1982. In addition, one day-night 48-hr study was made at the mouth of the bay in September 1982. These studies indicated that there were no significant differences between surface and bottom densities (number per cubic meter) of total small zooplankton; however, there were significant taxon-specific differences observed in both short-term studies. During their peak abundances in the warm months, both adult and copepodid stages of *Acartia tonsa* had higher bottom densities than the surface waters during the day (Allen et al., 1984). *Pseudodiaptomus coronatus* had higher densities in bottom waters but barnacle nauplii were more abundant in surface waters. No vertical differences were observed for *Parvocalanus crassirostris*, but they were most abundant at high tide. As for the large zooplankters, higher densities for most categories occurred on the bottom, especially during strong current velocity conditions. Fish larvae were the most important group in surface collections, especially at slack tide (Allen et al., 1984).

LONG-TERM PATTERNS AND ISSUES

Because there are neither recent nor continuing studies of zooplankton in Winyah Bay, we cannot address the potential impacts of human activities or climate change in one of the nation's largest estuaries. If the global pattern of increasing ENSO events continues, and local rainfall and runoff patterns change, we could expect a compression of the salinity gradient (the zone between freshwater and oceanic water) within Winyah Bay, because higher river discharges would push and shift much of the mixing zone outside of the jetties. The effect of this water mass displacement on larval recruitment processes could be significant if current and salinity patterns are not favorable for species that require marsh habitats to complete development. Because many economically and ecologically important estuarine invertebrates (e.g., penaeid shrimps, blue crabs, clams) and fishes (e.g., red drum, spotted seatrout, flounder, mullets) use shallow marsh nursery areas in the middle bay, major alterations in salinity and temperature regimes could affect the abundance, growth, distribution, and other characteristics of these populations in Winyah Bay.

» Nekton

The nekton community in Winyah Bay is abundant, diverse, and dynamic, more so than in North Inlet. Differences are mostly related to the strong effects of the rivers on freshwater inflow and salinity. With a long axial salinity gradient, deeper channels, more expansive shallow subtidal bottoms, and a greater variety of wetland types, Winyah Bay provides habitat for many species that are uncommon or absent in North Inlet.

Much of what is known about the nekton in Winyah Bay comes from two studies. Wenner et al. (1981) conducted a bay-wide trawl study that included 5 stations along the main stem of the estuary and one additional station in each of the four rivers; a complete range of salinities was represented on each sampling date. In another study, the large creeks connecting the Mud Bay section of Winyah Bay and North Inlet (Allen et al., 1982) were sampled. This study used trawls, epibenthic sleds, and gill nets to collect nekton in No Man's Friend and South Jones Creeks; salinities here were typically brackish to high (24 – 32). Other information provided in this section comes from occasional scientific collections and observations from local recreational and commercial landings.

COMMON FISHES, SHRIMPS, AND CRABS

The majority of nekton taxa that occur in the high salinity, salt marsh-dominated North Inlet system also occur in the southern portion of Winyah Bay closest to the ocean. Comparisons between the lists of species collected in surveys of both estuaries indicate a high degree of overlap (**Appendix E**). Direct comparisons of relative abundances and size distributions cannot be made because of differences in the types of sampling gear and the timing of the collections in the two estuaries. Nevertheless, seasonal patterns of occurrence and associations with particular habitats (e.g., marsh, shoreline, and subtidal channels near the inlet) are similar for those species that favor high salinities. Species diversity is higher in lower Winyah Bay than in the middle and upper regions of Winyah Bay. Table 12 lists species which were collected in Winyah Bay but were absent from or uncommon in North Inlet and lower Winyah Bay. As is the case in North Inlet, most species found in lower Winyah Bay were represented by larval or juvenile life stages (Wenner et al., 1981).

DOMINANT SPECIES

Star drum (*Stellifer lanceolatus*) was the most abundant of 77 species of fishes and motile macro-invertebrates collected in the two-year trawl study of the bay (Wenner et al. 1981). It was especially abundant during the fall at locations between the lower and middle regions of the Bay. Curiously, the star drum is a rare fish in North Inlet, occurring in less than one percent of all of the collections made with various gear types during the past 30 years. Only a few small juvenile star drum were caught in trawls in the creeks, especially in the southern part of the system. The star drum is known to spawn from spring to fall along the Atlantic coast. Large star drum are found in the Bay in the spring, and much higher numbers of juveniles occur in the same area in the fall. Star drum appears to be more

Table 12. Partial list of fish species that occur in Winyah Bay but are uncommon or absent from North Inlet. Most of these were documented in the DNR trawl study conducted in 1977-78 (Wenner et al., 1981). Salinity ranges are defined as high (30-35), brackish (15-29), low (3-14) and freshwater (<2).

Common Name	Scientific Name	Salinity Range
star drum	*Stellifer lanceolatus*	high to low
white perch	*Morone americana*	brackish to fresh
striped bass	*Morone saxatilis*	brackish to fresh
white bass	*Morone chrysops*	brackish to fresh
longnose gar	*Lepisosteus osseus*	brackish to fresh
white catfish	*Ameiurus catus*	brackish to fresh
channel catfish	*Ictalurus punctatus*	fresh
blue catfish	*Ictalurus furcatus*	brackish to fresh
flat bullhead	*Ameiurus platycephalus*	fresh
brown bullhead	*Ameiurus nebulosus*	fresh
American shad	*Alosa sapidssima*	high to fresh
blueback herring	*Alosa aestivalis*	brackish to fresh
Atlantic sturgeon	*Acipenser oxyrhynchus*	brackish to fresh
shortnose sturgeon	*Acipenser brevirostrum*	brackish to fresh
redear sunfish	*Lepomis microlophus*	fresh
warmouth	*Lepomis gulosus*	low to fresh
redbreast sunfish	*Lepomis auritus*	fresh
largemouth bass	*Micropterus salmoides*	low to fresh
common carp	*Cyprinus carpio*	fresh
hogchoker	*Trinectes maculatus*	high to fresh

of an open water fish than the spot (which is also very common); it tends to be collected in deeper water such as channels rather than along the edges of marshes.

Atlantic croaker (*Micropogonias undulatus*) is common throughout the Winyah Bay estuary, and can be considered a resident species. It is especially abundant in early and mid-summer when small croaker that recruited as larvae the previous fall occur across a wide range of salinities and regions of Winyah Bay. In general, Atlantic croaker appears to be more common in the middle than in the lower bay, and juveniles can be found in very low salinities. Steady growth of young-of-the-year Atlantic croakers is evident from winter through fall. One-year-old-plus Atlantic croakers are also found in Winyah Bay during all seasons. This drum has a strong affinity for the bottom, but occurs from the deepest channels to the shallowest subtidal creeks and flats. Unlike the spot which is also very abundant (especially in shallow water in the mid and lower bay), the Atlantic croaker does not make excursions into the high intertidal flats and marshes at high tide. Atlantic croaker was much more abundant than spot in the channels sampled in the trawl study, but spot was the most abundant demersal fish in the creeks connecting the two estuaries. Spot was the most abundant demersal fish in North Inlet.

Hogchoker (*Trinectes maculatus*) is probably the most abundant and widely dispersed flatfish in Winyah Bay. However, its distribution is skewed toward the low salinity end of the system. The hogchoker is a year round resident. During summer, adults occur in the high salinity areas where they spawn and then move up the bay to freshwater.

Blue catfish (*Ictalurus furcatus*), an introduced species to the rivers of Winyah Bay, commonly occurs in salinities up to 10 in the upper and middle bay. White catfish (*Ictalurus catus*) favors the lower salinity areas of the upper bay. Catches of both catfishes in Winyah Bay tend to be highest in winter and spring following high river discharge; the distribution of these and other freshwater fishes shifts up the rivers in summer.

Atlantic menhaden (*Brevoortia tyrannus*) is also a year-long resident in Winyah Bay. This pelagic filter feeder is most abundant in the lower bay, but schools of juveniles occur far up the salinity gradient during the warmest seasons. Densely packed schools of medium and large menhaden are common and conspicuous features in the lower bay in all but the coldest months. Adults move into the coastal ocean to spawn in the fall, and larvae recruit during winter. Large schools of juvenile menhaden are often observed in shallow subtidal areas such as Mud Bay throughout the summer.

Blue crab (*Callinectes sapidus*) occurs from the shallow fringes to the deepest channels during all seasons. Adult blue crabs mate in the upper bay and egg-bearing females migrate toward the ocean where they release larvae. Females with egg masses have been collected from early spring to late fall. Once they have mated and moved to high salinity areas, they stay there. Males remain in the brackish and lower salinity reaches of the bay where they are sought by commercial trappers as the largest and most valuable members of the species. Most blue crabs live less than three years. Young blue crabs tend to favor the shallowest areas and occur across a wide range of salinities and habitat types.

A female blue crab, *Callinectes sapidus*

Penaeid shrimps constitute the most valuable fishery in the Winyah Bay area. White shrimp (*Litopenaeus setiferus*) larvae arrive from coastal ocean spawning grounds starting in May. The production of larvae continues until early summer. Juveniles grow quickly in the productive shallow expanses of the middle and upper bay. The first subadults move into the ocean in mid-summer, signalling the beginning of a directed commercial fishery that continues until early winter. This movement of white shrimp from the estuarine nursery to the ocean continues until mid-fall. Upon reaching adulthood in the ocean, white shrimp produce larvae that move into the estuary, thus completing the cycle. Young white shrimp overwinter in the deeper parts of the estuary and ocean where they grow slowly until spring, then they produce the next summer generation. Major freshwater inflow events such as those associated with tropical storms in the summer and fall are known to move small shrimp out of Winyah Bay prematurely.

The brown shrimp (*Farfantepenaeus aztecus*) also recruits from the ocean, but larvae arrive during winter. Juveniles favor higher salinity areas than the white shrimp and most juveniles leave the estuary as subadults by mid-summer. Brown shrimp comprise the early season penaeid fishery harvest, and the more numerous white shrimp comprises the mid-summer and fall crop. The pink shrimp (*Farfantepenaeus duoarum*) is generally the least common of the three species and often comprises <5% of the commercial catch. The occurrence of relatively high numbers in the DNR trawl study might indicate a tendency for them to remain in the deeper portion of estuaries. White and brown shrimp are much more common in shallow subtidal bottoms. The pink shrimp's seasonal distribution is similar to that of the white shrimp.

American shad (*Alosa sapidissima*) adults arrive from over-summering areas in New England waters every winter. They traverse the salinity gradient *en route* to spawning areas far up the rivers. After spawning, most adults return to the ocean. In spring, juvenile American shad move downstream and occur in brackish areas for the first year or two before joining the adult population in its migration up the Atlantic coast. There is evidence that, like salmon, American shad return to the estuaries/rivers from which they originated. The commercial fishery usually begins in January. Gill netters favor female shad with ripe ovaries (roe). American shad has comprised an important local fishery in Winyah Bay for more than a century, and it is the only finfish that is commercially harvested from the estuary.

Atlantic sturgeon (*Acipenser oxyrinchus*) also uses Winyah Bay as a nursery. Adults move long distances from the coastal ocean to freshwater streams where they spawn in the spring. Juveniles produced far into the river systems spend several years in the estuary. Individuals up to six feet in length have a curious habit of sky rocketing out of the water from time to time and reports of leaping sturgeons are common in Winyah Bay. These bony-plated fish are bottom feeders. Adults were intensively harvested to produce caviar until the 1970s. With individuals capable of reaching more than 50 years of age and females not reaching maturity until about age 15, recovery of the population has been slow. Harvesting has been prohibited since the late 1970s. The shortnose sturgeon (*Acipenser brevirostrum*), which is less common in Winyah Bay, is also listed as an endangered species.

Striped bass (*Morone saxatilis*) is a year-round resident of the Winyah Bay system, but remains in the rivers from spring to fall. Spawning takes place in freshwater and juveniles develop there. Older juveniles and adults move into the upper and middle reaches of the estuary, including Mud Bay and the Western Channel, in the late fall, but only during years when freshwater inflow is high. They can remain in low salinity waters throughout the winter months before moving upstream. Unlike striped bass populations from NC and northward, SC striped bass do not migrate to the ocean and almost no exchange is thought to occur among estuaries. White perch (*Morone americana*), a close relative of the striped bass, is common along low-salinity and riverine shorelines, especially at the mouths of creeks and old rice field canals. They are year-round residents that do not occur in the middle or lower bay.

Bay anchovy (*Anchoa mitchilli*) appears to be widely distributed along the salinity gradient and is likely one of the most abundant fishes occupying the open waters of Winyah Bay in all except the coldest months. Striped mullet (*Mugil cephalus*) is ubiquitous and conspicuous in the estuary, and multiple year-classes occur in the shallow waters, especially during the warmest seasons.

SEASONAL PATTERNS

Species diversity and abundance of nekton is highest during summer and early fall and lowest during the coldest months. Patterns of seasonal change described for the salt marsh and shallow-water nekton in North Inlet are similar for the same species in Winyah Bay. Catfishes, hogchoker, Atlantic croaker, and blue crab are among the most abundant of the channel-dwelling nekton throughout the Bay from spring through fall. Anchovies, Atlantic menhaden, and striped mullet account for much of the sharp increase in fish abundance in the water column and shallow portions of the Bay in summer and fall. During summer, penaeid shrimps, star drum, and blue crabs can be among the most numerous nekton in the main channels. Sharp decreases in transient species mark the beginning of winter when Atlantic menhaden, Atlantic croaker, and white catfish are among the most common inhabitants especially in the deeper channels. Except for species represented by early life stages that recruit from offshore, transient species diversity and abundance remains low in spring.

HABITATS AND FACTORS INFLUENCING DISTRIBUTION

Habitat types in Winyah Bay include the same kinds of salt marshes, intertidal creeks, and low energy shorelines found in North Inlet. However, this much larger system is dominated by open water rather than the large subtidal creeks that occur in the marsh-dominated North Inlet system. A wider range of habitats including deep (>8 m) channels, wider expanses of shallow subtidal habitats, steeper marsh edge shorelines, and a variety of marsh types along the long salinity gradient account for a greater diversity in the nekton in Winyah Bay.

Occasional collections with seines, trawls, and gill nets as well as angling experiences and reports from other anglers, indicate that many of the species familiar in higher salinity areas also occur well up the bay. Red drum, southern flounder, and striped mullet are sometimes caught in very low salinity waters far up the rivers. Black drum and sheepshead are regularly caught in low salinity waters in the upper bay during summer. Studies in other river-influenced estuaries indicate that small juvenile spot, southern flounder, Atlantic croaker, and Atlantic menhaden move far up the salinity gradient in the spring. American eels are much more abundant in Winyah Bay than in North Inlet, and adults spend several years in the rivers before migrating to mid-ocean spawning areas.

The DNR trawl study showed that high salinity areas of the bay yielded more nekton and were richer in species than locations further up the bay. The lowest values occurred in the tidal freshwater sections of the Black, Pee Dee and Waccamaw Rivers. The up-estuary sites had the lowest and least variable salinities. Rapid and major changes in salinity occur in the middle and lower bay after extended periods of rainfall and freshwater runs off the watershed into the rivers. Brown-stained, low-salinity water can extend into the lower bay and brackish conditions can occur outside of the jetties for days or weeks at a time. Such conditions displace high-salinity species to the ocean until more typical conditions are re-established.

Of course, other environmental conditions can influence nekton distribution in the area. Water clarity, dissolved oxygen, concentrations of dissolved and particulate materials, current velocities, availability of food, and presence of predators are among the many factors known to affect nekton distributions. Effects of pollutants and habitat modification, including the frequent dredging of navigation channels, are largely unknown but health advisories based on mercury content in some tidal freshwater species persist. Due to the complex and dynamic nature of aquatic environments and the difficult challenges associated with detecting movements and abundances of motile nekton, our knowledge of the effects of changing environmental conditions on nekton in Winyah Bay is insufficient.

» Reptiles, Amphibians and Mammals

A greater diversity of reptilian and mammalian species occur in and around Winyah Bay than in the North Inlet area. Of course, we might expect differences in the distributions and relative abundances of many of the species to occur due to the greater variety of habitat types along the Bay's salinity gradient. In addition, some species seen in the open waters and brackish marshes of Winyah Bay have not been sighted in the high-salinity, marsh-dominated North Inlet system. More complete information about the ecology and distributions of many of the following species can be found in Sandifer et al. (1980).

Loggerhead sea turtles, and less frequently juvenile green sea turtles, have been spotted from the jetties to the low-salinity waters of the Sampit River. Diamondback terrapins appear to be less abundant in Winyah Bay marshes and waterways than in North Inlet. Several turtles typical of freshwater are sometimes sighted in low-salinity marshes and waterways; these include the common snapping turtle (*Chelydra serpentina*), Florida cooter (*Chrysemys floridana*), yellowbelly slider (*Chrysemys scripta*), and chicken turtle (*Deirochelys* *reticularia*). The eastern mud turtle (*Kinosternon subrubrum*) and eastern box turtle (*Terrapene carolina*) are often observed on the uplands around old ricefields and low salinity marshes on the western and southern margins of Hobcaw Barony. Several other turtle species more typical of ponds are occasionally found around Winyah Bay.

Snakes commonly found in and around low-salinity marshes of Winyah Bay include the cottonmouth, banded water snake, eastern mud snake, rainbow snake, and yellow rat snake. The distributions and habits of these and other more terrestrial species including the canebrake rattlesnake, black racer, corn snake and green snake are described in more detail in the section on North Inlet reptiles and amphibians.

The American alligator is the most conspicuous reptile inhabiting the marshes, shorelines, canals, creeks, and open waters of Winyah Bay. Although they stray toward the ocean end of the estuary, alligators are most likely to be found in the low-salinity and freshwater areas of the upper bay. Under protection from hunters since the 1970s, alligators have become common in some areas. Individuals up to about 10 ft (3 m) live in tidally-influenced rice field canals and impoundments, and it is not unusual to see large individuals swimming across Winyah Bay.

Few amphibians are found outside of freshwater habitats, but the southern leopard frog (*Rana sphenocephala*) is sometimes observed in low-salinity marsh areas (Martof et al., 1980). The two-toed amphiuma (*Amphiuma means*) has been collected in traps in low-salinity rice field canals associated with Winyah Bay.

Among the aquatic mammals, the bottlenose dolphin is the most abundant, with groups of a few to ten or more moving throughout the bay especially during the summer months. Dolphins are most likely to be seen around the jetties and sometimes many dozens can be observed feeding on by-catch behind active shrimp trawlers outside the jetties. In most years a West Indian manatee is spotted in the Sampit River, but these are stray individuals which only remain in the area for days to weeks during coast-wide migrations. River otters occur near marshes from near the ocean to the tidal freshwater reaches of the Bay. Beavers are found almost exclusively around freshwater streams draining into tidal freshwater marshes. It is noteworthy that neither the muskrat nor the nutria, small mammals that are common in more southern and northern marshes, occurs in the Winyah Bay area.

Terrestrial mammals sighted on the barrier islands include raccoon, feral hog, white-tailed deer, gray fox, red fox, bobcat, raccoon, Virginia opossum, beaver, marsh rabbit, cottontail rabbit, gray squirrel, southern fox squirrel, southern flying squirrel, red bat, eastern wood rat, marsh rice rat, and cotton rat. These and several species of moles, voles, and shrews also occur in upland areas adjacent to marshes along brackish and freshwater marshes farther up the Bay. Although the following species are known to occur in coastal South Carolina, we are not aware of records of striped skunk, long-tailed weasel, and various other rats, mice, and voles (Webster et al., 1985). A survey using capture techniques in preferred habitats would likely document the occurrences of other mammals in the terrestrial systems around Winyah Bay.

» Birds

Much of the bird work directly tied to Winyah Bay was conducted on Pumpkinseed Island. This small 9-ha low elevation, tidally inundated island is situated in the shallow Mud Bay portion of Winyah Bay and historically hosted one of the largest wading bird colonies in the South Carolina. It was used by wading birds from at least the late 1960s through the 2002 breeding season. White Ibises, *Eudocimus albus*, were among the most numerous of the nesting waders during most years with over 20,000 nests counted in 1987 (Shepherd et al. 1991.) Other waders that utilized the island included Great Egrets, Snowy Egrets, Tri-colored Herons, and Glossy Ibises. Nest counts were conducted annually by Baruch investigators by ground surveys and/or aerial flights during the breeding season from 1979-1991. Aerial censuses of the wading bird colony were conducted by the South Carolina Department of Natural Resources Department (SCDNR) in the early 1990s through 2011. No wading bird nesting activity was noted on Pumpkinseed Island on any of the annual surveys conducted by SCDNR 2003-2011, indicating that the site was not used after the 2002 nesting season (C. Hand, personal communication). Figure 95 shows the number of breeding pairs of White Ibises on Pumpkinseed Island over the survey years, 1979-2003.

During the heyday of wading bird nesting on Pumpkinseed Island, ornithologists and graduate students flocked to the site to carry out research. Peter Frederick, a student in pursuit of a doctorate, spent long hours over five breeding seasons (1979-1983) on the island investigating various aspects of the mating behavior and mating strategies of White Ibis (Frederick, 1985). Frederick observed ibises from a portable 1x1x4 m tall burlap – covered blind camouflaged with needlerush. He was able to recognize individual ibises by distinct facial features, particularly the outline of the border between facial skin and feathers. In his dissertation and in a subsequent publication, Frederick described extrapair copulations (EPC) in this otherwise monogamous species and presented potential costs and benefits of this strategy (Frederick, 1985 and 1987a). EPCs were found to be a frequent and regular occurrence in White Ibises, with one-third to one-half of all observed copulation attempts between members of different pairs. Almost 93 % of all males and 96% of all females were involved in EPCs at least once. Frederick estimated that EPCs could result in fertilization of about 6% of the eggs. Responses of male White Ibises to their mate's EPCs were also observed and recorded (Frederick, 1987b.) In this study, no evidence of physical attacks by males on their mates, abandonment, or reduction of parental care as a result of EPCs was observed.

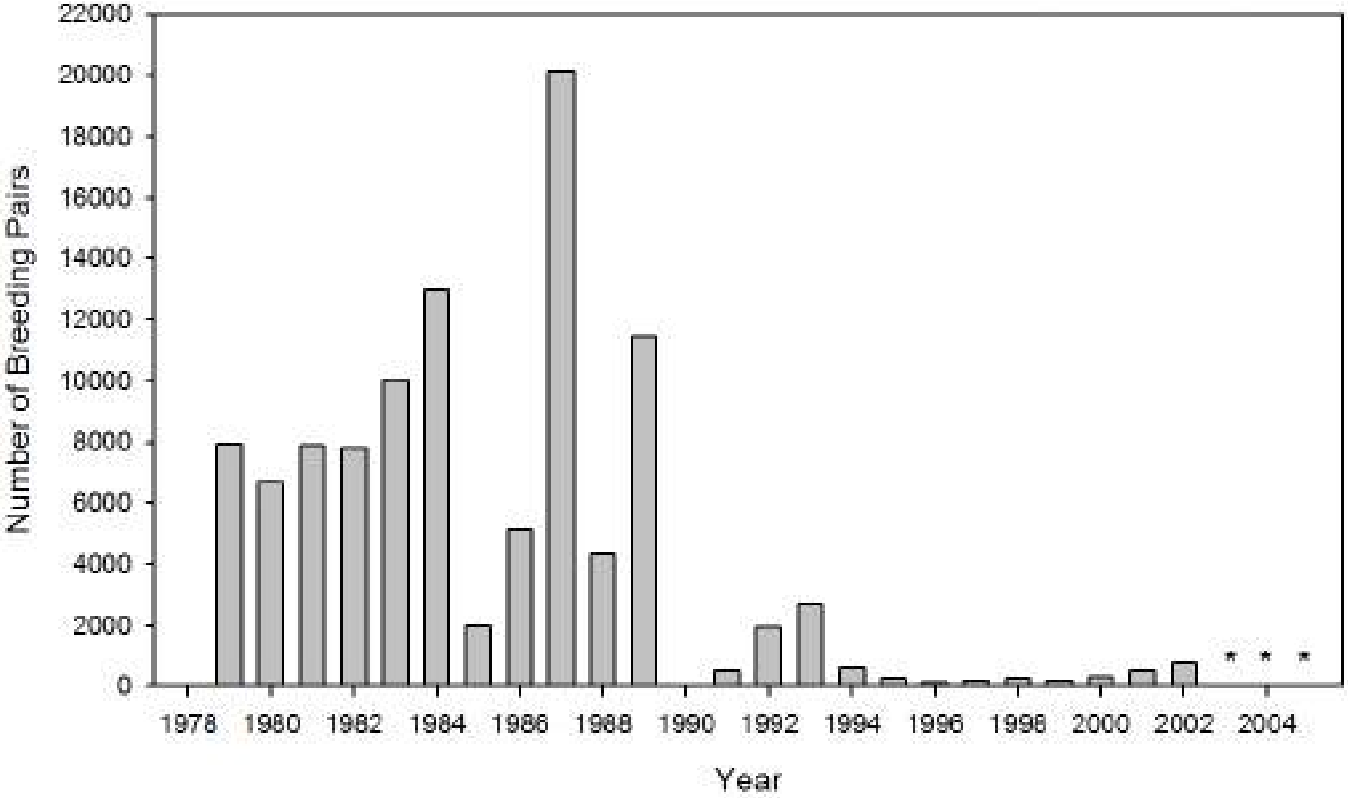


Figure 95. White Ibis nesting pairs on Pumpkinseed Island. None were observed during surveys conducted in 2003, 2004, 2005 or in subsequent years.

In a study of White Ibis mating behavior, individual ibis could be recognized by distinct facial features, particularly the outline of the border between facial skin and feathers.

Frederick (1987c) also investigated the impacts of tidal washovers on nesting White Ibises over five breeding seasons, 1980-1984. Aerial nest surveys were conducted before and after destructive tide events during each breeding season. Sixty-one percent of the nest starts were abandoned during or immediately following extremely high tides during this five year period. Tides high enough to wash over nests occurred at least once each season. Based on ground observations of the reactions of ibises to tidal inundations, eggs often floated out of nests or were washed out by wave action. Marked eggs known to have been covered with water for more than an hour during early incubation later hatched. Frederick pointed out that despite a history of destructive washovers, Pumpkinseed Island continued to support a stable population of White Ibises. Frederick suggested that other factors such as food abundance and low predator densities may be more important in determining site fidelity than breeding failure caused by tidal inundation.

Factors affecting the breeding success of White Ibises were further investigated by Bildstein et al. (1990). Breeding numbers of ibises, reproductive success, adult foraging behavior, nestling diets and rainfall were analyzed for two major White Ibis colonies in the state. White Ibis nesting pairs on Pumpkinseed Island were relatively constant with 6,000-8,000 pairs during the first four years of the study, 1979-1982. They increased in 1983 and 1984 to 12,973 and 13,763 pairs respectively and then declined to less than 2,000 pairs in 1985. This decline occurred even though similar numbers of ibises returned to the North Inlet – Winyah Bay area in late March and early April of 1985 and 1984. In 1986, more than 5,000 pairs bred on Pumpkinseed Island. Over 13,000 pairs of ibises bred on Drum Island near Charleston, SC in 1984, while fewer than 1,000 pairs nested in 1985. At Pumpkinseed Island, the peak number of ibises flying inland to feed in freshwater swamps was higher in 1984 than in 1985 or 1986. Nestlings were still being fed large numbers of crayfish into late June – early July in 1984 while in 1985 and 1986, crayfish were not a significant portion of the diet late in the breeding season. Ibises switched from feeding their nestlings crayfishes to feeding them mainly fiddler crabs in 1985. Starved, desiccated and seemingly abandoned nestlings were also observed in the Pumpkinseed colony during 1985 while none were seen in this condition in 1984. A regression analysis comparing rainfall to colony size showed that more ibises nested in wet years than in dry years and that variation in rainfall six months preceding hatching explained 71% of the annual variation in the maximum number of ibises nesting at the site. The authors suggested that declines in the nesting numbers and reproductive success at the two colony sites resulted from reduced availability of crayfishes during dry periods. These findings demonstrated the importance of freshwater wetlands and prey for breeding White Ibises.

Aerial surveys were used to investigate the impacts of tidal washovers on nesting White Ibises.

Johnston and Bildstein (1990) conducted a controlled experiment in summer 1985 designed to examine the hypothesis that ibis parents fly long distances (as observed with ibises nesting on Pumpkinseed Island) to secure freshwater prey for their young because nestlings cannot develop normally on brackish water prey. Nestlings from Pumpkinseed Island were collected and brought to the Baruch Marine Field Laboratory for the experiment. They were provided one of three different diets: unaltered crayfish, fiddler crabs, or crawfish soaked in brine to the approximate salt level found in fiddler crabs. During the first seven days of the feeding experiment, nestlings fed the unaltered crayfish diet gained significantly more mass than nestlings fed one of the saltier diets. Nestlings on the fiddler crab and salty crayfish diet lost approximately 3% of their body mass per day until freshwater instead of brackish water was made available to them at day 7 of the experiment. The authors concluded that nestling ibises can only tolerate high salt diets if freshwater is made available to them. The results also supported the hypothesis that ibises fly long distances inland to obtain freshwater prey for their young.

The movements of individual adult White Ibises were tracked over three breeding seasons, 1987-1989 (DeSanto et al. 1997). Adults captured on the Pumpkinseed nesting colony were equipped with backpack radiotelemetry units and were monitored from the ground and from fixed-wing aircraft. Individuals caring for pre-fledged young travelled to freshwater swamps, abandoned rice fields, impoundments and ponds, with distances ranging from 4-32 km from the colony site. Regurgitant and fecal samples collected at the colony site from the young of radiotelemetered adults contained bony fish, crayfish and insects. Salt marshes 2-5 km from the colony were visited less often. After the young fledged or nests failed, ibises decreased visits to freshwater habitats and doubled their relative use of salt marshes for foraging. DeSanto et al. (1990) also investigated the behavioral development of nesting White Ibises. DeSanto observed a total of 17 hand-reared White Ibis nestlings in 1986 and 1987 and also observed 400 parent-reared nestlings on Pumpkinseed Island 1985-1988, focusing on their physical characteristics and behavioral development. Radiotelemetry units were also placed on eight 25-31 day-old juveniles to determine when they leave the colony site to forage on their own. These birds left between 47-56 days of age. Similar plumage and behavior development was observed in hand-reared and parent-reared nestlings. In both cases, individual variation in bill markings and also begging calls was noted. The authors suggested that these individual differences may enable parent birds to locate and preferentially care for their young that leave the nests after about 15 days and live in groups or “crèches” of at least 30 similar aged birds.

Hurricane Hugo, a category 4 storm, ravaged the South Carolina coast in September 1989. Shepherd et al. (1991) examined the impact of Hurricane Hugo on the breeding ecology of wading birds at Pumpkinseed Island. They reported that damage to the vegetation on the island was slight overall, with the greatest damage to shrubs used by nesting Great Egrets and Snowy Egrets versus grasses and needlerush used by Tri-colored Herons, Glossy Ibises and White Ibises. The number of nesting pairs of Great Egrets and to a lesser extent Tri-colored Herons decreased after the storm while Snowy Egrets increased. Most dramatically, however, zero White Ibis nested on Pumpkinseed Island in 1990 when over 10,000 pairs had nested there in spring 1989. The authors suggested that Hurricane Hugo disturbed local freshwater feeding sites and reduced the availability of crayfish that the adults need to feed their young.

In the years following Hurricane Hugo, wading birds continued to use Pumpkinseed Island to varying degrees before abandoning the island completely after the breeding season of 2002. At least 35 years of use by wading birds is a long time for colonies that are reported to be nomadic. Why Pumpkinseed was abandoned after all those years remains a mystery but it is not unusual in the world of wading bird ecology. Pumpkinseed Island holds a special place in the history of wading birds in recent decades and in the hearts of so many who built their careers on studies carried out there.

» Insects

The insect discussion presented in the North Inlet section of the document also applies to Winyah Bay due to the very motile nature of most insect species. This said, some of the butterfly species that utilize specific host plants in marshes may be more abundant in brackish and freshwater marshes found along Winyah Bay versus the salt marshes of North Inlet. One example is the Palatka Skipper, *Euphyes pilatka* that uses Sawgrass, *Cladium jamaicense*, as its host plant. Sawgrass occurs in the brackish marshes within the Winyah Bay portion of the NERR. As mentioned in the North Inlet section, few studies have been conducted on insect dynamics and ecology within the NERR.

The Palatka Skipper occurs in the brackish marshes of Winyah Bay

» Invasive Species

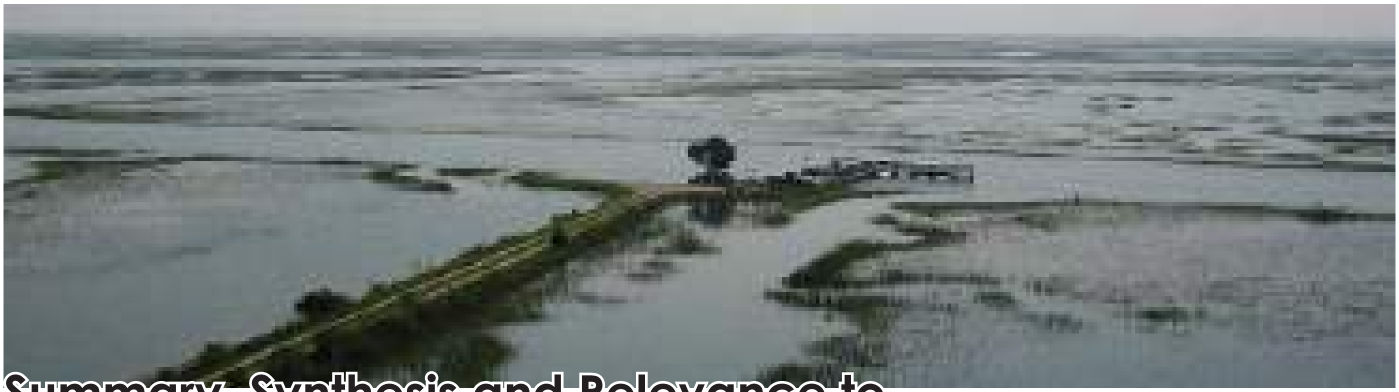
Most of the invasive species described in the North Inlet section are also present or of concern in Winyah Bay. The Asian tiger shrimp, *Penaeus monodon*, has been collected in Winyah Bay and directly offshore, and the most documented infestation of the spiny hands crab, *Charybdis hellerii*, in South Carolina is in Winyah Bay (SERTC, 2014).

The first infection of the invasive swimbladder parasite *Anguillicoloides crassus* in the wild in the United States was reported in Winyah Bay in 1995. This nematode is endemic to East Asia, and is considered one potential reason for the decline in American eel, *Anguilla rostrata*. A recent study found that 46% of the American eels in Winyah Bay were infected with adult and 31% with larval *A. crassus*, and approximately 20% of eels examined in Winyah Bay showed severe swimbladder damage (Hein, 2012).

Similar to North Inlet, the common reed, *Phagmites australis*, is found throughout the area adjacent to the waters of Winyah Bay. The Winyah Bay Invasive Species Cost-share Program is a partnership of the Winyah Bay Task Force and the South Carolina Department of Natural Resources, National Fish and Wildlife Foundation, US Fish and Wildlife Service, Natural Resource Conservation Service, The Nature Conservancy, Clemson University, Historic Ricefields Association, Ducks Unlimited and other organizations. Funding is provided to assist in the treatment and control of *Phragmites* on private properties in Winyah Bay and the surrounding watershed.

Large rafts of hydrilla, *Hydrilla verticillata*, are periodically washed into Winyah Bay following upriver floods. These rafts may temporarily persist and become a nuisance where they accumulate around docks and other structures, but the salinity of the bay is too high for *Hydrilla* to become established.

In 2006 a red-bellied pacu, a fish closely related to piranha and native to South American rivers, was caught in the upper Sampit River. This individual was likely a pet release as this species is a popular aquarium pet fish that can grow up to 33 inches. While this single individual did not pose a threat to the Winyah Bay system, it did draw attention to the issue of invasions through intentional release.



Summary, Synthesis and Relevance to Coastal Management

General Comparison of North Inlet and Winyah Bay

There are fundamental structural and functional differences between the North Inlet and Winyah Bay estuaries (Table 2). At the broadest scale, North Inlet is a barrier island-bounded, salt marsh-dominated system with such minor freshwater inflows that its waters remain highly saline most of the time. This is in sharp contrast to Winyah Bay which is mostly open water and subject to large changes in salinity due to discharges from five rivers.

Semi-diurnal tides originating from the coastal ocean control water flow and salinity in North Inlet. That tidal forcing overwhelms any freshwater introductions from the surrounding watershed or from the spillover through small creeks connecting North Inlet to the brackish portion of Winyah Bay. Although salinity at the south end of the North Inlet system can remain at intermediate levels for weeks or months during major river freshets, reduced salinities are rarely observed in the inlet area. The 30 year average salinity for the core of North Inlet at mid ebb tide is about 32; seawater is usually around 35. Periods of major rain runoff at Oyster Landing and Debidue Creek result in depressed salinities near the upland border for short periods, but tidal exchanges with the lower estuary make those short-lived events. Because almost one half of the volume of water in North Inlet at high tide leaves the inlet with a typical ebbing tide, the residence time of water in the system is short.

In Winyah Bay, a salinity gradient can be observed along the axis of the estuary throughout the year. Salinities are always highest near the mouth and nearly freshwater is usually found close to the Highway 17 bridge crossings about 25 km (15+ miles) upstream of the ocean entrance. Large river discharges force freshwater farther down the axis of the bay and salinities can be less than 15 at the ocean entrance at low tide. As the tide floods, lower salinity water is forced back up the bay and into the rivers creating rises and falls in water levels in the rivers for 10’s of kilometers upstream of the bridges. Although most of Winyah Bay is shallow and the water column is well mixed, stratification occurs in the ship channel (often 10 m or more deep) as the higher density salty water at the bottom resides under the lower salinity layers creating large differences between bottom and surface salinities. Thus, salinity patterns in Winyah Bay are highly variable laterally and vertically as tides and river discharges collide and mix or stratify to form a halocline. Tidal currents near the narrow inlet (jetty) of Winyah Bay have greater velocity than those near the proportionately wider mouth of North Inlet.

These hydrological differences account for differences in water chemistry and biological communities. Because of riverborne sediment, organic, and nutrient loads, the usually salty lower

Winyah Bay is different than the salty mouth of North Inlet, an area that is comparatively less turbid and nutrient poor. Even when freshwater runoff from North Inlet's watershed is high, nothing like the sediment and nutrient enriched water characteristic of Winyah Bay is found in North Inlet. Chlorophyll levels are higher and dissolved oxygen levels are lower in Winyah Bay.

Contaminant levels are low in North Inlet and higher in Winyah Bay. Although most of the shoreline of Winyah Bay is not developed, municipal and industrial discharges in the Sampit River watershed and pollutant loading originating from many communities and agriculture in the very large, multi-state watershed contribute to degraded water and sediment quality. Airborne pollutants from local industries, vehicles, and electrical power generating plants affect both Winyah Bay and North Inlet.

The most conspicuous difference between the systems is that *Spartina alterniflora* covers more than 70% of North Inlet whereas less than 5% of Winyah Bay's total area is populated by this species. Other species of grasses, rushes, sedges, and plants occur in Winyah Bay but their occurrence is limited to fairly narrow margins and to some islands in the open water of the lower and middle bay. Higher plant diversity occurs in the upper Bay where salt marsh cordgrass does not thrive. Formerly cultivated rice fields in the upper bay have reverted to tidal marshes and the old, man-made canal systems function as tidal creeks. The proportion of Winyah Bay that is open water is much greater than in North Inlet.

The zooplankton, benthos, and motile fauna of the lower bay are similar to those in much of North Inlet, but community composition changes considerably along the salinity gradient. Because of lower salinity and large variations, the infauna is less diverse and probably less abundant in the middle and upper bay than in most of North Inlet. Winyah Bay zooplankton distribution, which is strongly controlled by water movement, is highly variable but some forms have behavioral adaptations that promote either retention within or transport seaward from that dynamic system. Zooplankton and benthos in the upper bay are very different than those close to the ocean. Most nekton, mammals, turtles, and birds can respond to changes in the water and associated prey by moving to the most suitable locations. Some nekton have narrow salinity tolerances and are only found either near the ocean or in tidal freshwater whereas others can accept large changes over short periods and remain in the same general area of the bay over a wide range of conditions. Unlike North Inlet, Winyah Bay is the base of important commercial fisheries including penaeid shrimps, blue crab, and shad. Threatened and endangered species including short-nose and Atlantic sturgeons live along the salinity gradient of the bay. Marine reptiles (e.g. loggerhead and other sea turtles) and mammals (i.e. bottlenose dolphin, East Indian manatee) occur in both systems, sometimes occurring far upstream in Winyah Bay.

The sheer size, variety of habitats and dynamic character of Winyah Bay make it a more difficult estuary to characterize and monitor than North Inlet. Accordingly, there is much more to be learned about the ecology of Winyah Bay.

While *Spartina alterniflora* covers the majority of the North Inlet marshes (left), it is limited to narrow margins of Winyah Bay and some islands of the lower bay (right).

SYNTHESIS

» Long-Term Monitoring

Preceding sections of the Site Profile have provided results of long-term monitoring and summarized the findings of shorter-term studies conducted by hundreds of investigators over the past 40 or more years. Synthesizing all of this information is a daunting task, but in the spirit of providing some observations and thoughts and encouraging discussion, the following is offered.

The estuary of North Inlet is representative of salt marsh-dominated, barrier island-bounded estuaries in the Southeast region, but it is unusual in that (1) more than 90% of its watershed is in a natural forested state, (2) less than 10% of the bordering barrier islands are developed, (3) nutrient and contaminant levels are very low, and (4) boat traffic and pressure on living resources is low. The high rate of water exchange with the coastal ocean keeps the system well flushed. Water and habitat quality are rated outstanding by the South Carolina's environmental agencies. These conditions provide researchers with an excellent opportunity to study a relatively pristine ecosystem, one that has been minimally disturbed by historic or current human activities.

In the 1970s, investigators associated with the Baruch Institute recognized the potential value of tracking changes in key ecosystem characteristics over time. At first, the objective was to monitor the health of the estuary. The assumption was that conditions had been stable for a long time and without foreseeable threats from development or other local human activities, the estuary would likely remain stable. After a few years of collecting information on water quality, water chemistry, atmospheric variables, and key plant and animal assemblages, investigators recognized that no two years were exactly the same. By the late 1980s, it was still difficult to determine what was an average or typical year with respect to temperature, salinity, nutrients, primary production, animal reproduction and growth, and other metrics. In fall 1989, the time series measurements of all ecosystem features were punctuated by Hurricane Hugo and its impact on the uplands and high intertidal habitats. That 'once in a century' disturbance was followed by a series of ENSO events that brought increased rainfall, runoff, and decreased salinity to North Inlet through much of the 1990s. At that point in the long-term monitoring program, investigators became more convinced that regional and global scale changes in climate had impacts on the physical, chemical, and biological conditions in the estuary. Following the wet 1990s, a series of droughts affected the estuary in other ways. Many of the time series that were started in the late 1970s and early 1980s continue through the NI-WB NERR and with investigator specific funding from other sources. Collectively, these long-term time series represent what appear to be the longest continuous and comprehensive sets of measurements of ecosystem components for a non-riverine estuary anywhere in the world.

Three primary aspects of climate change and variability have been documented for the North Inlet area. Mean annual water temperature has increased by about 1^{o}C since 1979. Mean winter water temperature has increased by about 1.7^{o}C; with a long-term average of 11^{o}C, that is a 15% increase in the past 32 years. Salinity in North Inlet has increased and the volume of freshwater discharged by the rivers flowing into Winyah Bay has significantly decreased. Sea level has increased by an average of nearly 3 mm yr^{-1}; it has risen by about 100 mm (4 inches) since 1978.

Temperature and salinity are key controllers of chemical reactions and the metabolism of microbes, plants, and animals. Long-term measurements of animal populations in North Inlet have revealed changes in the timing of migrations, timing of reproduction, growth rates, and abundances of some, but not all organisms. The consequences of these changes in terms of community and food web structure are unknown at this point but new experimental approaches are beginning to identify the mechanisms and rates of changes for some species. Changes in sea level combined with changes in sediment accretion on the marsh surface are known to affect the production and survival of the salt marsh cordgrass, and researchers have speculated that major die offs of marsh could result from increasing rates of sea level rise. The result could be North Inlet and similar estuaries becoming more like open water lagoons. Such changes would have major effects on animal populations, including economically important species such as shrimps and crabs that rely on salt marshes for habitat and food.

» Modeling Studies

Long-term measurements will continue as existing data are being statistically analyzed to reveal new information that can be useful in planning and managing coastal systems and resources in the future. One powerful tool for exploring and understanding complex relationships is mathematical modeling. Models have been used throughout the North Inlet research program's history. What follows is a characterization of their use as tools to synthesize information, identify gaps in our knowledge, set priorities for future research, and, in some cases, predict responses of ecosystem services and structure. Also provided is a summary of the kinds of modeling studies that have been conducted, and some of the 'big picture' outcomes that have emerged.

The Outwelling Study's findings prompted construction of new and revisions of older models of subsystems within the estuary that examined fluxes of materials. Other models were designed to examine various ecophysiological and biogeochemical processes that take place in a systems perspective. Other models examine physical processes. Rather than describe each model individually, we have taken the approach to briefly list modeling references in chronological order within research themes for North Inlet and/or Winyah Bay.

The first formal models of material and energy flow in North Inlet and between the coastal ocean and North Inlet were described by Vernberg et al. (1977c, 1978b). These two EPA technical reports were cited in Vernberg (1993). Vernberg et al. (1976) is the precursor to the more formally presented model by Dame et al. (1977). Their closing thoughts were prophetic: "A good model is a constantly evolving entity which changes through time as man's understanding increases. There is no final model." Dame et al. (1977) proposed three subsystems: water column, intertidal zone, and a benthic subtidal zone. Each subsystem had its own compartments, e.g., the subtidal benthos had detritus, meio- and macro-omnivores, decomposers, and macroflora. There were 23 compartments total that were arranged into an input/output matrix of energy flow. Dame et al. (1977) also developed a separate, multi-compartmental, intertidal oyster community model. Both of these linear systems models helped focus future research and modeling efforts for the Outwelling Study. Summers and McKellar (1979) proposed four major subsystems (water column, intertidal marsh, subtidal benthic, and oyster reef) with forcing functions that influence material and energy exchanges, metabolism, trophic transfers, etc. Subsystem coupling and net exchange of energy with the coastal ocean were the foci. Additional iterations of this model are given in Summers et al. (1980), and Summers and McKellar (1981a,b). Dame and Patten (1981) proposed a model for energy flow within a typical oyster reef.

These earliest models served to bring structure, through compartmentalization, to simplify thinking about how a coastal estuarine system like North Inlet interacted with the adjacent ocean. The models also promoted ideas about how different compartments within North Inlet interacted before their collective outputs could be summed to test which were most important in the outwelling process. Subsequent sampling designs and measurements of various constituents of interest relevant to outwelling fluxes were made more efficient by running these models. A major outcome was that new studies were proposed and conducted based on gaps in our knowledge generated by the models. The Bly Creek Study of the marsh surface and research on oyster reefs as functioning ecosystems themselves resulted from the modeling effort. Once data were collected for these subsystems within the marsh rather than for the marsh as a whole, more detailed and comprehensive models were constructed incorporating the newer data. For instance, a model of interactions between phytoplankton, zooplankton, nutrients and other aspects of water column dynamics was presented by Childers and McKellar (1987). For material flux measurements related to the outwelling hypothesis, Spurrier and Kjerfve (1988) used statistical models to tighten confidence intervals around measured fluxes. Kjerfve et al. (1991) modeled water flux in North Inlet. Asmus and McKellar (1989) used an input-output analysis to model fluxes of energy in North Inlet, and Childers et al. (1993b) used a tidal hydrology model to create a dynamic budget for carbon, nitrogen, and phosphorus in several subsystems of North Inlet.

While the Outwelling Study and its related follow-up multi-researcher programs were underway, additional researchers examining smaller scale, but ecologically relevant phenomena within North Inlet included models in their work. For example, Grant (1981c) modeled shorebird predation on their amphipod prey. Aller and Yingst (1985) measured diffusion from animal burrows and modeled porewater distributions. Coull (1986) discussed how changes in sampling frequency in a time-series can be modeled statistically to reduce prediction error for future harpacticoid copepod population abundance estimates. In a follow-up study, Edwards and Coull (1987) provided an example of the use of autoregressive trend analysis for this purpose. Issues related to recruitment of crustacean larvae into coastal marshes were discussed in a model by Christy (1989).

Studies of primary productivity often include physiological models of how external factors influence production rates. Coutinho and Zingmark (1987) examined the photosynthetic response of benthic macroalgae in response to changes in sunlight. Based on earlier methodological aspects of constructing photosynthesis – irradiance curves, Pinckney and Zingmark (1993b) modeled annual production of microalgae in North Inlet, an estimate that was elaborated in greater detail by Pinckney et al. (1994a). The annual productivity of the epiphytic community living on *Spartina alterniflora* was estimated by Jackson et al. (2009) using published models of photosynthesis and irradiance (P vs I) relationships.

Several researchers interested in the dynamics between nutrient salts, organic matter, and porewater fluxes in the salt marsh also used models to study this relationship. A steady-state numerical model of the vertical concentration profiles for organic matter and other components in marsh sediments was described in detail by Gardner (1990). An idealized model simulation of salt marsh sediments was constructed to calculate salt and water balances for North Inlet by Morris (1995). Gardner (2005) proposed a model of how porewater moves through the marsh into tidal creeks and how this flow may offer better growth conditions for plants at the edges of these creeks. Continuing the examination of pore water flow through the marsh, Gardner and Wilson (2006) compared two different model structures to deduce that soil compression is an important factor in this process. Wilson and Gardner (2006) also modeled the effects of the tide on groundwater flow and solute exchanges in the marsh. Stratigraphic changes in marsh sedimentation and belowground carbon storage were examined using two different models by Mudd et al. (2009). Wilson and Morris (2012) employed numerical models to study how porewater exchange is affected by tidally-driven groundwater flow exchanges in the salt marsh.

With global climate change concerns about the ability of salt marshes to maintain their position relative to sea level rise, Mudd et al. (2004) developed a one-dimensional model specifically for *Spartina alterniflora* salt marshes. It incorporated data from North Inlet on sedimentation, hydrodynamics and plant community evolution. Dame et al. (1992) had earlier created an interesting model of the spatial and temporal evolution of salt marsh estuarine ecosystems. Another study of marsh elevation was conducted by Morris et al. (2005). They combined LIDAR images into a trained artificial neural network to characterize elevation in portions of the marsh populated by different plant species, all relative to sea level.

The most recent model of water flow within North Inlet by Traynum and Styles (2008) examined the interplay between tides, wind stress, and freshwater discharge to illustrate how flow in the interface between North Inlet and Winyah Bay is affected.

Comparative modeling studies incorporating pollution concerns have also been done. Porter et al. (1996) applied the Agricultural Non-point Source Pollution (AGNPS) model with GIS input for the Oyster Landing watershed in North Inlet. The AGNPS model was also used by Vernberg et al. (1999) to compare North Inlet and Murrells Inlet. The fecal coliform load was examined for Murrells and North Inlets to detect how a change from septic tanks to a municipal sewage system in Murrells Inlet affected water quality (Nelson et al., 2005). The regression models they utilized showed positive gains (decreased concentrations) in this parameter as a result of this intervention and no change in North Inlet's water quality, even when the new Baruch Marine Field Laboratory was constructed.

Porter et al. (2004) provided a model for how data collected during environmental monitoring programs such as the NERRS SWMP should be managed. They suggested that failure to do so effectively can compromise a long-term program's scientific integrity and future value.

Modelling efforts continue to be an integral part of understanding how various processes interact to influence important ecological and biogeochemical factors in the North Inlet-Winyah Bay landscape. Output from these models will inform future coastal development and management decisions, especially as coastal development activities and sea level continue to rise.

In summary, the research trajectory at North Inlet has been, first, discovery-type studies (e.g., what is here and how does it change over time), then one of big-picture, large spatial scale quantitative studies (e.g., testing the outwelling hypothesis) followed by modeling efforts that guided additional reductionist studies (e.g., Bly Creek, oyster reef studies). These multi-investigator programs resolved many mechanistic and physiological/metabolic questions about how the inner workings of the salt marsh translated into functional coupling with the coastal ocean. These studies were integral in identifying gaps that needed studies of physical flow, tidal effects, and how marsh sedimentation is impacted by sea-level rise. These major inquiries into how the marsh functions have been constantly punctuated and complemented by single-investigator and small-team investigations that have examined the functional and rate dynamics of primary and secondary productivity, predation and population dynamics, nutrient fluxes, pollutant impacts, and geochemistry. Other major research thrusts have examined the physiographic evolution of the salt marsh elevational landscape and dynamic temporal changes in various biotic and abiotic variables achieved mainly through long-term monitoring efforts. Scales of interest have included tidal periods, diel cycles, spring-neap asynchronies, seasonal shifts, annual average states, and even decadal trends in some climate-related variables. This monitoring continues today and likely has among the highest sampling frequency and longest duration of any similar monitoring programs at other NERR sites. The broadly-based, coordinated monitoring programs have already promoted studies of why such large community-level changes occur – especially at the seasonal and between-year scales – and an examination of the role of nutrient regeneration within the system as it drives overall marsh productivity. Researchers have only recently begun to ask whole system questions about how the marsh processes energy over long periods of time (e.g., is it net autotrophic or net heterotrophic?).

Future studies should build on the broad base of knowledge generated thus far to help resolve the coastal management-related questions of what ecological processes and functions are most necessary to protect if this salt marsh habitat and its culturally-relevant resources are to remain in a sustainably near- or relatively-pristine state. New comparative studies in the more impacted Winyah Bay will serve to emphasize how differently aquatic resources respond to perturbations, be they anthropogenically- or climate/weather-induced. The NI-WB NERR will also continue in its critical role in nurturing future generations of coastal ecologists whose job trajectories will naturally intersect with societal issues that are sure to emerge as economic and climate-change pressures continue to impinge on the ecological value of this nation's diverse coastal habitats. Its educational programs can positively impact all future generations of learners and enlist their assistance in promoting and projecting an awareness of how the coastal environment affects our quality of life.

The NI-WB NERR will continue in its critical role in nurturing future generations of coastal ecologists.

Research Needs and Priorities

With researchers from so many different disciplines conducting work in the NI-WB NERR, it is difficult to compile a list that differentiates between what types of studies people want to do, and what types of studies need to be done. However, given the knowledge base that exists in published studies, identification of gaps in our knowledge, and the comprehensive database that has been compiled from long-term monitoring work, certain disciplinary tendencies stand out for inclusion on a list of research needs. Accomplishing the needs is another matter entirely.

All scientific research depends on the successful blending of personnel, funding, and facilities. The NI-WB NERR can offer some of each component of this triumvirate - outstanding field and laboratory facilities, several highly skilled personnel, and a modest budget. In reality, when new researchers arrive on-site, they tend to either move on relatively quickly or stay to pursue their interests more deeply over a much longer period of time. Maintaining a critical mass of investigators who generate grant funding is a key to keeping a laboratory facility running in a sustainable manner, not to mention keeping long-term, time-series measurements uninterrupted.

As for the types of research needed, theory-based, hypothesis-driven, and manipulative studies must be included. Long-term monitoring efforts and short, one-time surveys are important to maintain, but curiosity-driven research must also be encouraged, because the more research that is done, the greater the number of new questions that arise. Good science begets more good science, and ecological modeling provides direction and guidance in many cases. The following unprioritized list of needed research is offered with the hope of stimulating intellectual interest and inspiring a commitment among investigators to apply for the additional fiscal resources needed from funding agencies.

Table 13. Research needs at the North Inlet-Winyah Bay National Estuarine Research Reserve.

- Process-oriented studies on sources, sinks, and turnover rates of inorganic and organic carbon and nutrients in the water column and sediments (i.e. key ecosystem rate data are almost entirely lacking for North Inlet and Winyah Bay)
- Identification of processes that control natural hydrology of the North Inlet and Winyah Bay watersheds, including the relative roles of surface and groundwater flows, and the ecological impacts of changing hydrology associated with coastal development (increases in water use, impervious surfaces and stormwater best management practices) and climate change
- Ecological modeling efforts that utilize existing long-term data and predict the impacts of long-term climate change and/or coastal development
- Updated assessment of contaminant (including emerging contaminants of concern and pharmaceuticals) sources and sinks in sediments and organisms and their ecological impacts
- Assessment of bacterial and viral pathogen sources and sinks, including the factors that influence their survival and growth, and the ecological and human-health risks of non-human fecal pathogens.
- Genomic and metabolomic studies to quantify microbial community assemblages and their dynamics in the water column and sediments
- Identification of physical and abiotic controls and regulators of temporal (tidal, seasonal and interannual) changes in ecosystem dynamics, trophic structure, and organism abundances
- Trophic analyses of most organisms, food web dynamics and carrying capacity studies
- Recruitment of vertebrates and invertebrates (including invasive species), both transient and resident: sources of larvae, survival/mortality, settlement timing/rates, post-settlement population dynamics
- Quantifying relationships between habitat structure and primary and secondary production
- Manipulative experiments to determine whether juvenile nekton and epibenthos use the marsh in an obligatory or facultative manner, i.e., clarify the nursery role of salt marsh estuaries
- Statistical modeling of long-term data sets to establish criteria for maintaining integrity of the time-series at reduced levels of sampling and identification effort
- Phytoplankton and microzooplankton community dynamics and trophic interactions
- Multibeam sonar assessments of motile fauna movements and size composition at representative bottlenecks or thresholds into and out of the marsh
- Impact of nearshore, coastal ocean biogeochemical processes and flow on North Inlet’s role in the coastal ecosystem
- High resolution bathymetric maps throughout North Inlet and Winyah Bay
- Identification of sources of sediment and organic matter and their accumulation rates on the marsh surface as sea-level changes in the future
- Determination of current rates of salt marsh carbon sequestration and identification of physical controls and ecological processes regulating carbon sequestration capacity
- Renewed/expanded sampling efforts in Winyah Bay, which has been severely under-studied with respect to hydrology, water quality, biology and ecology.
- Documentation of turtle and marine mammal use of Winyah Bay and North Inlet
- Bird surveys and studies of their energy and nutrient fluxes; what changes when migratory species are abundant?

Table 13 continued.

- Assessment of and research on archaeological sites (in conjunction with the Baruch Foundation)
- Archival research: more effective preservation, storage, and cataloging of biological specimen collections
- Development of identification keys to larval organisms via laboratory rearing efforts and genetic affinities with adult forms (e.g., DNA typing)
- Social science and economic studies on the market and nonmarket value of key coastal habitats and resources, including the integration of ecological and economic modeling to forecast socio-economic impacts of habitat degradation and overuse of coastal resources as well as the links between resource use and ecosystem sustainability

Given the NI-WB NERR's value as an un-degraded, natural site, its current though limited capabilities in technology and research infrastructure, its extensive databases and publications from site-based research, its capacity (personnel, equipment, etc.) for taking on additional research efforts, and budgetary issues, several items rise to the top tier of the list, each having equally compelling, though different, justifications. Prioritizing the list of research needs is a matter of practicality and cost. Some of the listed needs are less expensive, less labor-intensive, do not require facilities or equipment beyond what is already available, and will take less time to accomplish. Others will require a team approach for a major new research initiative that will take a considerable amount of time and funding.

» Disciplinary Priorities

What follows is an attempt to identify what might be the most important disciplinary priorities for future research efforts at the NI-WB NERR and Baruch Marine Field Laboratory. These are organized according to the sub-disciplines of science recognized by most coastal researchers.

PHYSICAL SCIENCES

Renewed sampling efforts in Winyah Bay; this estuary is severely under-sampled for toxicants, nutrients, primary producers, and all faunal categories. Also needed is a better assessment of the riverine influences on the dynamics and health of both North Inlet and Winyah Bay.

Justification Flow dominates the ecology of Winyah Bay. Freshwater discharge into Winyah Bay and flows into North Inlet will change as climate change takes place. We need to understand the influences of these inputs/outflows on water quality, chemistry, and community changes within both estuaries to understand and mitigate impacts of future climate change.

CHEMICAL SCIENCES

Identification of sources, sinks, and turnover rates of inorganic and organic nutrients and materials in the water column and sediments.

Justification Understanding chemical and microbial processes and their relationships to plant and animal ecology is essential; this requires modeling and biogeochemical expertise.

GEOLOGICAL SCIENCES

Identification of sources of sediment and organic matter and their accumulation rates on the marsh surface as sea-level changes in the future.

Justification Research regarding relationships between these forces and plant productivity is translatable and can be a model for many other at-risk coastlines, nationally and globally.

BIOLOGICAL SCIENCES

Development of relevant DNA probes to monitor changes in the microbial community in the water column and sediments.

Justification Microbial processes drive many biological patterns and trends observed in time-series observations. We need to understand how/why changes in microbial community structure are driven.

ECOSYSTEM SCIENCES

Determination of spatial and temporal variations in habitat quality for economically and ecologically important species and how the growth, reproduction, feeding, movements, and abundances of these organisms relate to the abiotic and biotic features of the habitat.

Justification In light of changing temperature, salinity, sea level and other climate-related factors, estuarine habitats are changing and affecting populations and communities. Information is needed to inform the future management of habitats and associated fauna, including those considered to be harvestable resources.

SOCIAL SCIENCES

Communicating the value of research in the above disciplines to the public and all immediate stakeholders is of paramount importance in sustaining the NI-WB NERR. As social media and technology evolve, so must educational mechanisms evolve. Making the value, both economic and aesthetic/recreational, of scientific research known more broadly is key.

Justification Without public support, federally-funded efforts will wither and die. The expertise of social scientists with deep knowledge of existing societal trends and attitudes and how these are shaped is needed to support the efforts of the National Estuarine Research Reserve program. A blending of and partnerships between social and natural scientists is required to achieve this long-term objective.

Although North Inlet and, to a lesser extent, Winyah Bay have been studied by research scientists for at least four decades, the status of our knowledge remains incomplete and insufficient to provide all of the insights, projections, and recommendations that coastal managers need. The research needs and priorities listed above identify a path toward filling some major gaps in our knowledge; however, collaborations between researchers, educators and managers will be necessary to achieve our common goal for a balanced, productive, and healthy future for all coastal ecosystems.

Linking Science to Coastal Management

South Carolina's coast is known for its expansive marshes and beaches, abundant recreational opportunities, and vacation destinations. However, its coastal ecosystems and water quality are increasingly challenged by rapid development. Historically, the land areas surrounding NI-WB NERR, including Georgetown and Horry counties, have been defined by their rural character, relying upon agricultural and timber production as economic mainstays. As Myrtle Beach has been realized as a vacation and retirement destination, undeveloped landscapes throughout the Grand Strand have been converted into golf course communities, vacation resorts, and commercial establishments to support a rapidly growing tourism industry. Development, especially along scenic waterways and beachfronts, has fragmented and changed ecosystems, altered surface and groundwater hydrology, and impacted water quality. The same coastal resources that so many enjoy for their aesthetic quality, recreational amenities, and for their livelihoods are threatened by the compounded impacts of increased development and consumptive uses. Scientific research and long-term monitoring are necessary to understand the complex interactions between human systems and coastal ecosystems. Research performed by the NI-WB NERR can help improve the understanding of the impacts of increased development on coastal ecosystems, while also informing future policy and management.

The broad conceptual model of the interactions between the human systems and the coastal ecosystems. From Devoe and Sanger (2009)

» Ecosystem-Based Management

Science, monitoring, and management all play a role in the overall success of enhancing and maintaining healthy coastal ecosystems. Current environmental policies were established with the best available scientific information and prevailing politics at the time. “However, scientific discovery is rapidly evolving, new tools are always in development, and oftentimes new information negates old information. Furthermore, access to relevant information can be difficult. Therefore, past decisions may not coincide with today’s best available knowledge, and may have led to adverse conditions in coastal regions” (Chasse, 2009). There remains a need for new, locally-based research and long-term monitoring to improve the understanding of how coastal systems are responding to natural phenomena and current management practices. The relatively pristine NI-WB NERR serves as a control site that researchers can use for comparative studies of similar sites in developed watersheds.

A range of research and monitoring activities at the NI-WB NERR and the USC Baruch Marine Field Laboratory, in addition to the efforts of Clemson’s Baruch Institute for Coastal Ecology and Forest Science and Coastal Carolina’s Center for Marine and Wetland Studies, provide information about the relative health of South Carolina’s northeastern coast. These in turn provide a rational basis for updating existing and establishing new policies and best management practices that more effectively protect coastal resources.

» Aligning Research and Management

The NI-WB NERR Management Plan outlines three priority issues in which to focus research, education, and stewardship activities through 2016, including improving understanding of the:

- Impacts of coastal growth on water and habitat quality and ecological communities;
- Impacts of naturally occurring short-term, stochastic and long-term, large-scale climate events on coastal ecosystems and human communities;
- Impacts of invasive species and habitat loss on biodiversity (NI-WB NERR Management Plan, 2011).

These priority issue areas align with the NERRS Strategic Plan and the current funding priorities of the NERR System and will not likely change in the coming years. These priority issues have strong management implications and will drive research activities at the Reserve. Other locally-relevant research findings associated with these issue areas are shared with coastal decision-makers in and around the Reserve as well.

Partner research institutions and funding sources have also identified research priorities that align with the Reserve’s priority issue areas. A report compiled by the South Carolina Sea Grant Consortium indicated four specific areas in which to focus future research in the South Carolina coastal zone, including improving understanding of (1) land use/land cover changes, focusing on impervious cover, (2) stormwater pond system dynamics, (3) hydrological changes and resultant pollutant loads and hydrodynamic changes, and (4) ecosystem “goods and services” (Devoe and Sanger, 2009). These research needs have been identified to understand how projected development activities will impact coastal ecosystems, human health and well-being, and account for the effects and interactions of climate change in South Carolina (Devoe and Sanger, 2009). Research findings associated with the priority areas have the ability to inform land use management practices and coastal resource protection.

Research and long-term monitoring is often pursued to answer a research question being asked by a scientist or to keep a pulse on the health of a particular system. Rarely do scientists seek the input of coastal decision-makers to identify research priorities. Coastal decision-makers often rely on healthy coastal resources to support their jobs and their communities, whether they realize it or not. Coastal decision-makers include, but are not limited to:

- Elected and appointed officials (e.g. council members or planning commissioners);

- Local government staff (e.g. planners, public works staff, stormwater engineers, and water and waste water engineers);
- State and federal government representatives (e.g. coastal management staff, ecologists and restoration practitioners, and land managers);
- Development and real estate professionals (e.g. architects, landscape architects, developers, real estate agents);
- Conservationists (e.g. land trusts and owners of large tracts of land); and
- Residential managers (e.g. property managers, homeowners associations, and landscapers).

While the scientific research needs of these varying groups are not necessarily the same, each can benefit from new and emerging research to help them manage their community, neighborhood, or watershed. Through interaction with Reserve staff, coastal decision-makers in the northeastern coast of South Carolina have identified a number of research needs that could inform their management practices and policies. This list is not fully encompassing of local research needs, but provides examples of the type of research that can inform future policy and management in and around the Reserve:

- **Water Quality Protection**
  - Pollutant removal effectiveness of existing stormwater management practices vs. low impact development practices
  - Effectiveness of stormwater pond management strategies (e.g. vegetated buffers, dredging, floating wetlands, aeration)
  - Water supply and waste water management in coastal watersheds under a changing climate
- **Habitat Protection**
  - Presence of and changes in invasive species, both aquatic and terrestrial, under existing and future conditions
  - Prioritizing coastal land conservation strategies in the light of climate change
  - Impacts of offshore wind and transmission lines on coastal ecosystems in Winyah Bay
- **Climate Change and Coastal Hazards**
  - Beach and estuarine shoreline change
  - Effectiveness of shoreline stabilization practices (e.g. groins, beach nourishment, living shorelines)
  - Sea level rise threats to stormwater management and development
  - Socio-economic vulnerability of coastal populations to hurricanes and sea level rise

» Science Communication and Translation

Scientists and decision-makers serve inherently different roles in protecting coastal ecosystems, with each having its own set of values, interests, concerns, and perspectives (Jacobs et al., 2005). In turn, scientific research findings are not typically made available in a form that is useful to decision-makers, nor are research projects typically tailored to meet the information needs of coastal decision-makers. Many grant opportunities are now requiring researchers to incorporate outreach as a component of their work, but most scientists are not trained to effectively communicate with non-scientists. Researchers often propose to present their findings to decision-makers at seminars, workshops, or conferences, where they typically convey their results through complex graphs and terminology. Additionally, they speak in terms of accuracy and highlight a number of caveats, which may undermine their credibility among non-scientists. In some cases, researchers develop products and tools, such as brochures and websites, to convey their findings, but they fail to verify their utility with their intended users, if they even know who their intended users encompass (Jacobs, 2002). The complexity of research findings to a non-scientist often makes decision-makers weary of asking clarifying questions in a public forum or basing policy on seemingly uncertain data. This results in a great deal of federal funding being spent on research without tangible or measurable societal benefits (Jacobs, 2002). Because scientists do not typically have formal training in communicating with non-scientists, natural science researchers can benefit by partnering with social scientists and outreach specialists to ensure that their messages are properly conveyed to coastal decision-makers and the public.

» Reaching Decision-Makers through Education and Training

A number of agencies and organizations recognize the value of coastal education and training as a means to convey science-based information to coastal decision-makers (Chasse, 2009). In an effort to promote more informed and confident coastal decision-making, the NERRS established a Coastal Training Program (CTP) system-wide that is implemented in all 28 reserves and serves local decision-makers. The NI-WB NERR launched its CTP in 2003. The CTP at the NI-WB NERR provides training opportunities and technical assistance based on needs identified by local decision-makers. This information is generated in formal audience needs assessments such as one conducted by the NI-WB and ACE Basin NERRs (Pollack and Szivak, 2007), workshop evaluations, and informal discussions with stakeholders. The CTP shares current science on priority issues, increases audience understanding of the environmental, social, economic, and policy consequences of human activities, and facilitates interaction among stakeholders. The NI-WB CTP provides a variety of programs centered on land-use management, water quality protection, habitat conservation and restoration, and coastal hazards and climate change. Programs target a range of audiences, such as elected and appointed officials, developers, land-use planners, engineers, environmental non-profits, regulators, business and applied scientific groups. Typically, training programs provide opportunities for professionals to network across disciplines and develop collaborative relationships to solve complex environmental problems. The NI-WB CTP also provides a forum for professional audiences to inform local and regional science and research agendas. Programs are developed in a variety of formats, including seminars, skill-based training, participatory workshops, and field-based learning and demonstration projects. Whenever possible, training is based on local case studies to maximize the relevancy of research and monitoring occurring in South Carolina's northeastern coast.

Improving the management and use of coastal resources and services is vital to ensuring that healthy coastal ecosystems are protected and sustained. The NI-WB CTP has extensive experience developing meaningful programs that are designed to fulfill a specific local education need. Scientists are encouraged to contact the Reserve to discuss opportunities to share their research with coastal decision-makers. Table 14 lists a few examples of past trainings that have included locally-based research.

The Coastal Training Program works with partners, like Clemson Extension, to teach local decision-makers about innovative stormwater management practices.

Table 14. Examples of past Coastal Training Program trainings that have included locally-based research. For more information on past CTP events, visit: **http://www.northinlet.sc.edu/training/past_events.html**.

Isolated Wetlands: Roles, Regulations, and Rulings Workshop

Isolated wetlands are dynamic hydrologic systems that recharge groundwater, filter pollutants, and provide habitat for numerous species in the coastal zone. This half-day workshop for engineers, planners, regulators, and special interest groups highlighted the ecological role of isolated wetlands in coastal South Carolina and informed the participants about wetland regulations and recent court rulings associated with defining their jurisdiction. This training involved research faculty from USC and representatives of the US Army Corps of Engineers, the South Carolina Environmental Law Project, and the EARTHWORKS Group.

Drought and Salinity Intrusion in the Coastal Yadkin-Pee Dee Basin

Saltwater intrusion is a threat to water suppliers and conservation practices in the coastal Yadkin-Pee Dee river basin. During this half-day day workshop for water suppliers and natural resource managers, researchers presented hydrologic and climatic models that served as the basis for the development of a decision-support tool that projects how coastal drought and sea level rise may impact water supplies and coastal ecosystems in this region. Researchers from Carolinas Integrated Sciences and Assessments (CISA), SC/NC Sea Grants, the University of South Carolina, and the US Geological Survey contributed to this event. Through this workshop the researchers also received feedback on effective ways to tailor their tools to meet their intended-user's needs.

LID in Practice: Case Studies from Hobcaw Barony

Low impact development (LID) attempts to mimic the natural hydrology of a site through the use of stormwater best management practices (BMPs). This ¾ day training included classroom and field-based instruction centered on site design, meeting local regulations, pervious paving alternatives, and bioretention cells, including design, media, plants, and monitoring results. The workshop included a walking tour of BMPs at Hobcaw Barony and offered resources to help local communities implement these pollution control measures. This partnered program with the Coastal Waccamaw Stormwater Education Consortium, Carolina Clear, and Clemson's Restoration Institute included presentations by University of South Carolina and Clemson University scientists and a representative from a company that manufactures LID products.

» Lessons Learned

A number of important lessons can be distilled from the CTP's past experience. Local decision-makers turnover regularly, and it is important to repeat select training topics and concepts—either as a mantra to be repeated at the beginning of each event on the subject matter or as independent, easily-repeatable training programs or pre-packaged sessions. While this does not easily allow for new science to be conveyed, it provides a baseline of knowledge among local decision-makers. Additionally, the constant turnover of elected and appointed officials should be considered when bringing new management and policy considerations to the table, especially if it is an election year. Furthermore, local governments establish their budgets well in advance; therefore any requests for funding should be thoroughly thought through and presented many months in advance. Training experience has also affirmed the importance of couching coastal environmental issues in socioeconomic terms. While it is important to promote science-based decision-making, CTP recognizes that this tourism- and development-driven region relies on healthy coastal ecosystems to drive its economy.

» Additional Education Providers

There are a variety of other education providers that work with local government staff and officials to improve the understanding and management of coastal resources. The Coastal Waccamaw Stormwater Education Consortium (CWSEC) and the South Carolina Coastal Information Network (SCCIN) serve as overarching education groups for the northeastern coast of South Carolina. The CWSEC includes representatives from Clemson's Carolina Clear Program, Coastal Carolina University's Waccamaw Watershed Academy, Murrells Inlet 2020, the NI-WB NERR Coastal Training and Education Programs, South Carolina Sea Grant Consortium, and the Waccamaw Riverkeeper, all of which provide water quality outreach and education to local governments in Georgetown and Horry counties. Local government education is provided to stormwater managers, planners, public works staff, and locally elected and appointed officials through workshops and seminars, in addition to one-on-one technical assistance with locally appointed stormwater advisory committees. Education topics often include ways to reduce non-point source pollution and stormwater pond management. Education programs on watersheds and water quality are also provided to K-12 students who will become the decision-makers of tomorrow and indirectly influence their adult caretakers today. For more information on the CWSEC, visit: **cwsec-sc.org**. The SCCIN is also a consortium of education providers, local governments, and locally-based federal agencies from throughout coastal South Carolina. Like those involved in the CWSEC, the SCCIN members work in partnership to enhance coordination of the coastal community outreach efforts in South Carolina on a variety of environmental issues. This organization was established for the purpose of maximizing the efficient delivery of quality training and educational material to coastal decision-makers, community planners, local officials, and the public. More information on the SCCIN can be found at: **www.sccoastalinfo.org**. The education providers with both the CWSEC and the SCCIN are great at connecting coastal research to decision-makers through education materials, tools, seminars, workshops, and demonstration projects. The NI-WB and ACE Basin NERRs also coordinate and collaborate on coastal training events on topics of mutual relevance to decision-makers in their target communities.

» Integrating Scientists and Managers through Collaborative Learning

Overcoming communication barriers and meeting the research needs of coastal decision-makers is not an easy task. In order for science to be useful in a decision-making process, it has to be relevant to answering a specific policy question, must be accessible and easily understood in a management context, come from a trusted source, and be presented at an appropriate time in the decision-making process (Jacobs et al., 2005). Scientists, planners, regulators, and policy makers can all benefit from sharing their diverse perspectives on a particular environmental concern prior to initiating a new research project or establishing new policies or guidelines. The Collaborative Learning Guide for Ecosystem Management defines an interdisciplinary approach to understand complex environmental issues, bringing together key ideas from complex systems theory, conflict theory and adult learning theory to design and implement solutions to environmental problems (Fuert, 2008). The NI-WB NERR is currently applying such processes through two NERRS Science Collaborative funded projects. One project has brought together state and local water quality researchers and municipal and county stormwater engineers and planners to design a water quality monitoring project occurring in two swashes in the Grand Strand. Another project is currently bringing together diverse opinions of engineers, planners, developers, and researchers to develop a low impact development manual for coastal South Carolina. While these projects have varying goals, they have both brought together scientific researchers with applied scientists and managers to resolve a water quality concern in coastal South Carolina. Establishing relationships in the community and with intended users is especially important for ensuring the success of these projects. Through early interaction in a project, scientists and decision-makers gain a better understanding of a management concern and can work together to protect a coastal resource which they mutually value. Such collaboration will result in greater acceptance of research findings in the end, thus, having a greater likelihood to inform policy and management practices. The Coastal Training Program and partnering education providers, due to their established relationship in the community and experience as facilitators, play a key role in the success of this type of integration and can provide similar assistance to help others bridge the gap between scientists and coastal decision-makers.

Swashes are relic tidal creeks in the Grand Strand, which now serve as conduits for stormwater into the ocean. Scientists are working with local decision-makers to better understand the role of swashes in hypoxia formation in coastal waters.

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Index

Species, research and monitoring programs, topics of concern, and places commonly associated with the NI-WB Reserve.

Appendix A

Supplemental Background Information

Appendix A – Supplemental Background Information

This appendix provides additional background information on some topics presented in the Site Profile. These entries provide definitions of terms and explain process and relationships among environmental variables.

ENVIRONMENTAL SETTING

» Water Quality in North Inlet

pH and Redox Potential (page 58)

As sediments change from oxidizing to reducing conditions, they experience changes in their electrochemical redox potential (Eh). Metallic electrodes are used to measure the redox potential in much the same way that pH is routinely measured. The depth in the sediment where this oxic/anoxic transition occurs is usually quite visible to the naked eye as the place where sediment color changes from light brown to darker shades or black. Sulfides produced within the redox layer are toxic to most organisms, but burrowing species such as clams and some macrobenthic worms can survive there by making oxygenated water flush through their burrows. Most of the biomass of benthic infauna occurs within the oxic zone above the redox layer. Anaerobic bacteria live within the redox layer and promote the breakdown and remineralization of buried organic matter. The redox status of the sediments also determines the relative abundance of nitrogen species (ammonium, nitrite and nitrate ions). This dark layer beneath the muddy and sandy surfaces of the salt marsh is thus critically important to the ecological balance of the estuarine environment. Changes in pH can also affect how pollutants and chemical contaminants react in the water and with flora and fauna.

Sediments and Turbidity (page 58)

Input of sediments to estuaries comes from both land (deforestation, farming practices, surface mining, river runoff, dust, etc.) and from the ocean during flooding tides and storm events. Creek bank erosion adds sediments to the water as well. These sediments can settle to and accumulate on the bottom and thereby help the marsh grow vertically in response to sea level rise. Turbidity caused by suspended particulate matter, inorganic and organic, is an optical property of water that can be measured electronically by assessing changes in transparency over a fixed distance at some depth in the water. Turbidity blocks sunlight entering the water and thus can reduce rates of photosynthesis by photoautotrophs. Suspended particles cause the water to become turbid, especially during summer, and thus make visual predators work harder to find prey while simultaneously affording those prey a refuge from their predators. Suspended sediments also carry attached bacteria (ingested by filter-feeders and deposit-feeding worms) and chemical species bound electrostatically or by strong chemical bonds. Because suspended organic sediments carry carbon, researchers sometimes use measurements of particulate organic carbon (POC) as a surrogate measurement for organic suspended sediments (OSS). Technically, however, these two measurements are not the same. Sediments, including larger sand particles, are frequently re-suspended by wind, rain, and currents, but can be bound in a mucus-like layer (microbial biofilm) that inhibits re-suspension at relatively low current velocities.

Although not directly addressing North Inlet *per se*, Kana et al. (1999) provide an overview of mesoscale (years to decades) sediment transport for southeastern U.S. tidal inlets like North Inlet. Their conceptual model explains how sediment transport occurs in four inlet domains: main ebb channels, ebb-tidal deltas, shoal-bypassing zones, and recurved spits. Much of the sand moving in and out of inlets is recycled back into inlet channels, completing the “inlet transport loop”.

DISSOLVED OXYGEN (page 63)

Despite its critical importance to most life and to water quality, technically speaking oxygen, like water, is not a true "nutrient" like C, N, and P. Depending on wind speed and current velocity, oxygen diffuses from the air at various rates and dissolves in water, regardless of whether it is fresh or salty. If the water is undersaturated, oxygen will diffuse from the air into the water. If it is supersaturated (> 120% of normal saturated concentration), oxygen will diffuse from water to air. The amount that dissolves depends on how much is already present in the water, and the rate of dissolution is temperature-dependent. Cold water holds more O_2 in dissolved form than warm water. Photosynthesis by autotrophs in the water releases oxygen gas that dissolves in the water and increases its O_2 concentration. Respiration by heterotrophs (and autotrophs) consumes dissolved oxygen and causes its concentration to decline over time. When thermoclines or pycnoclines develop and restrict vertical mixing of the water column, hypoxic (levels of DO < 28% of saturated values) conditions can develop in the layer of water above the sediment. Dissolved oxygen concentration is usually measured in units of mg per liter (mg L^{-1}) or as percent of saturation under prevailing conditions. Stagnation, elevated temperature and high loads of organic matter in the water are conditions that promote hypoxia and possibly anoxia as bacteria multiply and require more oxygen to decompose the extra load. This is called a high biological oxygen demand (BOD) situation. Some chemical processes in the sediment also consume dissolved oxygen. When, over a set period of time, an aquatic ecosystem produces more oxygen via photosynthesis than it consumes by respiration, the net ecosystem metabolism (NEM) is positive, or autotrophic. If respiration exceeds photosynthesis, NEM is negative or heterotrophic during that time period.

» Water Chemistry in North Inlet

NITROGEN AND PHOSPHORUS (page 67)

The availability of N and P and other macro- and micronutrients is often determined by the physical and chemical properties of sediments and porewater, as most N and P is bound to clay minerals, metal complexes, and humic acids in marsh grass environments. The composition and behavior of these organic complexes is incompletely known, so it is challenging to determine how much of either the dissolved or particulate pools of organic matter are actually available. Particulate and dissolved phases of these nutrients are defined and sampled only as an operational artifact. Concentrations of each form depend on both mechanical separation of the two phases using filters and analytical chemical differentiations. However, standardized methods have been agreed upon so that data are comparable from study to study. The advent of auto-analyzers has made nutrient analyses almost routine, but there are still many methodological difficulties encountered.

In oxygen-limited environments denitrifying bacteria use nitrate as an electron acceptor rather than O_2 and NO_3^- is reduced in a cascade first to NO_2^- and then to NO, N_2O, and finally to N_2 gas. Thus this process removes nitrogen from soil and can ameliorate pollution from nitrate-laden fertilizer, for instance, and possibly prevent eutrophication of receiving waters.

Biogeochemical cycles include not just chemical "species", but biological species as well. Every herbivore, carnivore, omnivore and every prey organism (plant, animal, bacterium, etc.) contains chemical elements that come from the food we eat. Metabolic wastes, excreta, and feces return these constituents to the environment. Food webs are an integral part of most, if not all, biogeochemical cycles. Hence every time a fish eats something here and defecates or excretes somewhere else, it is moving nutrients around. For example, migrating birds bring nutrients to the NI-WB NERR from elsewhere and take some with them when they leave. Their foraging activities in freshwater ecosystems move nutrients from there to North Inlet where some get deposited as excreta.

SULFUR (page 79)

Although sulfur is an essential component in virtually all living organisms, most of the attention to sulfur in the NI-WB NERR has been directed at sulfate reducing bacteria that live in the sediments along with a host of fermenters and methanogens. Organic sulfides, primarily dimethyl sulfide, and hydrogen sulfide, H_2S, cause the familiar rotten egg odor of anoxic marine sediments. The hydrogen sulfide gas is a by-product of sulfate reducing bacteria that use hydrogen and organic compounds produced by plant roots, for example, as electron donors and sulfate ions as electron acceptors. Many anaerobes also produce pyrite (fool's gold or iron sulfide, FeS_2) that can be seen in the sediments. Sulfate reduction is also fueled by metabolically-produced carbon dioxide or methane. Sulfur is thus an integral part of biogeochemical cycles in the salt marsh, and the activities of sulfate reducers, methanogens, and fermenters are closely coupled in the anaerobic layer beneath the marsh surface. Thickness of this layer is greater in the high marsh than in the low marsh where the longer duration of tidal inundation and higher plant densities bring more dissolved oxygen to the sediments.

CARBON (page 80)

All organic matter (OM) contains carbon, hence whether OM occurs in dissolved (DOM) or particulate (POM, living or dead) forms, the non-carbon portion can be burned off or oxidized until all that remains is the carbon. Thus measured amounts of dissolved organic carbon (DOC) and particulate organic carbon (POC) reveal the presence of organic materials of which the C was previously a part. Because most OM also contains other elements like N and P, it is often the case that nutrient-oriented studies also collect data on the C content of the OM. Is carbon a "nutrient"? Definitely, because, as a building block for living organisms, carbon uptake is essential for the growth of new tissues, including reproductive products. There are many reservoirs for carbon, and studies of the carbon cycle in any ecosystem attempt to measure not only the amounts of C in each type of reservoir, but also the magnitudes and rates of C flux between reservoirs. Every time a piece of plant material falls to the ground and starts to decompose, the carbon in that tissue changes forms as part of this flux. Plants and other autotrophs like phytoplanktonic algae ultimately get their carbon from the atmosphere directly through uptake of inorganic CO_2 gas or, in aquatic ecosystems, through uptake of dissolved inorganic carbon dioxide, DIC. When organic matter (detritus, fecal material) sinks to the bottom, much of the carbon in it is stored temporarily in the sediments where microbes and benthic fauna utilize the energy contained in these organic substances for their own growth and metabolism. Some carbon also gets mineralized and stored as, for instance, carbonates. Some carbon-rich compounds are reactive or easily decomposed (the "labile" component), while other compounds or parts of the labile ones are decay-resistant, i.e., they are "refractory" and do not break down easily. All predator-prey interactions involve carbon and energy flow, as do most parts of biogeochemical cycles. The carbon cycle, besides it major role in buffering seawater's pH, is thus intimately linked to the chemo-autotrophic uptake of energy and its subsequent conversions from more concentrated, energy-rich, forms to less concentrated forms. The energy contained in OM as carbohydrates, lipids and such, unfortunately, does not recycle. Lastly, a disproportionate supply of carbon and increased (or decreased) residence times in some reservoirs (atmospheric carbon dioxide, withdrawals of coal, oil and natural gas from underground reservoirs) can have profound consequences for life on Earth.

ECOLOGICAL/BIOLOGICAL SETTING

North Inlet's Major Biota

» Primary Producers

At the base of the food web are the primary producers, autotrophic organisms that take up carbon dioxide and produce oxygen and sugars as they photosynthesize and participate in the carbon and other biogeochemical cycles. For a coastal salt marsh like North Inlet (and many others throughout the southeastern US), salt marsh cordgrass (*Spartina alterniflora*) dominates the visible landscape. Many other primary producers also contribute significantly to the salt marsh food web, including phytoplankton, microphytobenthos, macroalgae, and other vascular plants.

PHYTOPLANKTON (page 130)

Phytoplankton is a general term for photosynthetic single-celled organisms occurring in the water column. These taxonomically diverse cells span a range of sizes from micrometers to millimeters. A proxy for the biomass of total phytoplankton in the water is obtained by measuring the concentration of a volumetric water sample's chlorophyll *a* (also abbreviated as chl-*a*) pigment. However, not all phytoplankton cells or species have the same amount of this pigment. Other techniques, e.g., HPLC (high pressure liquid chromatography), are used to quantify other types of pigments in a sample. Some of these pigments are taxon-specific, and ratios between the amounts of these pigments can be used to characterize the structure and composition of the total phytoplankton community. Laborious cell counts and visual identifications of species also provide valuable information, but microscopy is very tedious and the taxonomy of the unicellular primary producers is difficult. Fluorometric methods can also be used to estimate phytoplankton biomass, and other cell sorting techniques are available to count and characterize phytoplankton cells. However, for quantitative monitoring purposes, measures of chlorophyll *a* are usually made to estimate the amounts of phytoplankton in the water.

BENTHIC MICROALGAE (page 136)

Benthic microalgae (BMA) or microphytobenthos are generally called edaphic because they are associated with sediments, epipelic if they live freely on and migrate (motile forms) within the sediment, or epipsammic if they live attached to sand grains and have no or reduced motility. BMA also live attached to plant stems as part of an epiphytic community. They are difficult to sample quantitatively, they are a challenge to identify microscopically and, as a consequence, their ecological roles are not well known. In addition, compared with phytoplankton and vascular plants, their productivity is more difficult to measure. These small cells, despite their motility, are easily resuspended and mobilized by currents and become part of the phytoplankton community quite frequently. Their populations may also be inextricably linked with bacterial biofilms on surfaces, adding yet more complexity for studying their functional interactions within the carbon cycle. BMA are also difficult to culture in the laboratory. Thus benthic microalgae have been difficult to "remove" from the ecosystem and isolate for research purposes.

The vertical migration of the BMA community is a common phenomenon that can be the subject of field experiments conducted by students. Because chlorophyll-*a* is so easily measured spectrophotometrically, students can readily measure changes in the vertical distribution of BMA biomass within the time constraints of relatively short field studies possible in the laboratory or field portions of ecologically-oriented classes. It is a great hands-on practicum experience for students to test hypotheses about what factors might control BMA vertical migration on a sandy beach or in a muddy salt marsh.

MACROALGAE (page 139)

A subtidal macroalgal community persists throughout the year in North Inlet and becomes most prominent during winter when water clarity is greatest and maximum insolation is much lower than during summertime. The intertidal macroalgae populate sediments and shallow benthic structures (e.g., oyster reefs). Many organisms incorporate macroalgae as part of their cryptic behaviors (e.g., decorator crabs) or utilize it as part of their burrow infrastructure (e.g., the tubes of *Diopatra*, a polychaete worm). The macroalgae, although adapted to living in places where current velocities may be high, almost continuously slough off considerable biomass that becomes part of the water column community of primary producers.

VASCULAR PLANTS (page 140)

A majority of North Inlet's low marsh is dominated almost exclusively by *Spartina alterniflora* with a mix of about eight species occurring in the high marsh areas. Stresses include high (and occasionally low) temperatures, intense sunlight during summer, freshwater runoff variations from droughts to floods, waterlogging of soils, soil porosity, permeability, and compressibility, nutrient concentration variations, salinity variations in both overlying and groundwaters, sediment anoxia and hypoxia, sulfide buildup, changes in redox potential, fossorial invertebrates (burrowers and diggers), insect and marine invertebrate grazers, and strong, often violent, storm events. Rhizosphere microbial communities may also stress some plants in the salt marsh. Some of the questions addressed by researchers concern not just the plants' physiologies, but also their abilities to withstand slow, gradual sea-level rise that, without sediment subsidies to the marsh surface, would result in mass die-offs of this hardy vegetation. As evidenced by the presence of large tree root structures beneath marsh sediments, sea-level rise also causes the salt marsh to migrate slowly landward. Thus the youngest part of the salt marsh lies close to the upland forest.

» Benthos (page 156)

Aquatic animals that live within, on the surface of, or in association with the bottom are members of a group called the benthos. Some of the larger common estuarine benthic animals are snails, oysters, clams, sand worms, and fiddler crabs. Benthic organisms differ in their size, feeding habits, sediment preferences, reproductive behavior, means of locomotion, and coloration. Those that live within the bottom (infauna) are typically sampled using small coring tubes or metallic devices which grab a known volume of sediment. The animals are then recovered by washing the sediment away through a sieve whose wire or nylon mesh (usually 0.5 or 1.0 mm) retains the animals for examination. Animals that live attached to or upon the bottom (epifauna) are sampled quantitatively using cores, by scraping them off hard surfaces of known area (quadrats), or by using suction devices. The epifaunal benthos (soft corals, sponges, hydroids, bryozoans, etc.) may also be collected using a dredge, a metal device with a net attached that is dragged along the bottom in much the same fashion as a shrimp trawl, for instance. The estuarine benthos is a very diverse community. It is comprised by thousands of species that range from fist-sized bivalve molluscs (clams, oysters) and nearly meter-long worms to smaller, more familiar invertebrates like snails and shrimplike crustaceans and finally to microscopic forms like ciliates and bacteria that live neatly on the surface of sand grains and amongst other fine particles that make up the sediment. An intermediate-sized group of microscopic animals is called, collectively, the meiobenthos. Meiobenthic organisms will go through a 0.5 mm mesh but are retained by a 0.063 mm mesh. Most meiofauna are just barely visible to the naked eye. These animals live interstitially within the sediment fabric or plow through unconsolidated sediments and detrital material that lies upon or just below the sediment surface. They do not construct burrows but crawl around amongst and between sand grains. Numerically common meiobenthic invertebrates include nematode worms and tiny crustaceans called harpacticoid copepods and ostracods. Bottom-feeding, young juvenile fishes like spot and flounders individually eat hundreds to thousands of meiobenthic-sized prey each day. Almost all commercially valuable fishes, shrimps and crabs feed upon benthic animals during or after the early stages of their lives, and many benthic animals themselves are desirable foodstuffs for people, e.g., clams, oysters. Wading birds of many kinds also eat large numbers of small benthic animals.

Besides their key roles in estuarine food webs, the benthic organisms contribute to basic ecosystem functions in other ways as well. These include sediment re-working (called bioturbation) that serves to enhance rates of nutrient remineralization (breakdown of organic matter into its constitutive components – nitrates, phosphates - that are then re-cycled in the ecosystem), oxygenation of the sediment, removal of suspended particles from the water (e.g., filter-feeding by clams and oysters), and stimulation of benthic algal growth via their contribution of nitrogen-bearing waste products (especially ammonia) to this portion of the habitat. Benthic animals reproduce and spawn in two general ways: via release of eggs or larvae that drift with currents and later settle to the bottom or via release of larvae that stay in the vicinity of where they were born. Benthic animals feed in diverse ways as well. Some ingest sediment particles and digest the bacteria attached to the particles (deposit-feeders). There can be up to a thousand bacteria attached to a single grain of sand. Many marine worms feed in this manner. Other worms and animals like clams and oysters actually filter food suspended in the overlying water (filter- or suspension-feeders). This feeding mode is most common among animals that can't move around very much if at all. Many other types of benthos are highly motile and either scavenge for food or behave as predators. Many of the larger benthic crustaceans get their food this way - crabs and shrimp, for example. There are some worms, e.g., nemerteans, that plow their way through the sediments beneath the sediment surface in search of prey.

Measures of sediment and water quality in an area often include assessments of the benthic community present in the vicinity. Generally speaking, the higher the number of species present, the healthier the habitat. Degraded habitats have considerably lower numbers of benthic species and/or much lower numbers of individuals, but there are sometimes large numbers of a very few pollution-tolerant species because nothing else can survive under the degraded conditions present. These are often called "indicator species" because they are almost always found in or associated with degraded habitats. Interestingly, these same indicator species are also found in natural, un-degraded, habitats.

DEFINITIONS OF BENTHOS ACCORDING TO SIZE

The life spans of benthic fauna seem to correlate well with their sizes (see classifications below) and range from months to years for macrobenthos, from weeks to several months for meiobenthos, and from hours to a few days for microbenthos.

Macrobenthos: Bottom-dwelling animals that are retained by a 0.5 mm mesh. Major members of this group include polychaete and oligochaete worms, bivalves, and small crustaceans (amphipods, isopods, cumaceans). Burrowing and motile worms dominate this group in soft sediments (mud, sand), whereas harder substrates (rocky) are dominated by attached forms such as mussels, barnacles, and oysters. Macrobenthos abundance typically ranges between hundreds of animals per square meter on the open coast beaches to tens of thousands per square meter in muddy subtidal areas.

Meiobenthos: Metazoans which pass through a 0.5 mm mesh but are retained by a 0.063 mm mesh. Major members include nematode worms, harpacticoid copepods, ostracods, turbellarian flatworms, foraminiferan protozoans, and representatives from minor phyla such a kinorhynchs, gastrotrichs, and pycnogonids. Temporary members of the meiofauna include juvenile forms of the macrobenthos as well, especially polychaetes, oligochaetes, and bivalves. Some insect larvae also fall into the meiofaunal size classification. The meiofauna can be extremely abundant, with over a million individuals per square meter in some muddy intertidal and subtidal habitats. The submerged sediments on a sandy beach may harbor up to a few thousand individuals beneath an area the size of a footprint.

Microbenthos (sometimes also called Nanobenthos): These animals pass through a 0.063 mm mesh but are larger than 0.002 mm. Included are small rotifers, ciliates, flagellates, amoebae and some juvenile forms of animals that are meiobenthic in size as adults, e.g., harpacticoid copepod nauplii. This diverse community of algae, bacteria, and "animalcules" is poorly known and difficult to identify and sample quantitatively despite their widespread occurrence in virtually all marine and estuarine shallow-water habitats. We do not know exactly how abundant the microbenthos is in most habitats, but it is probably safe to say that this size-class of animals is the most abundant of all bottom-dwellers except for algae, bacteria and viruses. It must be noted that bacterial communities are present in abundance in all benthic habitats and are particularly important in the ecosystem for their role as food for sediment-eating animals (deposit-feeders) and as remineralizers (recyclers) of organic matter and as promoters of all biogeochemical cycles known, e.g., carbon, nitrogen, phosphorus, etc.

Habitats/Setting

The kinds and varieties of benthic animals present in an area depends mostly upon physical characteristics of the habitat and the nature of the substrate. As mentioned above, soft-bodied forms numerically dominate muddy and sandy bottoms, while hard-bodied forms attach to and numerically dominate hard (e.g., pilings) or rocky bottoms. Besides sediment grain size, tides are another major factor that limits where certain benthic animals can thrive. Nearer the forest border and throughout the salt marsh, the intertidal benthos must withstand periodic exposure to the air (and rain!) and the wide temperature variations that ensue, whereas the subtidal benthos is subject to much less variation in the physical components of the habitat because they are constantly covered by seawater.

Unvegetated Mud and Sand Flats*:* A trip to the mud flat at low tide reveals evidence for the presence of many different types of benthos visible by virtue of their tube structures (e.g., *Diopatra cuprea*, a polychaete worm that decorates its tubes with shell bits and algae), feeding marks from sand anemones, holes from which bivalves project their siphons during high tide, mounds of sandy defecation products that may form coiled structures (from hemichordate acorn worms), and many other "signs" and "shows". Virtually every pockmark or small structure can be associated with a benthic organism. Mud flats are among the most densely populated, dynamic and interesting places on the planet, yet most who see them from a distance simply regard them as lifeless areas. Far from it – they are teeming with life.

Oyster Reef*:* Many of the individual oysters in the reef are oriented upright such that a person walking on them would be likely to cut their feet or ankles on the edges of the shells. Oyster harvesters typically wear rugged thick boots. These tasty animals obtain food by extracting algae and other particles from suspension in the water column, hence intertidal oysters feed only when submerged by the tide. Subtidal oysters often grow larger than intertidal oysters because they can feed longer. The presence of a large aggregation of hard substrate (the oysters' shells) attracts a diverse community of fishes and invertebrates that use the convoluted structures as more or less permanent habitat. So attractive is this habitat that many researchers use empty oyster shells as collection devices, placing trays full of them onto creek bottoms. When the trays are collected a week or two later, they are found to contain diverse animals that cannot be collected any other way. This suggests that hard substrate is in short supply in the area.

Creek bottoms (shell hash) and tidal pools: The dredge is a heavy metallic device with a net attached that is dragged behind a boat, scooping up the large animals and plants and shell material that lie on the bottom. The epibenthic sled moves across the bottom on skids and collects small animals living near or in association with the bottom. A variety of fishes, shrimps, and crabs are collected in this manner.

» Zooplankton (page 170)

Sampling zooplankton

Zooplankton (i.e., not viruses, bacteria, phytoplankton) range in size from about 20 microns (1/50th of 1 mm) to >2000 mm (if the large jellyfishes are included), but those sampled with zooplankton nets are mostly from 0.2 – 20 mm. This size category is referred to as the mesozooplankton and it is dominated by copepods, an important holoplanktonic group of crustaceans that are typically smaller than 2 mm long. Different size mesh nets are used to capture different size fractions of the zooplankton, and a 153-micron mesh is often used to collect copepods and small invertebrate larvae. However, the straining efficiency of such fine mesh nets decreases quickly when high densities of diatoms and detritus clog the mesh and create a head pressure that is sensed by larger zooplankton in front of the tow path. Thus, fine mesh nets are not suitable for collecting zooplankton more than a few millimeters long. Larger mesh sizes (e.g. 365-micron) do a better job at collecting these larger forms, but most of the copepods pass through that mesh. To more fully characterize the wide size range of zooplankton, at least two mesh sizes are needed, and the 153- and 365-micron mesh nets are adequate for sampling the full range of mesozooplankton in estuaries. Mesh sizes of 750-microns and 1000-microns (1 mm) are sometimes used to sample large decapod and fish larvae and jellyfishes.

Many different strategies can be used to collect zooplankton. Conically shaped nets attached to a ring (usually 30, 50, or 1000 cm diameter) are commonly towed, but these usually sample only one depth within the water column. When tidal currents are strong enough to fully extend and open the nets, plankton nets can be deployed from an anchored boat. Specially rigged "opening-closing" nets can sample discrete levels in the water column by lowering them to the desired depth in a closed position and sliding a weight down the cable to a triggering mechanism which opens the net mouth; this can be followed by another weight to close the mouth. Similarly, the entire water column can be evenly sampled by using a single trigger designed to open the net near the bottom, then lifting the net toward the surface, timing the ascent to ensure equal filtering time near the bottom, mid-water and surface. Another technique for sampling very close to the bottom involves using an epibenthic sled which consists of a rectangular metal frame with skis or skids that keep the net within a few centimeters of the bottom during the tow. In the long-term zooplankton sampling program in North Inlet, large mesozooplankton were collected with an epibenthic sled fitted with a 365-micron net and small mesozooplankton were collected with a modified opening (single trigger) net fitted with a 153-micron mesh net. The fine-mesh net was deployed for 1 minute at each of three levels from an anchored boat during the ebbing tide. The sled was towed along the axis of the creek in the same direction as the ebbing tide for 5 minutes.

In order to determine changes in the abundance and distribution of zooplankton over time and between locations, sampling must be quantitative. We need to know how much water is filtered by the net so that the total number of individuals in the sample can be expressed as a density or number per cubic meter of water. The amount of water filtered between even carefully timed tows can vary quite a bit. A flowmeter mounted inside the mouth of a net is used for this purpose. In the lab, various categories of zooplankton are counted under a microscope and the determination of their densities allows for direct comparisons to be made between collections made at different stages of the tide, time of year, season, or locations. In order to statistically compare abundances, multiple collections or replicate samplings must be made. For the long-term study, two identical 153-micron nets were used at the same time to obtain two replicate samples. The 365-micron mesh sled was towed three consecutive times to obtain quasi-replicate samples. Abundances from these replicates were used to calculate an average (mean) density as well as a measure of the variation (standard error) in abundance at that time and place. These values make it possible to statistically compare samples from different times and places. High variability in abundance is typical of the plankton and much of it can be attributed to patchiness in the distribution of organisms in both space and time. Another reason for high variability in the numbers between replicate net tows is the fact that it is impossible to sample the exact same volume of water twice. Although acoustic and digital photographic methods have been developed and are useful for counting at broad taxonomic levels especially in clearer waters, zooplankton sampling with nets is still the most acceptable method for use in more turbid estuarine waters.

» **Nekton** (page 184)

Sampling the nekton

Scientists use many devices and techniques to measure and describe distributions of nekton in estuaries. Because of the wide range of sizes, shapes, swimming capabilities, and general abundance among fishes, no single type of collection gear can be used to characterize all the nekton. Furthermore, any characterization is biased both by the kind and spatial and temporal extent of sampling conducted. Familiar devices include seines, trawls, gill nets, and traps. These and other techniques used by scientists to understand the nekton of North Inlet are described in the table below. Certain gear and approaches have been developed for particular habitats or groups of fishes. Even slight modifications in size, mesh, or the way a certain gear type is used can make a difference in what is caught. A medium mesh seine can provide a good indication of the occurrence of adult silversides in a shore zone, but could completely miss the much more abundant juveniles when adults are not there. Changes in the influence of current, speed of towing, clarity of the water, temperature, or time of day can affect catches at any location. Because time and personnel are often limited, surveys are usually restricted to the use of one or two gear types which are deployed the same way every time they are used. Scientists cannot determine how much of an observed change between sampling dates is due to technique, environmental conditions, or the movement of the animals to other locations. The tendency of many of the nekton to occur in schools or patches also complicates assessments of abundance. Gobies, blennies, and speckled worm eels are likely among the most abundant nekton in North Inlet, but, because of their cryptic habits, few are collected with nets that skim over the bottom where these fishes live. As is the case in most efforts to describe nature, our efforts are far from precise, but new technology (such as electronic systems that can identify, count, and measure nekton moving through a field of sensors) will likely enable us to be more quantitative in the future. In the meantime, multiple gear types (see table below) and deployment strategies (different tides, time of day, months, habitat types, and locations) will continue to be used to characterize nekton in an estuary.

Most frequently used gear and deployment techniques used by researchers to sample nekton in North Inlet

Seine

- a panel of nylon net of uniform mesh of ⅛ in to ½ in
- usually about 3 ft deep and 20 -50 ft long, sometimes with a 'bag' in the middle
- bottom line with lead weights and surface line with floats or floating line
- pulled perpendicular to the bottom in shallow water with one person on each end; foot in loop in bottom line and hand on top line or with a pole that keeps the end of the net spread
- most effective if hauled onto a smooth sloped shoreline
- advantage: collects in water too shallow to use a boat to tow a net
- disadvantage: moves too slow to capture faster swimmers and if pulling causes bottom line to lift or if used on irregular bottom, nekton easily escape underneath; not useful on rough bottom with snags (Allen et al. 1992)

Trawl

- a tapered net with larger mesh (1-2 in) in the broad body in front and smaller mesh (½ – ⅛ in) in the more constricted tail end
- usually about 3 ft high and 15 ft across the mouth tapering to a 1 x 1 ft bag end
- bottom line across mouth weighted with leads and or chain, floats on top line
- pulled by a boat with lines extending to 1 x 3 ft wood/metal doors that are rigged to ride perpendicular to the bottom and spread the mouth of the net when pulled forward
- advantage: collects in deeper channels and sounds, weighted trawls take nekton on or just above the bottom, floating trawls collect midwater or at the surface; effort can be standardized by distance covered; can capture some of largest demersal fish in the system
- disadvantages: fast swimmers and nekton elsewhere in the water column are missed; retention of small animals low due to large mesh in body of net.

Beam trawl

- a fairly short tapered, trawl-like net with uniform mesh (¼ – 1 in) mounted on a rigid (metal) rectangular frame mouth
- usually about 1.5 ft high and 5 ft across the mouth
- pulled by boat but a small one can be hauled by hand; especially effective for small flatfishes

Blocknet

- funnel shaped net with mouth dimensions comparable to mouth of creek to be sampled, slow taper to narrow tail end
- mesh size uniform at ⅛ to ½ in
- suspended in rigid frame secured to posts and set perpendicular to bottom, extra flanking walls to force all water and animals into the net mouth
- usually used starting at high tide to passively catch nekton leaving a creek with the ebb
- disadvantages: labor intensive, most nekton die during confinement
- advantages; very effective in collecting all animals occupying the habitat thus more quantitative than other techniques

Gill net

- panel of monofilament mesh from 1 - 6 or more in, 20 -100’s of feet long, and 3 -8 ft high
- set perpendicular to bottom with leaded bottom line and floating upper line
- either staked in shallow water or tended from boat in which case it is held in place by large weights on either end, floats as markers on top
- set for 15 min to many hours
- advantages: collects larger, faster swimming fishes not collected by other gear
- disadvantages: as entanglement gear that snags fish under the gill plates, it usually means mutilation and death of the fish; a variation called a trammel net is less damaging; entangled oyster clumps, crabs, and debris are tedious to remove; net repairs are constant

Trap

- wire or plastic enclosures with funnels designed for easy entry and more difficult exit
- mesh and overall size selected for size of targeted species
- often baited and deployed for 30 min to a day or more
- disadvantages: selective since many species will not enter or be retained in traps
- advantages; can be used in pools and other areas where pulling nets is not possible

Habitat tray

- wire mesh trays (often 2 x 2 ft) with short sides and open tops
- usually filled with shell and set on bottom in deeper areas to sample structure dwelling nekton that will not enter traps
- quickly lifted from above by a pulling single line that terminates in a bridle attached to corners of tray
- effective for sampling small demersal animals which tend to hide in the rubble when lifted

Lift net

- rectangular nylon net that is buried in the bottom and lifted to entrap nekton on marshes
- vertical sides tall enough so that area remains surrounded at high tide; no top
- bottom edge with chain is permanently installed deep in mud, walls tucked into groove
- ropes connected to top center of opposite side panels, routed through top of poles
- lifted from afar at specified depth of coverage; secure in extended position, await low tide
- remove catch from basins with tops at marsh levels
- advantages: very good technique for quantitatively sampling marsh surface at different levels of flooding
- disadvantages: very labor intensive, requires removable boardwalks to approach nets

Longline

- nylon mainline with perpendicular monofilament or wire leaders that terminate in hooks with bait
- lines are usually 30- 150 ft long, set along the bottom or at specific depths regulated by floats
- set in deeper waters by boat, soaked for 15 min to hours
- advantages: only means of catching largest fishes besides hook and line, effort can be standardized
- disadvantages: labor intensive, potentially dangerous with large sharks and rays

SUMMARY, SYNTHESIS AND RELEVANCE TO COASTAL MANAGEMENT

General comparison of North Inlet and Winyah Bay

Mathematical models are used globally to predict the weather, estimate stock market ups and downs, chart hurricane paths in the days ahead, track animal migrations, calculate allowable catches for fisheries, and for thousands of other things that affect our daily lives. They rely on good data inputs and the quality of their predictions is often quite accurate. Uncertainties in the input data, however, make model predictions less reliable. The same is true for models of ecological processes. Arguably, one of the goals of ecological modeling is prediction. If X changes, what will happen to Y? A major challenge in modeling biogeochemical processes in estuarine ecosystems has been that physical (abiotic) forcings are highly variable in both magnitude and space over time, hence model input data have high uncertainties. To get around this, a reductionist approach has been used to isolate discrete, more easily measurable parts of the ecosystem to gain accuracy and then to assemble these parts into the larger whole.

Appendix B

USC Baruch and NI-WB NERR Archived and Web Published Databases

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: LTER MACRO Jan 1981 through Jan 1992							
LTER MACROBENTHOS (MACRO)	Macrobenthos	Taxa, abundance (per m2), biomass estimates	2 - 10.3 cm cores	10 to 18 days (approx. biweekly)	1	BB, DD	BB: 01/20/1981 - 01/31/1992 DD: 01/20/1981 - 01/08/1985
LTER MACROBENTHOS (MACRO)	Sediment/Water Interface temperature	degrees celsius	mercury filled thermometer	10 to 18 days (approx. biweekly)	1	BB, DD	BB: 01/20/1981 - 01/31/1992 DD: 01/20/1981 - 01/08/1985
BARUCH DATA ARCHIVES: OLFISH Jan 1984 through Mar 2003							
OYSTER LANDING FISH (OLFISH)	NEKTON (fish, shrimp, and crab) in Low Tide Pool	Taxa, abundance, length (mm SL), weight (g)	2 tows with a 1/4" bag seine at low tide -> 1 tow	10 to 18 days (approx. biweekly)	1	OL	01/04/1984 - 03/31/2003
OYSTER LANDING FISH (OLFISH)	Water parameters in Low Tide Pool	Water temp	mercury thermometer -> Hydrolab datalogger	10 to 18 days (approx. biweekly)	1	OL	01/04/1984 - 03/31/2003
OYSTER LANDING FISH (OLFISH)	Physical parameters in Low Tide Pool	Air Temp	mercury filled thermometer	10 to 18 days (approx. biweekly)	1	OL	01/04/1984 - 03/31/2003
OYSTER LANDING FISH (OLFISH)	Water parameters in Low Tide Pool	Dissolved Oxygen	DO meter -> titrations -> Hydrolab datalogger	10 to 18 days (approx. biweekly)	1	OL	01/04/1984 - 03/31/2003
OYSTER LANDING FISH (OLFISH)	Water parameters in Low Tide Pool	Turbidity	Secchi disk	10 to 18 days (approx. biweekly)	1	OL	02/28/1991 - 03/31/2003
OYSTER LANDING FISH (OLFISH)	Water parameters in Low Tide Pool	Salinity	Refractometer -> Hydrolab datalogger	10 to 18 days (approx. biweekly)	1	OL	01/04/1984 - 03/31/2003
OLFISH LOW TIDE SEINE EFFICIENCY Study	fish, shrimp, crab collection efficiency	taxa, abundance, length (mm SL), weight (g)	15 tows with a 1/4" bag seine + Rotenone & dipnets	once per season	1	OL	05/01/1984 - 03/16/1988
OYSTER LANDING FISH POOL BATHYMETRY	Change in Low Tide Pool Volume	bathymetry	2 meter grids over pool	yrs	1	OL	02/22/1991

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: LTER MOTILE EPIBENTHOS Jan 1981 through Dec 2003							
LTER EPIBENTHOS (EPI)	Motile epibenthic macrozooplankton & Larval fish	Taxa, life stage, length, abundance (per m3)	3 sequential 365 µm net sled tows, 2 to 30 cm off the creek bottom, tow with the ebbing tide	10 to 18 days (approx. biweekly)	2 -> 1	BB, DD -> BB	DD:01/20/1981 - 01/04/1985
BARUCH DATA ARCHIVES: LTER SPARTINA 1984 through 2011							
Spartina	fertilization effects	height	census	monthly	1 - 6 in sm scale location	GI	04/30/1980
Spartina	Primary Productivity	height	census	monthly	2 - 6@ OL, 3@ GI	OL, GI	06/30/1982
Spartina	Below ground Productivity	root biomass	sand core	monthly sum	1	GI	02/28/1990
Spartina	porewater major ions	Cl-, SO4-, Na+, K+, Mg+, Ca+	porewater peepers	monthly	2 - 2@ OL, 3@ GI	OL, GI	07/31/1990
Spartina	Below ground Reserves	above ground dry biomass	marsh core	yearly	2 - 6@ OL, 3@ GI	OL, GI	06/30/1982
Spartina	porewater salinity	g/L Cl-	silver titration	monthly	2 - 2@ OL, 3@ GI	OL, GI	11/30/1989
Spartina	porewater nutrients	ammonia, PO4	colorimetric analysis	monthly	2 - 2@ OL, 3@ GI	OL, GI	11/30/1989
Spartina	porewater sulfide	Sulfide	colorimetric analysis	monthly	2 - 2@ OL, 3@ GI	OL, GI	11/30/1989
Spartina	Marsh elevation	cm	SET	monthly	1	GI	02/29/1992
BARUCH DATA: LTER Microbial ATP 1981 through 1985							
LTER Microbial ATP	adenosine 5'-triphospate (ATP)	nanograms per milliliter	3 -20 ml aliquots from a single 1 liter water sample	once per day at 10 am	3	CB, OL, TC	03/17/1981 - 03/31/1985

USC Baruch and NI-WB NERR Archived and Web Published Databases:

Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA: CREEK Project 1996-2000; Testing the Role fo Oyster Reefs in the structure and function of tidal creeks							
CREEK Project: Role of Oyster Reefs	Oyster Biomass	grams dry body Wt per cubic meter per creek	Measuring reef area and quantifying oyster biomass in square meter quadrates	Approx 1 time per year	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1996 - 2000
CREEK Project: Role of Oyster Reefs	Water Chemistry, Water Quality, Chlorophyll a, and Suspended Sediment	Chlorophyll a (CHLA), Total Suspended Solids (SUSSol), Inorganic Susp. Solids (ISS), Organic Susp. Solids (OSS), Water Temp. (TEMP), Salinity (SAL), Total Nitrogen Filtered (TNF), Total Phosphorus Filtered (TPF), Dissolved Organic Carbon (DOC), Ammonia (NH4), Nitrate (NO3), & Orthophosphate (PO4)	colorimetric analysis on technicon autoanalyser, acetone extraction and fluorometer & combustion at 450 C on glass fiber filters	One liter of water taken one meter below water surface weekly at each creek	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	03/19/1997 - 02/23/2000
CREEK Project: Role of Oyster Reefs	Nekton (fish, shrimp, and crab)	Species abundance (#/m^3) and biomass (g/m^3) collection data and species list for bank-full high tides only.	Block nets set at early morning slack high tide; low tide pools seined	Seasonal	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	3/221997 - 11/03/1998
CREEK Project: Role of Oyster Reefs	Oyster Growth and Survival	Increase in Length and Number alive	Four plastic mesh bags with 25 oysters each set out in each creek at same tidal elevation	Seasonal	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1997 - 1999

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
CREEK Project: Role of Oyster Reefs	Microzooplankton	Replicate and abundance data, means and standard deviations for heterotrophic and phototrophic nanoflagellates, ciliates, chlorophyll a, and NH4.	Replicated morning mid-ebb water samples incubated for 72hr	19 March, 17 July, and 29 August 1997 (pre-manipulation year), and monthly from March through September 1998 (first post-manipulation year)	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1997 - 1998
CREEK Project: Role of Oyster Reefs	Phytoplankton Pigments	Species Abundance of phytoplankton	High Performance Liquid Chromatorgraphy (HPLC)	Pre-manip yr: Seasonally; Post-Manipulation yr: monthly	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1997 - 1999
CREEK Project: Role of Oyster Reefs	Internal Creek Habitat Survey	Amount of habitat that was oyster reef or shell, mud, sand and slope characteristics	Survey using tape measure and quadrates; 16 categories from mud to dense shell	once	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	Dec-93
BARUCH DATA: Coastal Intensive Site Network (CISNet) Molecular to landscape-scale monitoring of estuarine eutrophication							
CISNet Project: Phytoplankton Pigment Monitoring	Phytoplankton Pigments	Species Abundance of phytoplankton	High Performance Liquid Chromatorgraphy (HPLC)	sesaonally	5 locations: North Inlet and ACE Basin	Creek Codes: NI or ACE (1, 2, 3, 4, 5)	7/27/1999 - 9/18/2001
CISNet Project: Water Quality Monitoring	Water Quality & Water Chemistry	Water temperature, salinity, dissolved oxygen, light, pH, nitrogen, phosphorus, suspended solids, carbon, silicate, & chlorophyll a	triplicate 1-liter water samples, approx mid-way between daytime high and low tide stage	varying intervals from spring through early fall each year	5 locations: North Inlet and ACE Basin	Creek Codes: NI or ACE (1, 2, 3, 4, 5)	7/27/1999 - 9/18/2001

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA: LTER MEIOBENTHOS 1972 through 1995 (managed onsite & in process of archival and web publication)							
LTER MEIO (meiobenthos)	Meiobenthos	Taxa, abundance (per 10 cm2)	4-4.4cm, 3.48cm, 2.66cm diameter cores -> 2-2.66cm diameter cores	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	09/06/1968
LTER MEIO (meiobenthos)	Physical parameters for Meio	Air temperature	mercury filled thermometer	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	01/19/1977
LTER MEIO (meiobenthos)	Physical parameters for Meio	Surface Water temperature	Salinometer (or Refractometer) -> Hydrolab datalogger	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	01/19/1977
LTER MEIO (meiobenthos)	Physical parameters for Meio	Sediment-Water Interface (Surface Sediment) temperature	mercury filled thermometer	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	09/06/1968
LTER MEIO (meiobenthos)	Physical parameters for Meio	Redox (Eh) of sediment	platinum electrode -> visually	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	09/06/1968
LTER MEIO (meiobenthos)	Physical parameters for Meio	Surface Water Salinity	Salinometer (or Refractometer) -> Hydrolab datalogger	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	09/06/1968
LTER MEIO (meiobenthos)	Physical parameters for Meio	sediment grain size	Phi series sieves & pipette analysis	Monthly -> 10 to 18 days (approx. biweekly)	2	DD, BB	09/06/1969
LTER MEIO (meiobenthos)	Physical parameters for Meio	sediment organic content	wet dichromate method	Monthly -> 10 to 18 days (approx. biweekly)	2	DD,BB	09/06/1969

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Biological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA: NERR High Tide Nekton 1994 through 2011 (managed onsite & in process of archival and web publication)							
OL High Tide Fish	Nekton (fish, shrimp, and crab)	Taxa, abundance, length (mm SL), weight (g)	1/4" Funnel Net Deployed at Slack High; Animals collected at Low Tide	Monthly -> 10 to 18 days (approx. biweekly)	1	OI	08/17/1990
OL High Tide Fish	High Tide Bottom Water parameters	High Tide Water temp, Dissolved Oxygen, & Salinity	Hydrolab datalogger	Monthly -> 10 to 18 days (approx. biweekly)	1	OI	08/17/1990
OL High Tide Fish	Water parameters in Low Tide pool	High Tide Turbidity	Secchi disk	Monthly -> 10 to 18 days (approx. biweekly)	1	OI	08/17/1990
BARUCH DATA: LTER seine & trawl survey 1981 through 1984 (Paperback publication completed; in process of archival and web publication)							
LTER Seine & Trawl survey	fish, shrimp, crab	taxa, abundance, length, weight	2 beach hauls with 1/4" bag seine & 1-13 min Otter trawl in creek channel	10 to 18 days (approx. biweekly)	2	DD, BB	01/20/1981 - 11/07/1984
BARUCH DATA: LTER Zooplankton Monitoring 1981 through 2008 (in process of archival and web publication)							
LTER ZOOPLANKTON (ZPK)	Zooplankton	Taxa, life, stage, abundance (per m3)	153 µm paired nets, suspended into ebbing tide for 3 min Total (1 min each @ bottom, middle, surface waters)	10 to 18 days (approx. biweekly)	2 -> 1	DD, BB -> BB	DD:01/20/1981 - 01/04/1985
LTER ZOOPLANKTON (ZPK)	Physical parameters collected for zpk	depth at time of zpk	0.25 m increment marked rope used for ZPK collections	10 to 18 days (approx. biweekly)	2 -> 1	BB, DD -> BB	DD:08/26/1981 - 01/04/1985

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Meteorological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: LTER MET Jun 1982 through Apr 1996							
LTER MET (meteorological)	air temperature	degrees Celsius	YSI 703 Dual element epoxy coated thermistor	hrly ave. based on 1 sec samples from previous hour	1	OL	06/03/1982 - 04/29/1996
LTER MET (meteorological)	wind direction	1-360 degrees (no correction for magnetic declination)	Windmark III wind vane	Before 09/21/1989 hrly ave. based on 30 sec samples -> hrly ave. based on 1 sec samples from previous hour	1	OL	6/3/1982 - 04/29/1996
LTER MET (meteorological)	wind speed	meters/second	Windmark III 3cup anemometer	hrly ave. based on 1 sec samples from previous hour	1	OL	6/3/1982 - 04/29/1996
LTER MET (meteorological)	maximum hrly wind speed	meters/second	Windmark III 3cup anemometer	hrly maximum based on 1 sec samples from previous hour	1	OL	01/01/1993 - 04/29/1996
LTER MET (meteorological)	barometric pressure	940-1040 millibars	YSI 2014 pressure transducer	hrly ave. based on 1 sec samples from previous hour	1	OL	6/3/1982 - 04/29/1996
LTER MET (meteorological)	solar radiation	400-700 nm wavelengths (µE/M2/Sec or micromoles/M2/Sec	LI-COR LI190SB Quantum Sensor	hrly ave. based on 1 sec samples from previous hour	1	OL	10/5/1994 - 04/29/1996
LTER MET (meteorological)	solar radiation	(Langleys/min or mV/cal per cm-2 per min-1)	Eppley black and white 8-48 radiometer measuring 280-2800 nm wavelengths	hrly ave. based on 1 sec samples from previous hour	1	OL	6/3/1982 - 04/29/1996
BARUCH DATA ARCHIVES: LTER RAINDAZE Apr 1978 through Dec 2001							
RAINDAZE (meteorological)	precipitation	rainfall (mm & inches) {does not measure snowfall}	Belfort 5-780 tipping bucket -> NWS approved Dip-stick gauges -> Sierra-Misco & Campbell Scientific Tipping buckets	By event: Begin Date&Hr - End Date&Hr OR during a 24 hour period	1	OL	04/01/1978 - 12/31/2001

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Meteorological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: LTER NWS Dec 1986 through Mar 1996							
National Weather Service	Current & Min & Max Air Temperature	degrees Celsius	Visual inspection of thermometer OR Weekly charts: 2hr resolution	Daily at 1000 for previous 24hrs OR Interpreted from charts for 0000 to 2400 time period	1	OL	12/01/1986 - 02/04/1996
National Weather Service	Min & Max Barometric Press	millibars	Qualimetric weekly chart driven sensors: 2hr resolution	Min & Max Values derived from 0000 to 2400 time period	1	OL	10/10/1989 - 03/03/1996
National Weather Service	Min & Max Relative Humidity	percent saturation	Qualimetric weekly chart driven sensors: 2hr resolution	Min & Max Values derived from 0000 to 2400 time period	1	OL	12/29/1986 - 03/03/1996
National Weather Service	Precipitation	millimeters	Visual inspection of rain gauge OR Weekly charts: 2hr resolution	Daily at 1000 for previous 24hrs OR Interpreted from charts for 0000 to 2400 time period	1	OL	12/01/1986 - 03/03/1996
BARUCH DATA ARCHIVES: NIW NERR MET July 1997 through Dec 2004							
NERR MET (meteorological)	Air temperature	Degrees C	Campbell Scientific HMP35 Temperature and Humidity Probe with Thermistor -> Platinum Resistance Temp. Detector	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	7/2/1997 - 12/31/12004
NERR MET (meteorological)	Wind direction	1-360 degrees (no correction for magnetic declination)	R.M. Young Wind Sentry 03001-5 Anemometer and Vane Set	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	4/3/1998 - 12/31/2004
NERR MET (meteorological)	Wind speed	meters/second	R.M. Young Wind Sentry 03001-5 Anemometer and Vane Set	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	4/3/1998 - 12/31/2004
NERR MET (meteorological)	Barometric pressure	940-1040 millibars	CS105 Barometric Pressure Sensor using Barocap silicon capacitive press. Sensor	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	8/15/1997 - 12/31/2004

USC Baruch and NI-WB NERR Archived and Web Published Databases:

Meteorological Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
NERR MET (meteorological)	Relative humidity	percent saturation	Campbell Scientific HMP35 Temperature and Relative Humidity (RH) Probe with Capacitive RH sensor -> HUMICAP 180 capacitive RH sensor	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	7/2/1997 - 12/31/2004
NERR MET (meteorological)	Solar radiation	280-2800 nm wavelengths (Langleys/min or mV/cal per cm-2 per min-1)	Eppley black and white 8-48 pyranometer	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	6/30/1998 - 12/31/2004
NERR MET (meteorological)	Precipitation	rainfall (in mm) does not measure snowfall	Sierra-Misco 2500-8 tipping bucket	15 min instan; hrly & daily totals	1	OL	7/2/1997 - 12/31/2004
CDMO: NIW NERR SWMP Meteorological Data Jan 2001 through Dec 2010							
NERR MET (meteorological)	Air temperature	Degrees C	Campbell Scientific HMP35 Temperature and Humidity Probe with Thermistor -> Platinum Resistance Temp. Detector	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	
NERR MET (meteorological)	Relative humidity	percent saturation	Campbell Scientific HMP35 Temperature and Relative Humidity (RH) Probe with Capacitive RH sensor -> HUMICAP 180 capacitive RH sensor	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	
NERR MET (meteorological)	Barometric pressure	940-1040 millibars	CS105 Barometric Pressure Sensor using Barocap silicon capacitive press. Sensor	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	
NERR MET (meteorological)	Wind speed	meters per second	R.M. Young Wind Sentry 03001-5 Anemometer and Vane Set	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	
NERR MET (meteorological)	Wind direction	1-360 degrees (no correction for magnetic declination)	R.M. Young Wind Sentry 03001-5 Anemometer and Vane Set	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	
NERR MET (meteorological)	Precipitation	15 minute rainfall (millimeters) does not measure snowfall	Sierra-Misco 2500-8 tipping bucket	15 min instan; hrly & daily totals	1	OL	
NERR MET (meteorological)	Total Photosynthetic Active Radiation (PAR)	millimoles per square meter per 15 minutes	LI-190SB (LICOR) Quantum Terrestrial Radiation Sensor; 400-700 nm wavelengths	15 min instan; hrly & daily ave based on 5 sec samples	1	OL	

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Chemistry Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: LTER Daily Water Sample (DWS) Water Chemistry 1978 through JUNE 30, 1993							
LTER DWS (Water Chemistry)	Particulate organic carbon (POC)	microgram atoms/liter	Beckman 915A TOC analyzer -> after 01/23/1981 Oceanigraphics International TOC analyzer	once per day at 10 am	3	CB, OL, TC	04/14/1981 - 04/15/1987
LTER DWS (Water Chemistry)	Total organic carbon (TOC)	microgram atoms/liter	Beckman 915A TOC analyzer -> after 01/23/1981 Oceanigraphics International TOC analyzer	once per day at 10 am	1	TC	09/01/1978 - 08/17/1989
LTER DWS (Water Chemistry)	Dissolved organic carbon (DOC)	microgram atoms/liter	Beckman 915A TOC analyzer -> after 01/23/1981 Oceanigraphics International TOC analyzer -> after 10/02/89 Shimadzu TOC-500 analyzer	once per day at 10 am	4	CB, OL, TC, DB*	01/28/1980 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	total solids (TSS), inorganic sediment (ISS), organic sediment (OSS)	milligrams per liter	combustion at 450 C on glass fiber filters	once per day at 10 am	4	CB, OL, TC, DB*	02/12/1981 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	chlorophyll (CHLa) & Phaeophytin	Chlorophyll a & Phaeophytin -> Chlorophyl a	acetone extraction and fluorometer	once per day at 10 am	4	CB, OL, TC, DB*	09/08/1978 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	nitrate+nitrite (NN)	microgram atoms/liter	colorimetric analysis on technicon autoanalyser	once per day at 10 am	4	CB, OL, TC, DB*	06/16/1980 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	orthophosphate (OP)	microgram atoms/liter	colorimetric analysis on technicon autoanalyser	once per day at 10 am	4	CB, OL, TC, DB*	06/16/1980 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	ammonia (NH4)	microgram atoms/liter	colorimetric analysis on technicon autoanalyser	once per day at 10 am	4	CB, OL, TC, DB*	06/16/1980 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	total nitrogen whole (TNW) & filtered (TNF)	microgram atoms/liter	colorimetric analysis on technicon autoanalyser	once per day at 10 am	4	CB, OL, TC, DB*	06/16/1980 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	total phosphorus whole (TPW) and filtered (TPF)	microgram atoms/liter	colorimetric analysis on technicon autoanalyser	once per day at 10 am	4	CB, OL, TC, DB*	06/16/1980 DB=11/12/1985 - 11/16/1988

*DB data collected but not included in archived dataset

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Chemistry Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
BARUCH DATA ARCHIVES: NIW NERR Estuarine Surface Water Chemistry Jun 1993 through Dec 2004 (2002-2004 not available online)							
NERR WCHEM (Water Chemistry)	Dissolved organic carbon (DOC)	milligrams per liter	Shimadzu TOC-500 analyzer	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	total solids (TSS), inorganic sediment (ISS) & organic sediment (OSS)	milligrams per liter	combustion at 450 C on glass fiber filters	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 8/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	chlorophyll (CHLa)	micrograms per liter	acetone extraction and fluorometer	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	nitrate+nitrite (N-N)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	orthophosphate (OP)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	ammonia (NH4)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	total nitrogen whole (TNW) & filtered (TNF)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	Nitrite (NO2)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	4	CB, DC, OL, TA	3/22/2003 for all sites
NERR WCHEM (Water Chemistry)	total phosphorus whole (TPW) & filtered (TPF)	micromoles per liter	colorimetric analysis on technicon autoanalyser	every 20 day every 2hr4min for 25 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Chemistry Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection and end date (if different than rest of sites or main database)
CDMO System-Wide Monitoring Program (SWMP) NUTRIENT DATA: NIW NERR January 1, 2002 to September 30, 2010							
NERR WCHEM (Water Chemistry)	nitrate+nitrite (NN)	milligrams per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2002 for all sites
NERR WCHEM (Water Chemistry)	Nitrate (NO3)	milligrams per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2002 for all sites
NERR WCHEM (Water Chemistry)	Nitrite (NO2)	milligrams per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	3/22/2003 for all sites
NERR WCHEM (Water Chemistry)	orthophosphate (OP)	milligrams per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2002 for all sites
NERR WCHEM (Water Chemistry)	chlorophyll a (Chla)	milligrams per liter	acetone extraction and fluorometer	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2002 for all sites
NERR WCHEM (Water Chemistry)	ammonium (NH4)	milligrams per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2002 for all sites
BARUCH DATA: NIW NERR Estuarine Surface Water Chemistry Jan 2005 to Sep 2012 (managed onsite & not part of SWMP)							
NERR WCHEM (Water Chemistry)	total nitrogen whole (TNW) & filtered (TNF)	micromoles per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2005
NERR WCHEM (Water Chemistry)	total phosphorus whole (TPW) & filtered (TPF)	micromoles per liter	colorimetric analysis on technicon autoanalyser	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2005
NERR WCHEM (Water Chemistry)	total solids (TSS), inorganic sediment (ISS) & organic sediment (OSS)	milligrams per liter	combustion at 450 C on glass fiber filters	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2005
NERR WCHEM (Water Chemistry)	chlorophyll a (Chla)	micrograms per liter	acetone extraction and fluorometer	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2005
NERR WCHEM (Water Chemistry)	Dissolved organic carbon (DOC)	milligrams per liter	Shimadzu TOC-500 analyzer	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	4	CB, DC, OL, TA	01/01/2005
NERR WCHEM (Water Chemistry)	water wavelength absorbance	absorbance @ 355	550-250 nm Spectrophotometer	20 day every 2hr4min for 25 hrs + 2 reps @ end (13+2)	2	OL & TA	OL=03/26/2006 TA=03/25/2010

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Quality Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection (and end date if different than rest of sites or main database)
BARUCH DATA ARCHIVES: Daily Water Sample (DWS) Water Quality 1979 THROUGH JUNE 30, 1993							
LTER DWS (Water Chemistry)	salinity	parts per thousand	refractometer	once per day at 10 am	4	CB, OL, TC, DB*	08/27/79 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	Water Temperature	degrees Celsius	Hand Held Mercury Filled Thermometer	once per day at 10 am	4	CB, OL, TC, DB*	09/13/1979 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	Water Clarity	Secchi Disk	2M PVC Pole with Secchi Disk mounted at end; Pole marked at 10cm increments	once per day at 10 am	4	CB, OL, TC, DB*	02/25/1982 DB=11/12/1985 - 11/16/1988
LTER DWS (Water Chemistry)	Sediment (Water) Color	Sediment Color from Filtered Water Sample	Sediment Filter Color compared to Munsell Chart; code written down	once per day at 10 am	4	CB, OL, TC, DB*	06/1988 DB=11/12/1985 - 11/16/1988
							*DB data collected but not included in archived dataset
BARUCH DATA ARCHIVES: LTER MET JUNE 1982 THROUGH APRIL 1996							
LTER MET	Water Physicals	Water Temp (degrees Celsius)	YSI 070/44018/NA/RN/300 plastic coated thermistor	hrly ave. based on 1 sec samples from previous hour	1	OL	01/01/1993 - 04/29/1996
LTER MET	Water Physicals	Water level @ 0.0-3.0 meters (corrected for barometric pressure)	Enviro-Labs water level sensor -> Kellar PSI PT108V-50-15PSI VENTED Water level sensor	6 min & hrly instantaneous	1	OL	01/01/1993 - 04/29/1996
LTER MET	Water Physicals	Conductivity @ 0.0-2.0 millivolts per centimeter	YSI Conductivity Sensor (glass cond. cell and temp. compensator) -> RoseMont 1181T-00-02-99 water conductivity probe	hrly ave. based on 1 sec samples from previous hour	1	OL	01/01/1993 - 04/29/1996
BARUCH DATA ARCHIVES: NIW NERR Estuarine Surface Water Chemistry Jun 2, 1993 to Dec 2001							
NERR WCHEM (Water Chemistry)	salinity	parts per thousand	refractometer	every 20 day every 2hr4min for 26 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994
NERR WCHEM (Water Chemistry)	Sediment (Water) Color	Sediment Color from Filtered Water Sample	Sediment Filter Color compared to Munsell Chart; code written down	every 20 day every 2hr4min for 26 hrs	3 -> 2 -> 4	CB, OL, TA -> OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Quality Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection (and end date if different than rest of sites or main database)
BARUCH DATA ARCHIVES: NIW NERR Estuarine Water Quality Oct 25,1993 to Dec 31, 2002							
NERR WatQual (Water Quality)	salinity	parts per thousand	YSI or Hydrolab water quality sensor	every 30 min	3 -> 4	CB, OL, TA -> CB, DC, OL, TA	CB=10/25/1993-6/30/1995; 8/17/2001 DC=03/05/1998 OL=10/25/1993 TA=04/15/1994
NERR WatQual (Water Quality)	specific conductivity	millisiemens per cm	YSI or Hydrolab water quality sensor	every 30 min	3 -> 4	CB, OL, TA -> CB, DC, OL, TA	CB=10/25/1993-6/30/1995; 8/17/2001 DC=03/05/1998 OL=10/25/1993 TA=04/15/1994
NERR WatQual (Water Quality)	Water Temperature	degrees Celsius	YSI or Hydrolab water quality sensor	every 30 min	3 -> 4	CB, OL, TA -> CB, DC, OL, TA	CB=10/25/1993-6/30/1995; 8/17/2001 DC=03/05/1998 OL=10/25/1993 TA=04/15/1994
NERR WatQual (Water Quality)	dissolved oxygen	mg/L and % saturation	YSI or Hydrolab water quality sensor	every 30 min	3 -> 4	CB, OL, TA -> CB, DC, OL, TA	CB=10/25/1993-6/30/1995; 8/17/2001 DC=03/05/1998 OL=10/25/1993 TA=04/15/1994
NERR WatQual (Water Quality)	pH		YSI or Hydrolab water quality sensor	every 30 min	2 -> 4	-> OL, TA -> CB, DC, OL, TA	CB=8/17/2001 DC=03/08/1998 OL=01/08/1997 TA=01/22/1996
NERR WatQual (Water Quality)	turbidity	NTU	YSI or Hydrolab water quality sensor	every 30 min	2 -> 4	-> OL, TA -> CB, DC, OL, TA	CB=8/17/2001 DC=03/08/1998 OL=01/08/1997 TA=01/22/1996
NERR WatQual (Water Quality)	Depth	meters	YSI or Hydrolab water quality sensor	every 30 min	3 -> 4	CB, OL, TA -> CB, DC, OL, TA	CB=06/02/1993-12/30/1995; 12/19/2001 DC=03/08/1998 OL=06/02/1993 TA=04/18/1994

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Water Quality Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning of data collection (and end date if different than rest of sites or main database)
BARUCH DATA ARCHIVES: Motile Epibenthos Biweekly Water Physicals Jan 18, 1981 to Dec 2003							
LTER/NERR Biweekly Epibenthos Water Physicals	salinity	parts per thousand	Conductivity meter -> YSI or Hydrolab water quality sensor	every 10-18 day (biweekly)	3 -> 1	DD, BB -> BB	DD=01/18/1981- 12/18/1984 BB=01/18/1981
LTER/NERR Biweekly Epibenthos Water Physicals	Water Temperature	degrees Celsius	Conductivity meter -> YSI or Hydrolab water quality sensor	every 10-18 day (biweekly)	3 -> 2	DD, BB -> BB	DD=01/18/1981- 12/18/1984 BB=01/18/1981
LTER/NERR Biweekly Epibenthos Water Physicals	dissolved oxygen	mg/L	YSI or Hydrolab water quality sensor	every 10-18 day (biweekly)	3 -> 2	BB	BB=09/23/1993
LTER/NERR Biweekly Epibenthos Water Physicals	Light	micromoles per meter^2 per second	LI-COR LI-193SB Underwater Spherical Quantum Sensor	every 10-18 day (biweekly)	3 -> 2	DD, BB -> BB	DD=01/18/1981- 12/18/1984 BB=01/18/1981
LTER/NERR Biweekly Epibenthos Water Physicals	Tide velocity	meters per second	Marsh McBirney Model 201D Portable Water Current Meter	every 10-18 day (biweekly)	3 -> 2	DD, BB -> BB	DD=01/18/1981- 12/18/1984 BB=01/18/1981

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Rescued and Archived Data

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Forest-Marsh-Tidal Creek Groundwater Dynamics	Groundwater water level (Head pressure)	Piezometer readings	15 minute datalogger readings at different piezometer depths along transects	10 to 15 days	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	03/16/1994 - 05/02/1996
Forest-Marsh-Tidal Creek Groundwater Dynamics	Station Elevations	Topographic elevations	1993: TopCon Total Station and Prism Reflector; 1996: Leveling Telescope	1 time 1993; 1 time in 1996	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	1993 & 1996
Forest-Marsh-Tidal Creek Groundwater Dynamics	Water Level Groundtruthing	Dipstick Measurements	PVC pipe with two wires protruding from holes in a rubber stopper at the bottom end, sounded when immersed in water	bimonthly	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	1994 - 1996
Forest-Marsh-Tidal Creek Groundwater Dynamics	Botanical Zonation along Transects	Plant identifications, heights, and communities	Measured and documented along transects	once in summer	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	June - August 1993
Forest-Marsh-Tidal Creek Groundwater Dynamics	Hydraulic conductivities	Slug Test	Recorded time between slug was inserted into piezometer and when water returned to ambient level	Once only for 292 of 306 piezometers	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	unknown
Forest-Marsh-Tidal Creek Groundwater Dynamics	Groundwater salinities	Salinity	piezometer well water salinity measured by optical refractometer	bimonthly	3 (Transects)	Transects across CrabHaul Creek; Codes: B, C, D	1994 - 1996
NADP (National Atmospheric Deposition Program)	Precipitation Chemistry	Sulfate, Nitrate, Ammonium, Chloride, Calcium, Magnesium, Potassium, and Sodium, Acidity (pH)	Samples collected with strict clean-handling procedures and sent to Analytical Laboratory for analysis	Weekly	1	OL	01/08/2002

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Oyster Growth	Oyster Growth	Shell length & width (mm); Weight (grams)	40 oysters per Replicate; 3 Reps per depth; 2 depth levels: 1 & 3ft below water surface	bimonthly	2	OL & CB	11/1984 - 03/1987
Oyster Spat Recruitment	Number of Oyster Larvae Settled onto Mid and Low Intertidal & Subtidal plates	Abundance (#/225cm2) of Spat on Top and Bottom of Plate	6 plates per site; 2 plates each at 3 different depths	Every 12 to 16 days	3 -> 1	OL, OM, TC -> TC	04/01/82 - 1986
Oyster Spat Recruitment	Number of Spat Settled onto Plates at Differing Days of Deployment	Number of Spat on Top and Bottom of Plate	2 replicate plates per level at three levels	3, 7, 10, 14 days	1	TC	April 1986 - October 1986
LTER Spartina	sediment temp	degrees Celsius	tempmentor	20 minutes	2 OL,GI	OL, GI	unknown
LTER Decomposition	LTER intersite litterbag decomposition	weight loss of bag contents + animal taxa	decomposition bags	annual	2	OL, GI	1991 - 1995
LTER Ibis Feeding	Number of White Ibis Feeding	Life Stage and Number by Hour in 65 ha plot	Visual Census from Spotting Scope at Clambank Tower	Weekly & Biweekly	1	Bly	6/15/1984 - 7/26/1989
LTER Ibis Feeding	Vegetation Cover	% Coverage by Subtrate in 65 ha feeding plot	Field Inspection; Quadrate Analysis	Weekly & Biweekly	1	Bly	6/15/1984 - 7/26/1989
LTER Ibis Feeding	Substrate Cover	% Coverage by Subtrate in 65 ha feeding plot	Field Inspection; Quadrate Analysis	Weekly & Biweekly	1	Bly	6/15/1984 - 7/26/1989
LTER 48 Hour Zooplankton/Fish Study	Zooplankton	Surface & Bottom Abundance	Stationary boat using 153 micron Nets & centrifical pump	Every Hour for 48 Hours	1	BB	Two studies: June 4-5, 1985 & August 6-8, 1986

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
LTER 48 Hour Zooplankton/Fish Study	Motile Epizooplankton	Surface & Bottom Abundance	365 micron mesh Sled towed behind a boat	Every Hour for 48 Hours	1	BB	Two studies: June 4-5, 1985 & August 6-8, 1986
LTER 48 Hour Zooplankton/Fish Study	Zooplanktivorous Fish	Surface & Bottom Abundance	Otter Trawl with 1/4 inch bag liner & Surface Trawl	Every Hour for 48 Hours	1	BB	Two studies: June 4-5, 1985 & August 6-8, 1986
LTER 48 Hour Zooplankton/Fish Study	Water Physicals	Water Temperature, Salinity, Water Velocity & Light Penetration	Salinometer, Marsh McBirney Current Meter, LI-Cor Quantum Sensor	Every Hour for 48 Hours	1	BB	Two studies: June 4-5, 1985 & August 6-8, 1986
LTER 48 Hour Zooplankton/Fish Study	Zooplanktivorous Fish Gut Contents	Zooplankton Species Abundance and Volume in Guts	Dissection and Visual Identifications and measurements via microscope	Every Hour for 48 Hours	1	BB	Two studies: June 4-5, 1985 & August 6-8, 1986
LTER Biweekly Zooplankton/Fish Study	Zooplankton	Surface, Midwater, & Bottom Abundance	Stationary boat using 153 micron Nets	Every 10 to 18 days	1	BB	06/28/1985 - 02/11/1987
LTER Biweekly Zooplankton/Fish Study	Motile Epizooplankton	Epibenthic Abundance	365 micron mesh Sled towed behind a boat	Every 10 to 18 days	1	BB	06/28/1985 - 02/11/1987
LTER Biweekly Zooplankton/Fish Study	Zooplanktivorous Fish	Surface & Bottom Abundance	1/4 inch Surface Trawl & Otter Trawl with 1/4 inch bag liner	Every 10 to 18 days	1	BB	06/28/1985 - 02/11/1987
LTER Biweekly Zooplankton/Fish Study	Water Physicals	Water Temperature, Salinity, Water Velocity & Light Penetration	Salinometer, Marsh McBirney Current Meter, LI-Cor Quantum Sensor	Every 10 to 18 days	1	BB	06/28/1985 - 02/11/1987
LTER Biweekly Zooplankton/Fish Study	Zooplanktivorous Fish Gut Contents	Zooplankton Species Abundance and Volume in Guts	Dissection and Visual Identifications and measurements via microscope	Every 10 to 18 days	1	BB	06/28/1985 - 02/11/1987
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Carbon	Total Organic Carbon (TOC), Particulate organic carbon (POC), Dissolved Inorganic carbon (DIC), & Dissolved organic carbon (DOC)	Wet Persulfate Digestion & Oceanographic Carbon Analyzer	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Suspended Sediments	total solids (TSS) & inorganic sediment (ISS)	combustion at 450 C on glass fiber filters	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Water Parameters	salinity	refractometer	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Chlorophyll a	chlorophyll (CHLa) & Phaeophytin	acetone extraction and fluorometer	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Microbial biomass	Microbial ATP (adenosine 5'-triphospate) nanograms per milliliter	3 -20 ml aliquots from a single 1 liter water sample	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Nutrient Chemistry	nitrate-nitrite (N-N)	colorimetric analysis on technicon autoanalyser	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Nutrient Chemistry	orthophosphate (OP)	colorimetric analysis on technicon autoanalyser	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Nutrient Chemistry	ammonia (NH4)	colorimetric analysis on technicon autoanalyser	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Nutrient Chemistry	total nitrogen whole (TNW) & filtered (TNF)	colorimetric analysis on technicon autoanalyser	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Marsh Flume, Creek Transect, Oyster Flume, or Marsh Weir Nutrient Chemistry	total phosphorus whole (TPW) & filtered (TPF)	colorimetric analysis on technicon autoanalyser	Every 10 days	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984
Blycreek Ecosystem Flux Study	Flux Study at Marsh Flume, Oyster Reef, and Creek Transect	All above plus POC, PN, DON, PP, DOP, DO, H20 Discharge with incoming and outgoing tide	See documentation at Field Laboratory or Baruch's website	Half Hourly every 21st tidal cycle	4	BC, MF, OF, MW	04/15/1983 - 06/19/1984

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	Total Nitrogen	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	Total Phosphorous	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	ammonia (NH4)	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	nitrate-nitrite (N-N)	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	orthophosphate (OP)	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	Sulfate	colorimetric analysis on technicon autoanalyser	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	Cations: Chloride, Sodium (Na), Potassium (K), Calcium (Ca) & Magnesium (Mg)	Flame Atomic Adsorption Analysis	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992
Forest Rainfall Chemistry	Rainfall, Throughfall, Stemflow, Litter water, Stream Flow, and Soil water Nutrients	pH	pH meter	Every Precipitation/ Storm Event	6	TF, LY, GD, SF, BU, & SR	5/23/82 - 10/09/1992

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Motile epibenthic macrozooplankton & Larval fish	Taxa, life stage, length, abundance (per m3)	3 Sequential 365 µm net sled tows, 2 to 30 cm off the creek bottom, tow with the ebbing tide	48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Zooplankton	Taxa, life, stage, abundance (per m3)	2 Sequential Oblique tows, boat moving against current	48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Fish, shrimp, and crab	Taxa, life, stage, abundance	16ft headrope Otter (Shrimp) 1 1/2 in. to 1 1/4 in. Trawl; towed against current along designated tow path & Gill nets	48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Physical parameters collected for Epi and Zpk	Surface & Bottom water temperature	Salinometer	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Physical parameters collected for Epi and Zpk	Surface & Bottom salinity	Salinometer	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Physical parameters collected for Epi and Zpk	water velocity	Marsh McBirney Model 201D Portable Water Current meter (m/sec) 50cm Increments: Surface to Bottom	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Physical parameters collected for Epi and Zpk	vertical visibility	Secchi disk	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Physical parameters collected for Epi and Zpk	depth at time of zpk	0.25 m increment marked rope	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Nutrient Data	nitrate-nitrite (N-N)	colorimetric analysis on technicon autoanalyser	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982

USC Baruch and NI-WB NERR Archived and Web Published Databases:
Historical Data Needing Rescue, Archival and Web Publication

Core database group name	Core Parameters measured	Variables collected	Collection protocol	Collection Frequency	Number of sites - See map	Site designation code	Beginning and end Date of data collection
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Nutrient Data	orthophosphate (OP)	colorimetric analysis on technicon autoanalyser	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Nutrient Data	ammonia (NH4)	colorimetric analysis on technicon autoanalyser	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Nutrient Data	total nitrogen whole (TNW) & filtered (TNF)	colorimetric analysis on technicon autoanalyser	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Nutrient Data	total phosphorus whole (TPW) & filtered (TPF)	colorimetric analysis on technicon autoanalyser	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Carbon Data	Total organic carbon (TOC) & Dissolved organic carbon (DOC)	Beckman 915A TOC analyzer -> after 01/23/1981 Oceanigraphics International TOC analyzer	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
Estuarine Characterization & Petroleum Impact of Winyah Bay, SC	Surface & Bottom Phytoplankton Pigments	chlorophyll (CHLa) & Phaeophytin	acetone extraction and fluorometer	Hourly: 48 Hr, 3 Week, and 6 weeks	3 -> 14	SJ, NMF, WB -> PR, SR, PD, WR, US, BI, TA, PS, MS, TC, EP, MB, SB, MN	August 1980 - September 1982
CREEK Project: Role of Oyster Reefs	Creek Geomorphology	elevations of marsh surfaces and creeks	Total Station?	Over the course of 6 months?	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1997
CREEK Project: Role of Oyster Reefs	Oyster Disease	unknown	unknown	unknown	Four Creeks each in Clambank & Town Creeks	Creek Codes: 1, 2, 3, 4, 5, 6, 7, 8	1997 - 1999
NADP (National Atmospheric Deposition Program)	Precipitation Chemistry	Sulfate, Nitrate, Ammonium, Chloride, Calcium, Magnesium, Potassium, and Sodium, Acidity (pH)	Samples collected with strict clean-handling procedures and sent to Analytical Laboratory for analysis	Weekly	1	OL	01/08/2002

Appendix C

Vascular Plant List for Hobcaw Barony and Adjacent Estuarine Habitats

Vascular Plant List for Hobcaw Barony and Adjacent Estuarine Habitats

Source: John M. Barry. 1966. A Survey of the Native Vascular Plants of the Baruch Plantation. B.S. Honor's Project. University of South Carolina. Edited 1998 by John Baden, Army Corps of Engineers, Wilmington, NC, and Dick Stalter, Dept. Biol. Sciences, St. John's University Taxonomic verifications: Integrated Taxonomic Information System (http://www.itis.gov) by Ginger Ogburn-Matthews, BMFL. 2006.

Species	Common Name	Synonym Name
Pinaceae		
Pinus palustris	longleaf pine	
Pinus taeda	loblolly pine	
Pinus serotina	pond pine, marsh pine, pocosin pine	
Taxodiaceae		
Taxodium distichum	bald or swamp cypress	
Taxodium ascendens	pond cypress	
Cupressaceae		
Juniperus virginiana	red cedar juniper, eastern red cedar	
Juniperus virginiana var. silicicola	coast juniper, southern red cedar, coastal red cedar	
Typhaceae		
Typha angustifolia	narrow-leaf cat-tail	
Typha domingensis	southern cat-tail	
Alismataceae		
Sagittaria lancifolia	bulltongue arrowhead	
Poaceae		
Arundinaria gigantea	giant cane	
Arundo donax	giant reed	
Phragmites australis	common reed	*Phragmites communis*
Distichlis spicata	saltgrass, marsh spikegrass, seashore saltgrass	
Chasmanthium laxum	slender woodoats, spike uniola	*Uniola laxa*
Uniola paniculata	seaoats	
Poa annua	annual blue grass, walk grass	
Melica mutica	onion grass, twoflower melic grass	
Elymus virginicus	Virginia wild rye	
Sphenopholis obtusata	prairie wedge grass, prairie wedgescale	
Aristida Purpurascens var virgata	arrowfeather threeawn	*Aristida virgata*
Sporobolus indicus var. indicus	smutgrass	*Sporobolus poiretii*
Sporobolus virginicus	seashore dropseed	
Cynodon dactylon	Bermuda grass	
Ctenium aromaticum	toothache grass	
Eustachys petraea	pinewoods finger grass	*Chloris petraea*
Setaria magna	giant bristle grass	*Chaetochloa magna*
Setaria parviflora	knot root or marsh bristlegrass	*Setaria geniculata*
Spartina alterniflora	saltmarsh, Atlantic, or smooth cordgrass	
Spartina cynosuroides	big or giant cordgrass	

Species	Common Name	Synonym Name
Poaceae		
Spartina patens	saltmeadow or marsh hay cordgrass	
Phalaris canariensis	common or annual canary grass	
Leersia lenticularis	catchfly grass	*Homalocenchrus lenticularis*
Zizaniopsis miliacea	giant cutgrass	*Zizania miliacea*
Cenchrus tribuloides	sanddune sandbur, sandspur	
Oplismenus hirtellus	shortleaf or bristle basketgrass	*Oplismenus setarius*
Paspalum notatum	Bahia grass	
Paspalum urvillei	Vasey or Vasey's grass	
Paspalum boscianum	bull crown grass	
Paspalum bifidum	pitchfork crown grass	
Paspalum setaceum	fringeleaf, sand, or thin paspalum	
Digitaria sanguinalis	hairy, large, purple, or redhair crab grass	
Digitaria filiformis	slender crab grass	
Digitaria cognata var. cognata	fall witch grass or Carolina crabgrass	*Leptoloma cognatum*
Sacciolepis striata	American cupscale	
Panicum anceps	beaked panic grass or panic grass	
Panicum virgatum	switch grass, old switch panic grass	
Panicum dichotomiflorum	fall panicum or panic grass, western witch grass	
Panicum verrucosum	warty panic grass	
Panicum tenerum	bluejoint panic grass or panicum	
Dichanthelium strigosum var. leucoblepharis	roughhair rosette grass	*Panicum ciliatum*
Dichanthelium aciculare	needleleaf rosette grass	*Panicum angustifolium*
Dichanthelium dichotomum var. dichotomum	cypress panic grass	*P. dichotomum, P. lucidum, P. microcarpon*
Dichanthelium wrightianum	Wright's rosette grass	*Panicum wrightianum*
Dichanthelium acuminatum var. fasciculatum	tapered or western rosette grass, Huachuca panic	*Panicum curtifolium*
Panicum rigidulum var. pubescens	redtop panic grass	*Panicum longifolium*
Dichanthelium sphaerocarpon var. sphaerocarpon	roundseed panic grass or panicum	*Panicum sphaerocarpon*
Dichanthelium scoparium	velvet panicum	*Panicum scoparium*
Saccharum brevibarbe var. contortum	bentawn or sortbeard plume grass	*Erianthus contortus*
Andropogon ternarius	split beard bluestem	
Andropogon virginicus	broom sedge, broomsedge or yellow bluestem	
Andropogon glomeratus	bushy bluestem or broom sedge	
Sorghum halepense	Johnson grass	
Cyperaceae		
Cyperus filicinus	fern flatsedge	*Cypress nuttallii*
Cyperus flavicomus	white-edge flatsedge	*Cyperus albomarginatus*
Cyperus distans	Piedmont flatsedge	
Cyperus esculentus	chufa, chufa flatsedge, yellow nutgrass, yellow nutsedge	
Cyperus compressus	poorland flatsedge	
Cyperus dentatus	toothed flatsedge	
Cyperus pseudovegetus	marsh flatsedge	
Eleocharis quadrangulata	squarestem spikerush or spikesedge	
Eleocharis tuberculosa	cone-cup spikerush	

Species	Common Name	Synonym Name
Cyperaceae		
Eleocharis microcarpa	smallfruit spikerush	
Rhynchospora colorata	starrush whitetop	*Dichromena colorata*
Rhynchospora nitens	shortbeak beaksedge	*Psilocarya nitens*
Bulbostylis capillaris	densetuft hairsedge, threadleaf beakseed	
Schoenoplectus americanus	American, chairmaker's, or Olney bulrush	*Scirpus americanus*
Scirpus robustus	saltmarsh robustus	
Scirpus polyphyllus	leafy bulrush	
Scirpus cyperinus	bulrush, woolgrass	
Scirpus divaricatus	spreading bulrush	
Scirpus pendulus, S. lineatus	drooping, hanging, pendulous, rufous bulrush	*S. fontinalis*
Fuirena pumila	dwarf umbrella sedge	
Rhynchospora tracyi	Tracy's beaksedge	
Rhynchospora corniculata	shortbristle horned beaksedge	
Rhynchospora fascicularis	fascicled beaksedge	
Rhynchospora rariflora	fewflower beaksedge	
Rhynchospora miliacea	millet beaksedge	
Araceae		
Orontium aquaticum	goldenclub	
Peltandra virginica	green arrow arum, Virginia peltandra	
Arisaema triphyllum	Jack-in-the-pulpit, Indian jack in the pulpit	
Lemnaceae		
Lemna perpusilla	minute duckweed	
Wolffiella gladiata	Florida mudmidget	*W. floridana*
Xyridaceae		
Xyris torta	common or slender yelloweyed grass	*X. flexuosa*
Xyris smalliana	Small's yelloweyed grass	
Xyris ambigua	coastal plain yelloweyed grass	
Xyris difformis	bog or southern yelloweyed grass	
Xyris jupicai	Richard's yelloweyed grass	
Xyris caroliniana	Carolina yelloweyed grass	
Eriocaulaceae		
Eriocaulon decangulare	tenangle pipewort	
Eriocaulon compressum	flattened pipewort	
Lachnocaulon minus	Small's bogbutton	
Lachnocaulon anceps	whitehead bogbutton	
Bromeliaceae		
Tillandsia usneoides	Spanish moss	
Pontederiaceae		
Pontederia cordata	pickerelweed	

Species	Common Name	Synonym Name
Juncaceae		
Juncus effusus	common, soft, or lamp rush	
Juncus gymnocarpus	Pennsylvania rush	
Juncus roemerianus	needle rush	
Juncus repens	lesser creeping rush	
Juncus biflorus	bog rush	
Juncus abortivus	annual rush	
Juncus polycephalus	flatleaf or manyhead rush	
Juncus elliottii	Elliott's rush	
Juncus articulatus	jointed rush, jointleaf rush	
Liliaceae		
Asparagus officinalis	asparagus, garden asparagus	
Aletris farinosa	white colicroot	
Hymenocallis floridana	Florida spiderlily	*H. crassifolia*
Smilacaceae		
Smilax pseudochina	bamboo vine	*S. tamnifolia*
Smilax rotundifolia	bullbriar, greenbrier, common catbriar	
Smilax bona-nox	saw greenbrier	
Smilax glauca	cat greenbrier, sawbrier	
Smilax walteri	coral greenbrier	
Agavaceae		
Yucca aloifolia	aloe yucca, Spanish bayonet	
Yucca gloriosa	mound-lily yucca	
Iridaceae		
Iris virginica	Virginia iris, southern blue flag	
Orchidaceae		
Habenaria repens	Water-spider bog orchid	
Platanthera flava var. flava	pale-green orchid	*Habenaria flava*
Platanthera clavellata	small green-wood orchid	*Habenaria clavellata*
Platanthera cristata	crested yellow orchid	*Habenaria cristata*
Salicaceae		
Salix nigra	black willow	
Salix caroliniana	coastal plain or swamp willow	
Myricaceae		
Morella cerifera	wax myrtle	*Myrica cerifera*
Betulaceae		
Alnus serrulata	alder, brook-side or hazel alder	

Species	Common Name	Synonym Name
Fagaceae		
Quercus virginiana	live oak	
Quercus nigra	water oak	
Quercus michauxii	swamp chestnut oak	
Quercus margaretta	sand post oak	
Quercus pagoda	cherrybark or swamp Spanish oak	*Quercus falcata var.pagodifolia*
Quercus laevis	turkey oak	
Quercus laurifolia	laurel oak	
Ulmaceae		
Ulmus americana	American elm	
Urticaceae		
Boehmeria cylindrica	small spike false nettle	
Polygonaceae		
Rumex acetosella	sheep, field, or red sorrel	
Rumex hastatulus	heartwing dock or sorrel	
Polygonum hydropiperoides	swamp smartweed or water pepper	
Polygonum setaceum	bog smartweed	
Polygonum sagittatum	arrowleaf tearthumb or knotweed, arrowvine	
Chenopodiaceae		
Chenopodium album	lambsquarters, white goosefoot	
Atriplex cristata	crested saltbush	*Atriplex arenaria*
Atriplex patula	spear saltbush or saltweed	
Salicornia maritima	slender glasswort	*Salicornia europaea*
Salicornia virginica	Virginia glasswort	
Suaeda linearis	annual seepweed, sea blite	
Amaranthaceae		
Alternanthera philoxeroides	Alligator or pig weed	
Amaranthus cannabinus	tidalmarsh amaranth	
Caryophyllaceae		
Stellaria media	chickweed	
Cerastium glomeratum	sticky chickweed	*Cerastium viscosum*
Nymphaeaceae		
Nymphaea odorata	American or white waterlilly	
Ranunculaceae		
Ranunculus pusillus	low spearwort, weak buttercup	
Magnoliaceae		
Liriodendron tulipifera	tulip tree or popular, yellow popular	
Magnolia virginiana	sweetbay	
Magnolia grandiflora	southern magnolia	

Species	Common Name	Synonym Name
Lauraceae		
Persea borbonia	redbay	
Sassafras albidum	sassafras	
Brassicaceae		
Cardamine pensylvanica	Pennsylvania or Quaker bittercress	
Grossulariaceae		
Itea virginica	Virginia sweetspire	
Hydrangeaceae		
Decumaria barbara	woodvamp or climbing hydrangea	
Hamamelidaceae		
Liquidambar styraciflua	sweet gum	
Rosaceae		
Duchesnea indica	Indian strawberry	
Rubus argutus	sawtooth or prickly Florida blackberry	*Rubus betulifolius*
Rubus hispidus	bristly dewberry	
Rubus trivialis	southern dewberry	
Rosa palustris	swamp rose	
Photinia pyrifolia	red chokeberry	*Sorbus arbutifolia*
Prunus serotina	black cherry, black chokecherry	
Prunus caroliniana	Carolina laurel cherry	
Fabaceae		
Chamaecrista fasciculate var. fasciculata	sleeping plant	*Cassia fasciculata*
Chamaecrista nictitans var. nictitans	partridge pea	*Cassia nictitans*
Crotalaria purshii	Pursh's rattlebox	
Crotalaria rotundifolia	rabbitbells	*Crotalaria angulata*
Crotalaria spectabilis	showy crotalaria or rattlebox	
Desmodium nudiflorum	barestem tickclover, nakedflower ticktrefoil	
Desmodium canescens	hoary tickclover or ticktrefoil	
Glottidium vesicarium	bagpod	
Wisteria frutescens	American wisteria	
Strophostyles helvola	wild bean, fuzzy bean	
Linaceae		
Linum striatum	ridged yellow flax, rigid flax	
Linum virginianum	woodland flax	
Polygalaceae		
Polygala mariana	Maryland milkwort	
Euphorbiaceae		
Triadica sebiferum	chinese tallow-tree	*Sapium sebifera*
Chamaesyce polygonifolia	seaside sandmat or spurge	*Euphorbia polygonifolia*
Chamaesyce maculata	large spurge, spotted sandmat	*Euphorbia maculata*

Species	Common Name	Synonym Name
Anacardiaceae		
Toxicodendron radicans	poison ivy, eastern poison ivy	*Rhus radicans*
Toxicodendron pubescens	poison oak, Atlantic poison oak	*T. toxicodendron*
Rhus copallina	dwarf or winged sumac	
Aquifoliaceae		
Ilex vomitoria	yaupon	
Ilex glabra	inkberry	
Ilex opaca	American holly	
Aceraceae		
Acer rubrum	red maple	
HippocastanaceaE		
Aesculus pavia	red buckeye	
Vitaceae		
Parthenocissus quinquefolia	Virginia creeper, woodbine, fiveleaved ivy	
Vitis rotundifolia	muscadine, muscadine grape	
Vitis aestivalis	summer grape	
Ampelopsis arborea	peppervine	
Tiliaceae		
Tilia americana var. caroliniana	Carolina basswood	*Tilia caroliniana*
Malvaceae		
Hibiscus moscheutos	crimsoneyed rosemallow, swamp rosemallow	
Hibiscus laevis	halberdleaf or scarlet rosemallow	*Hibiscus militaris*
Clusiaceae		
Hypericum galioides	bedstraw St. Johnswort	
Hypericum cistifolium	roundpod St. Johnswort	
Hypericum setosum	hairy St. Johnswort	
Hypericum gymnanthum	claspingleaf St. Johnswort	
Hypericum mutilum	dwarf St. Johnswort	
Hypericum denticulatum	coppery St. Johnswort	
Cistaceae		
Helianthemum corymbosum	pinebarren frostweed	
Lechea maritima	beach pinweed	
Violaceae		
Viola X primulifolia	primrose violet	
Viola lanceolata	lanceleaf violet, bog white violet	
Cactaceae		
Opuntia ficus-indica	prickly pear, Indian fig, tuna cactus	*Opuntia compressa*
Opuntia pusilla	cockspur pricklypear	*Opuntia drummondii*

Species	Common Name	Synonym Name
Lythraceae		
Decodon verticillatus	swamp loosestrife	
Cuphea carthagenensis	Colombian waxweed	
Melastomataceae		
Rhexia petiolata	fringed meadowbeauty	
Rhexia alifanus	savannah meadowbeauty	
Rhexia aristosa	awnpetal meadowbeauty	
Rhexia mariana	Maryland meadowbeauty	
Onagraceae		
Ludwigia leptocarpa	anglestem primrose-willow	
Ludwigia virgata	savannah primrose-willow	
Ludwigia maritima	seaside primrose-willow	
Ludwigia microcarpa	smallfruit primrose-willow	
Ludwigia palustris	marsh primrose-willow	
Oenothera laciniata	cut-leaf evening-primrose	
Oenothera fruticosa	narrowleaf evening-primrose	
Haloragaceae		
Proserpinaca palustris	marsh mermaid-weed	
Proserpinaca pectinata	mermaid-weed	
Myriophyllum aquaticum	parrot feather watermilfoil	*M. brasiliense*
Araliaceae		
Aralia spinosa	devil's walkingstick	
Apiaceae		
Hydrocotyle umbellata	manyflower marsh pennywort, umbrella pennyroyal	
Hydrocotyle verticillata	whorled marsh pennywort, whorled pennyroyal	
Centella asiatica	spadeleaf	
Eryngium integrifolium	blueflower or simple leaf eryngo	
Sium suave	common or hemlock water-parsnip	
Lilaeopsis chinensis	eastern grasswort	
Ptilimnium capillaceum	herbwilliam, threadleaf mockbishopweed	
Ptilimnium macrospermum		
Oxypolis filiformis	water cowbane	
Nyssaceae		
Nyssa sylvatica	black gum or tupelo	
Nyssa biflora	swamp tupelo	
Nyssa aquatica	water tupelo	
Cornaceae		
Cornus foemina	stiff dogwood	*Cornus stricta*
Cornus florida	flowering dogwood	
Clethraceae		
Clethra alnifolia	coastal sweet pepperbush	

Species	Common Name	Synonym Name
Ericaceae		
Zenobia pulverulenta	honeycup	
Lyonia ligustrina	maleberry, he-huckleberry	
Lyonia lucida	fetterbush lyonia	
Lyonia mariana	staggerbush	
Gaylussacia dumosa	dwarf huckleberry	
Vaccinium arboreum	tree sparkleberry, tree-huckleberry	
Vaccinium tenellum	small black blueberry	
Vaccinium corymbosum	blueberry, highbush blueberry	
Vaccinium crassifolium	creeping blueberry	
Primulaceae		
Samolus valerandi ssp. parviflorus	water pimpernel	*Samolus parviflorus*
Plumbaginaceae		
Limonium carolinianum	Carolina sealavender	*Limonium nashii*
Symplocaceae		
Symplocos tinctoria	sweetleaf	
Oleaceae		
Fraxinus americana	American ash; white ash	
Osmanthus americana	devilwood, wild olive	
Loganiaceae		
Gelsemium sempervirens	Carolina or yellow jessamine	
Mitreola petiolata	lax hornpod, miterwort	*Cynoctonum mitreola*
Buddlejaceae		
Polypremum procumbens	juniper leaf	
Gentianaceae		
Sabatia difformis	lanceleaf rose gentian	
Sabatia stellaris	rose of Plymouth, common marsh-pink	
Sabatia calycina	coastal rose gentian	
Sabatia dodecandra	marsh rose gentian	
Menyanthaceae		
Nymphoides aquatica	big floatingheart	
Asclepiadaceae		
Asclepias perennis	aquatic milkweed	
Asclepias lanceolata	fewflower milkweed	
Cynanchum angustifolium	Gulf coast swallowwart	*Cynanchum palustre*
Convolvulaceae		
Ipomoea quamoclit	cypressvine, cypressvine morning glory	
Ipomoea purpurea	common morning glory	
Ipomoea sagittata	saltmarsh morning glory	

Species	Common Name	Synonym Name
Cuscutaceae		
Cuscuta compacta	compact dodder	
Verbenaceae		
Verbena urticifolia	white verbena or vervain	
Phyla nodiflora	sawtooth fogfruit, turkey tangle fogfruit	*Lippia nodiflora*
Phyla lanceolata	frog fruit, lanceleaf fogfruit	*Lippia lanceolata*
Callicarpa americana	American beautyberry	
Lamiaceae		
Teucrium canadense	wood sage; germander	
Hyptis alata	clushered bushmint, bitter mint	
Scutellaria integrifolia	helmet flower, skullcap	
Pycnanthemum muticum	clustered mountainmint	
Solanaceae		
Physalis walteri	Walter's or sand groundcherry	*Physalis viscosa ssp. maritima*
Solanum carolinense	horse nettle; bull nettle, sand briar	
Scrophulariaceae		
Bacopa caroliniana	blue waterhyssop	
Gratiola pilosa	shaggy hedgehyssop, hairy gratiola	
Verbascum thapsus	flannel plant; woolly mullein, velvet plant	
Nuttallanthus canadensis	Canada or oldfield toadflax	*Linaria canadensis*
Veronica arvensis	corn, rock, or wall speedwell	
Seymeria cassioides	yaupon blacksenna	
Agalinis maritima	saltmarsh false foxglove	
Bignoniaceae		
Bignonia capreolata	cross vine	*Anisostichus capreolata*
Campsis radicans	trumpet vine, cow-itch, trumpet creeper	
Lentibulariaceae		
Utricularia subulata	zigzag or wiry bladderwort	
Utricularia purpurea	purple bladderwort	
Utricularia gibba	conespur bladderpod, humped bladderwort	*Utricularia biflora*
Acanthaceae		
Justicia americana	American waterwillow (occurrence questionable)	
Justicia ovata	looseflower waterwillow	
Plantaginaceae		
Plantago lanceolata	English or lanceleaf plantain, ribgrass	
Plantago virginica	Virginia plantain, paleseed Indianwheat	
Rubiaceae		
Cephalanthus occidentalis	common buttonbush	
Diodia virginiana	Virginia buttonweed	
Diodia teres	poorjoe, rough buttonweed	

Species	Common Name	Synonym Name
Rubiaceae		
Mitchella repens	partridgeberry	
Galium pilosum	hairy bedstraw	
Galium obtusum	bluntleaf or bristly bedstraw	
Caprifoliaceae		
Lonicera japonica	Japanese or Chinese honeysuckle	
Campanulaceae		
Lobelia elongata	longleaf lobelia	
Lobelia nuttallii	Nuttall's lobelia	
Asteraceae		
Ambrosia artemisiifolia	ragweed	
Lactuca graminifolia	grassleaf or wild lettuce	
Sonchus oleraceus	common sow thistle	
Hieracium gronovii	Gronovis or leafy hawkweed, queendevil	
Krigia virginica	Virginia dwarf dandelion	
Pyrrhopappus carolinianus	Carolina false dandelion, Carolina desert chicory	
Taraxacum officinale	common dandelion, blowball	
Arnoglossum ovatum	ovateleaf cacalia	*Cacalia lanceolata*
Erechtites hieracifolia	burnweed, fireweed	
Cirsium horridulum var. horridulum	yellow thistle	*Carduus spinosissimus*
Cirsium repandum	sandhill thistle	*Carduus repandus*
Elephantopus tomentosus	hairy elephantfoot, devil's grandmother	
Eupatorium perfoliatum	boneset	
Eupatorium capillifolium	dog fennel	
Eupatorium rotundifolium	roundleaf eupatorium or thoroughwort	
Eupatorium album	white thoroughwort	
Mikania scandens	climbing hempweed or hempvine	
Pluchea rosea	rosy camphorweed	
Pluchea foetida	stinkweed, stinking camphorweed	
Pluchea camphorata	camphorweed	
Pseudognaphalium obtusifolium spp. obtusifolium	rabbit tobacco	*Gnaphalium obtusifolium*
Baccharis angustifolia	saltwater false willow	
Baccharis halimifolia	eastern baccharis	
Erigeron quercifolius	oakleaf fleabane	
Boltonia caroliniana	Carolina doll's daisy	
Sericocarpus linifolius	narrowleaf whitetop aster	*Aster bifoliatus*
Symphyotrichum tenuifolium	perennial saltmarsh aster	*Aster tenuifolius*
Solidago sempervirens	seaside goldenrod	
Euthamia tenuifolia var. tenuifolia	slender goldentop	*Solidago microcephala*
Borrichia frutescens	sea oxeye, bushy sea oxeye, bushy seaside tansy	
Coreopsis gladiata	coastal plain tickseed	
Marshallia graminifolia	grassleaf Barbara's buttons	
Artemisia ludoviciana	gray sagewort, prairie sage, white sagebrush	

Appendix D

Common Invertebrates (>5 mm) in North Inlet, SC

Common Invertebrates (>5 mm) in North Inlet, SC

Keys to the taxonomic abbreviations, habitat designations and relative abundance are provided at the end of the list. Although many other species continue to be encountered (especially with specialized sampling gear and strategies), this list includes species that would most likely be found by observers in the intertidal and shallow tidal areas of this high-salinity estuary. Documentation of the occurrences of most come from Fox and Ruppert (1985) and Ruppert and Fox (1988). Recent additions to their comprehensive lists are documented in unpublished data or digital files. Voucher specimens for many species are located in the preserved sample archives at the Baruch Marine Field Laboratory.

			Season			
Scientific Name	**Common Name**	**Habitat**	**W**	**Sp**	**Su**	**F**
Ph. Porifera - sponges						
Cliona celata		CS, OR	A	A	A	A
Cliona vastifica	yellow boring sponge	CS, OR		C		
Haliclona permollis		CS, OR	A	A	A	A
Haliclona loosanoffi		OR	C	C	C	C
Hymeniacidon heliophila		CS, OR	C	C	C	C
Lissodendoryx isodictyalis		OR	C	C	C	C
Microciona prolifera		OR	C	C	C	C
Ph. Cnidaria						
Cl. Anthozoa - anemones, corals, sea whips						
Aiptasia pallida	pale anemone	OR	A	A	A	A
Astrangia poculata (A. danae)	northern star coral	CS	C	C	C	C
Calliactis tricolor	hermit anemone	PB		C		C
Ceriantheopsis americanus	tube anemone	PB	C	C	C	
Haloclava producta	white burrowing anemone	PB	C	C	C	
Leptogorgia virgulata	sea whip	CS	A	A	A	A
Paranthus rapiformis	white burrowing anemone	PB	C	C	C	C
Renilla reniformis	sea pansy	CS, PB	A	A	A	A
Cl. Hydrozoa - Hydroids						
Hydractinia echinata	snail fur	PS			C	
Obelia dichotoma	sea thread hydroid	CS	C	C		
Plumularia floridana		CS			C	
Schizotricha tenella		OR		C	C	C
Tubularia crocea		PS	A			A
Bougainvillia carolinensis		TC		A	A	
Nemopsis bachei		TC		C	C	
Turritopsis nutricula		TC		C	C	
Cl. Scyphozoa						
Stomolophus melagris	cannonball jellyfish	TC		C	A	C
Chrysaora quinquecirrha	sea nettle	TC			C	
Aurelia aurita	moon jelly	TC			C	C
Cl. Cubozoa						
Chiropsalmus quadrumanus	box jelly	TC			C	C

			Season			
Scientific Name	**Common Name**	**Habitat**	**W**	**Sp**	**Su**	**F**
Ph. Ctenophora - comb jellies						
Mnemiopsis leidyi	warty comb jelly	CS	C	C	C	C
Beroe ovata		TC			C	C
Ph. Hemichordata - acorn worms						
Balanoglossus aurantiacus	golden acorn worm	PB	C	C	C	C
Saccoglossus kowalevskii	helical acorn worm	PB	A	A	A	A
Ph. Chordata						
sPh. Tunicata- tunicates, sea squirts						
Molgula manhattensis	sea grapes	CS, PS	A	A	A	A
Ph. Echinodermata						
Cl. Ophiuroidea - brittle stars, basket stars						
Hemipholis elongata	blood brittle star	PB	C	C	C	
Micropholis atra	burrowing brittle stars	PB	C	C	C	C
Micropholis gracillima		PB	C	C	C	C
Ophiophragmus wurdemanii		PB	C	C	C	
Ophiothrix angulata	spiny or angular brittle star	CS, OR	A	A	A	A
Cl. Echinoidea - sea urchins, sea biscuits & sand dollars						
*Mellita quinquiesperforat*a	sand dollar	CS, PB	A	A	A	A
Cl. Holothuroidea - sea cucumbers						
Leptosynapta tenuis	white synapta	PB	C	C	C	C
Pentamera pulcherrima		CS		A		
Thyonella gemmata	green sea cucumber	CS, PB				
Ph. Chaetognatha - arrow worms						
Parasagitta tenuis		CS	A	A	A	A
Flaccisagitta enflata		CS	A	A	A	A
Ferosagitta hispida		CS	A	A	A	A
Sagitta bipunctata		TC		C	C	C
Ph. Phoronida - phoronids						
Phoronis architecta		PB	C	C		C
Ph. Ectoprocta - bryozoans, moss animals						
Aeverrillia setigera		CS	C	C	C	C
Amathia distans	bushy bryozoans	CS	C	C	C	C
Bowerbankia gracilis		OR, CS	C	C	C	C
Bugula neritina	bushy bryozoans	CS	C	C	C	C
Electra monostachys		CS		C		
Membranipora tenuis	white crust	CS	C	C	C	C
Parasmittina nitida		CS	C	C	C	C
Schizoporella unicornis	orange crust	CS		C	C	
Zoobotryon verticillatum	bushy bryozoans	CS				C

Scientific Name	Common Name	Habitat	Season W	Sp	Su	F
Ph. Entoprocta - kamptozoans						
Barentsia laxa		CS, OR		C	C	
Pedicellina cernua		CS		C		
Ph. Mollusca - chitons, snails, squids, octopods						
Cl. Gastropoda - snails, sea slugs, gastropods						
sCl. Prosobranchia - snails						
Astyris lunata	lunar dove snail	CS	A		A	A
Busycon carica	knobbed whelk	PB	C	C	C	C
Cerithiopsis emersoni	awl miniature cerith	CS, OR	C	C	C	C
Cerithiopsis greeni	Greens miniature cerith	CS	C			C
Crepidula plana	eastern white slipper snail	CS, PB		C	C	
Fasciolaria (lilium) hunteria	banded tulip	PB		C	C	
Hydrobiidae sp A, B & C	hydrobiids	SM	C		C	C
Littorina irrorata	marsh periwinkle	SM	C	C	C	C
Melampus bidentatus	common marsh snail; eastern melampus	SM	C	C	C	C
Nassarius obsoletus (Ilyanassa)	eastern mud snail	PB, SM	A	A	A	A
Polinices duplicatus	Atlantic moon snail	PB	C	C	C	C
Simnialena uniplicata	single-toothed simnia	CS	C	C	C	C
Terebra dislocata	eastern or Atlantic auger	PB	C	C	C	C
Urosalpinx cinerea	Atlantic oyster drill	CS, OR	A	A	C	A
Buscycon spiratum	fig whelk	TC			C	
O. Heterostropha						
Boonea impressa	oyster mosquito	OR	A	A		A
Turbonilla sp. cf *T. holmesi*	name status unclarified	CS	C			
sCl. Opisthobranchia - sea slugs, sea hares, bubble shells						
O. Nudibranchia - nudibranchs						
Aplysia brasilian	sooty sea hare	TC		C		
Armina tigrina	striped sea slug; tiger armina	PB	A	A	A	A
Ancula evelinae		CS			C	C
Berghia coerulescens (verrucicornis)	anemone sea slug	OR	C			C
Cratena pilata		PS	C			C
Doridella obscura	obscure corambe	CS			C	C
Doriopsilla pharpa	lemon drop sea slug	CS, OR	A	A	A	A
Polycera hummi		CS		C		
Tritonia bayeri		CS	C		C	
Cl. Cephalopoda - squids octopods						
Lolliguncula brevis	Atlantic brief squid	CS		C	C	C
Octopus vulgaris	common octopus	TC	C	C	C	C
Cl. Bivalvia - clams, mussels, oysters						
Aligena elevata	eastern aligena	PB	C	C	C	
Brachidontes exustus	scorched mussle	PS, OR	A	A	A	A
Chione cancellata	cross-barred venus	CS	A	A	A	A
Crassostrea virginica	eastern oyster	OR,PS,SM,CS	A	A	A	A
Diplothyra smithii	Smiths or oyster piddock	CS		C		

			Season			
Scientific Name	**Common Name**	**Habitat**	**W**	**Sp**	**Su**	**F**
Cl. Bivalvia - clams, mussels, oysters (continued)						
Donax variabilis	coquina; variable coquina	OB	C	C	C	C
Gemma gemma	gem clam; amethyst gem clam	SM				C
Geukensia demissa	Atlantic ribbed mussle	SM	C	C	C	C
Ensis directus	razor clam	PB	C	C	C	
Lepton sp		PB	C			
Macoma tenta	elongate macoma	PB	C	C	C	
Mercenaria mercenaria	northern quahog	PB, CS, OR	A	A	A	A
Mulinia lateralis	dwarf surf clam	PB	C	C	C	C
Musculus lateralis	lateral mussel	PS		C		
Ostrea equestris	horse or crested oyster	CS		C		
Petricola pholadiformis	false angel wing	PS		A		
Solen viridis	slender razor clam; green jackknife clam	PB		C	C	
Tagelus divisus	divided sand clam; purplish tagelus	PB	C	C	C	C
Tagelus plebeius	common sand clam; stout tagelus	PB	A	A	A	A
Tellina texana	Texas or say tellin	PB	C	C	C	C
Ph. Nemertea- proboscis or ribbon worms						
Amphiporus ochraceus		CS	C	C	C	C
Carcinonemertes carcinophila		PB		C		
Carinoma tremaphoros		PB	C	C	C	C
Carinomella lactea		PB	C	C	C	C
Lineus bicolor		PS		C	C	
Lineus socialis		PS		C		
Nemertopsis bivittata	species name non-existent in itis	PS		C		C
Zygonemertes virescens		CS	C	C	C	C
Zygeupolia rubens		OB		C		C
Ph. Platyhelminthes - flatworms						
Bdelloura candida		PB		C		
Plagiostomum sp.		PS			A	
Stylochus ellipticus		PS, CS	C	C	C	C
Ph. Annelida - segmented worms						
Cl. Polychaeta - paddle-footed annelids						
F. Capitellidae						
Capitella capitata		SM	C		C	C
Heteromastus filiformis		PB, SM	A	A	A	A
Notomastus hemipodus		PB		C	C	C
Notomastus latericeus		PB		C	C	C
Notomastus lobatus		PB	C	C	C	C
F. Chaetopteridae						
Chaetopterus variopedatus	parchment tube worm	PB	C	C	C	C
Spiochaetopterus oculatus	cellophane tube worm	PB	C	C	C	C
F. Cirratulidae						
Caulleriella killariensis		PB	C			C

Scientific Name	Common Name	Habitat	Season W	Season Sp	Season Su	Season F
F. Cirratulidae						
Caulleriella killariensis		PB	C			C
Tharyx setigera		PB		C		
F. Dorvilleidae						
Dorvillea sociabilis	millipede worm	OR	C	C		C
F. Eunicidae						
Lysidice ninetta		OR	C	C		
Marphysa sanguinea	rockworm	OR, CS	C	C	C	C
F. Glyceridae - blood worms						
Glycera americana		PB, SM	C	C	C	C
Glycera dibranchiata	bloodworm	PB	A	A	A	A
F. Hesionidae						
Podarke obscura	swift-footed worm	CS, OR	C	C	C	C
F. Lumbrineridae						
Lumbrineris impatiens		OB	C	C	C	C
F. Magelonidae						
Magelona papillicornis		PB	C	C		C
Magelona phyllisae	shovel headed worm	PB		C		
F. Maldanidae - bamboo worms						
Axiothella mucosa		PB		C	C	
Branchioasychis americana		SM		C		C
Clymenella torquata		PB	C	C	C	C
F. Nephtyidae - shimmy worms						
Nephtys bucera		PB	C			C
Nephtys picta		PB	C	C	C	C
F. Nereididae						
Laeonereis culveri		SM	C	C	C	C
Nereis falsa		CS, PS, OR	C	C	C	C
Neanthes succinea (Nereis)		OR, PS, SM	C	C	C	C
F. Oenonidae	Arabellidae					
Arabella iricolor	opalworm	PB	C	C	C	C
Drilonereis magna	threadworm	PB	A	A	A	A
F. Opheliidae						
Armandia maculata		CS	C			C
F. Onuphidae						
Diopatra cuprea	plumed worm	PB	A	A	A	A
Kinbergonuphis jenneri	genus name not recognized by itis; soda straw worm	PB	A	A	A	A

			Season			
Scientific Name	**Common Name**	**Habitat**	**W**	**Sp**	**Su**	**F**
F. Orbiniidae						
Haploscoloplos fragilis		PB, SM	C	C	C	C
Haploscoloplos robustus		PB	C	C	C	C
Scoloplos rubra		PB		C	C	C
F. Oweniidae						
Owenia fusiformis	shingle tube worm	PB	C	C	C	C
F. Pectinariidae (Amphictenidae) - ice cream cone worms						
Pectinaria gouldi (Cistenides)	ice cream cone worm	PB	C	C	C	C
F. Phyllodocidae						
Nereiphylla fragilis (Phyllodoce)	green oyster worm	OR	A	A	A	A
F. Paraonidae						
Aricidea fragilis	unicorn worm	PB	C	C	C	C
F. Polynoidae - scaleworms						
Lepidasthenia commensalis (Lepidametria)		OR, PS	C	C	C	C
Lepidasthenia varius		PB	C	C	C	C
Lepidonotus sublevis		CS	C	C	C	C
F. Sabellidae - feather duster worms						
Demonax microphthalmus		CS	C	C	C	C
Fabricia sabella		CS	C	C		C
Manayunkia aestuarina		SM			C	
Notaulax nudicollis	name not found in itis	OR, CS	C	C	C	C
F. Serpulidae - feather duster worms						
Hydroides dianthus		OR, CS	A	A	A	A
F. Spionidae - palp worms						
Dispio uncinata		OB		C	C	C
Polydora colonia		CS, OB	C			C
Polydora ligni		OR		C		
Polydora websteri		OR	C	C	C	
Marenzellaeria viridis (Scolecolepides)		PB	C			C
Minuspio cirrifera (Prionospio)		CS, OB	C			
Scolelepis squamata		OB	A	A	A	A
Spio multioculata		PB	C	C	C	C
Spio setosa		PB	C	C		C
Spiophanes bombyx		PB		C	C	C
Streblospio benedicti		SM	C		C	C
F. Syllidae						
Autolytus fasciata (Proceraea)		CS	C		C	C
Brania clavata		CS, OR	C	C	C	C
Eusyllis lamelligera		CS, OR	C	C	C	C
Exogone dispar		CS	C	C	C	C

Scientific Name	Common Name	Habitat	Season			
			W	Sp	Su	F
F. Syllidae (continued)						
Odontosyllis fulgurans		CS	C	C	C	C
Syllis gracilis		CS		C		
F. Terebellidae - spaghetti worms						
Amphitrite ornata		CS		C		
Loimia medusa		CS		C	C	
Pista palmata		CS	C	C	C	C
Polycirrus eximius		CS, OR	C	C	C	C
Terebella rubra		OR	C	C	C	C
Thelepus setosus		CS, OR	C	C	C	C
Cl. Oligochaeta						
Oligochaeta sp.		SM	C			C
Ph. Arthropoda - crustaceans, insects and chelicerates						
sPh. Chelicerata - horseshoe crabs, sea spiders, mites						
Cl. Merostomata - horseshoe crabs						
Limulus polyphemus	horseshoe crab	PB		C		
Cl. Pycnogonida - sea spiders						
Anoplodactylus lentus	black sea spider	CS		A		A
Callipallene brevirostris		OR				C
Tanystylum orbiculare		CS	C	C	C	C
sPh. Crustacea - crustaceans						
Cl. Cirripedia - barnacles						
Balanus eburneus	ivory barnacle	OR	C	C	C	C
Balanus improvisus		OR, CS	C	C	C	C
Balanus venustus		CS	C	C		C
Chthamalus fragilis	fragile barnacle	PS, SM	A	A	A	A
Conopea galeata	seawhip barnacle	CS	C	C	C	C
Cl. Malacostraca						
O. Stomatopoda - mantis shrimps						
Squilla empusa	mantis shrimp	PB	C	C		C
O. Tanaidacea						
Hargeria rapax		SM	C			C
O. Decapoda - lobsters, shrimp, crabs						
Arenaeus cribrarius	speckled swimming crab	OB			C	C
Armases cinereum (Sesarma)	wharf crab	SM	C	C	C	C
Austinixa cristata (Pinnixa)	cristate pea crab	OB		C	C	
Callinectes sapidus	blue crab	CS, PB	A	A	A	A
Callinectes similis	lesser blue crab	PB			C	
Callinectes ornatus	shelligs crab	PB			C	
Clibanarius vittatus	thinstripe hermit crab	CS, PB		C	C	
Dissodactylus mellitae	sand dollar pea crab	PB	C		C	
Dyspanopeus sayi (Neopanope)	Say mud crab	PS	C	C		C
Emerita talpoida	Atlantic sand crab	OB	C	C	C	C

			Season			
Scientific Name	**Common Name**	**Habitat**	**W**	**Sp**	**Su**	**F**
O. Decapoda - lobsters, shrimp, crabs (continued)						
Euytium limosum	broadbacked mud crab	TC SM	C	C	C	C
Eurypanopeus depressus	flatback mud crab	OR	A	A	A	A
Hepates epheliticus	calico box crab	TC		C		
Libinia dubia	longnose spider crab	CS, PB		C	C	
Libinia emarginata	portly spider crab	CS		C	C	
Metaporhaphis calcarata	hairy arrow crab	CS		C	C	
Menippe mercenaria	Florida stone crab	CS, PB	C			
Ocypode quadrata	Atlantic ghost crab	OB		C	C	C
Ovalipes ocellatus	lady crab; ocellate lady crab	OB, CS		C		
Pagurus longicarpus	long-armed hermit crab	PB, CS	A	A	A	A
Pagurus pollicaris	flatclaw hermit crab	PB, CS		C	C	C
Panopeus herbstii	oyster or Atlantic mud crab	CS, OR	C	C	C	C
Petrolisthes armatus	invasive porcellanid	TC	A	A	A	A
Pinnixa chaetopterana	tube pea crab	PB	C	C	C	C
Polyonyx gibbesi	eastern tube crab	PB		C		
Portunus gibbesii	iridescent swimming crab	CS		C	C	C
Portunus sayi	Sargassum crab	CS			C	
Portunus spinimanus	blotched swimming crab	CS		C	C	
Sesarma reticulatum	marsh crab	TC SM	C	C	C	C
Uca pugilator	Atlantic sand fiddler	SM, PB	A	A	A	A
Uca pugnax	Atlantic marsh fiddler	SM	A	A		A
Zaops ostreum (Pinnotheres)	oyster pea crab	OR	C	C	C	
sO. Natantia - shrimps						
Acetes americanus carolinae		TC		C	C	C
Alpheus heterochaelis	bigclaw snapping shrimp	SM, CS	C			C
Alpheus normanni	green snapping shrimp	CS	A	A		A
Biffarius biformis (Callianassa)	biform ghost shrimp	PB	C	C	C	C
Callichirus major (Callianassa)	Carolinian ghost shrimp	OB	C	C	C	C
Latreutes parvulus		CS			C	
Lucifer faxoni		TC		C	C	
Lysmata wurdemanni	peppermint shrimp	CS			C	
Neopontonides beaufortensis		SC		A	A	
Palaemonetes pugio	daggerblade grass shrimp	SM, CS	A	C		A
Palaemonetes vulgaris	marsh grass shrimp	CS, OR	A	A	A	A
Farfantepenaeus aztecus	brown shrimp	CS		C	C	C
Farfantenaeus duorarum	pink shrimp	CS	C	C		C
Litopenaeus setiferus	white shrimp	CS		C	C	C
Cuapetes americanus	was Periclimenes longicaudatus	CS		C	C	C
Sicyonia dorsalis	rock shrimp	CS, PB			C	
Rimapenaeus constrictus	roughneck shrimp	CS		C	C	C
Upogebia affinis	coastal mud shrimp	PB	C	C	C	C
O. Mysida - opposum shrimp						
Chlamydopleon dissimile	was Bowmaniella floridana	OB		C	C	C
Metamysidopsis swifti		OB			A	
Neomysis americana		CS	C	A	C	C
Americamysis bigelowi		TC		C	C	
Americamysis bahia		TC		C	C	

Scientific Name	Common Name	Habitat	Season W	Sp	Su	F
O. Mysida - opposum shrimp (continued)						
Promysis atlantica		TC		C	C	
Heteromysis formosa		TC		C	C	
Brasilomysis castroi		TC		C	C	
O. Cumacea - cumaceans						
Cyclaspis pustulata		OB			C	
Oxyurostylis smithi		CS	C	C		C
Spilocuma watlingi		OB			C	
O. Isopoda - isopods, pillbugs						
Livoneca redmanii	was Aegathoa oculata	CS	C	C	C	
Ancinus depressus		OB	C		C	C
Sphaeroma quadridentatum		TC			C	
Edotia triloba/montosa		TC		C	C	C
O. Amphipoda - amphipods						
sO.Gammaridea - gammarid amphipods						
F. Ampeliscidae						
Ampelisca verrilli		PB	A	A	A	A
F. Ampithoidae						
Cymadusa compta		CS		C		
F. Aoridae						
Lembos smithi		CS	C	C	C	C
Lembos sp.		CS	C	C	C	C
F. Bateidae						
Batea catharinensis		CS	C	C	C	C
F. Corophiidae						
Corophium acherusicum		CS	C	C	C	C
F. Colomastigidae						
Colomastix halichondriae		CS	C		C	C
F. Liljeborgiidae						
Listriella clymenellae		PB		C	C	
F. Gammaridae						
Gammarus palustris		SM	C	C		C
Gammarus mucronatus		PS		C		
F. Haustoriidae						
Haustorius canadensis		OB	C	C	C	C
Neohaustorius biarticulatus		OB	C		C	C
Neohaustorius schmitzi		OB		C	C	
Parahaustorius longimerus		OB		C	C	C
Protohaustorius deichmannae		OB			C	
Pseudohaustorius caroliniensis		PB	C	C	C	C

Scientific Name	Common Name	Habitat	Season W	 Sp	 Su	 F
F. Ischyroceridae						
Cerapus tubularis		CS			C	C
Ericthonius brasiliensis		CS	C	C	C	C
F. Melitidae						
Dulichiella appendiculata		CS	C		C	C
Melita nitida		CS, OR	C	C	C	C
F. Photidae						
Microprotopus shoemakeri		CS				C
F. Phoxocephalidae						
Eobrolgus spinosus		CS	C	C	C	C
F. Pontoporeiidae						
Bathyporeia parkeri		OB			C	
F. Stenothoidae						
Stenothoe georgiana		PS, CS	C	C	C	C
Stenothoe minuta		PS			C	
F. Talitridae - beach hoppers						
Orchestia grillus		SM	C	C	C	C
Orchestia sp A		SM	C		C	C
sO. Caprellidea - skeleton shrimp						
Caprella equilibra		CS	C	C	C	C
Caprella penantis		PS		C		
Paracaprella tenuis		CS	C	C	C	C

Table Key

Taxonomic code abbreviations

Ph. = phylum
sPh.= subphylum
Cl. = class
sCl. = subclass
O. = order
sO. = suborder
F. = family

Seasonal abundance abbreviations

W = winter
Sp = spring
Su = summer
F = fall

A = Abundantly observed
C = Commonly observed
blank space = present in NI, but not abundantly or commonly observed

Habitat types and interpretation

OB = Outer Beaches - intertidal sand and high energy surf zone
PB = Protected Beaches - low energy intertidal sand and mud flats
SM = Salt Marsh - vegetated region of estuary with Spartina and Juncus
CS = Creeks and Sounds - subtidal areas which are always inundated with water
OR = Oyster Reefs - intertidal and subtidal oyster shell and growths of oysters
PS = Pilings and Seawalls - vertical structure in the subtidal and intertidal zones
TC = Post R&S additions from DM Allen, most occurring in/near Town Creek, North Inlet

If the listing of the habitat types are not in alphabetical order: this indicates that the first habitat in the list had the greater abundance of the animal or the animal occurred over more seasons than the following habitat.

Appendix E

Cartilaginous and Bony Fishes Collected in North Inlet and Winyah Bay Estuaries, Georgetown, SC 1978-2014

Cartilaginous and Bony Fishes Collected in North Inlet and Winyah Bay Estuaries, Georgetown, SC 1978-2014

Life stages observed in North Inlet are: L = larvae, J = juveniles, A = adults.
Sources for North Inlet records are: Ogburn et al., 1988; Allen and Barker, 1990; and subsequent catches.
Sources for Winyah Bay are: CCU = Abel et al., 2007; MRRI = Wenner et al., 1981; CEIP = Allen et al., 1982; and p= personal observations by DM Allen.
Common names are those designated by the American Fisheries Society.
Check **www.baruch.sc.edu** for species updates.

Scientific Name	**Common Name**	**North Inlet**			**Winyah Bay**
		L	**J**	**A**	
Carcharhinidae - requiem sharks					
Carcharhinus isodon	finetooth shark			A	CCU
Carcharhinus acronotus	blacknose shark		J	A	CCU
Carcharhinus brevipinna	spinner shark				CCU
Carcharhinus leucas	bull shark		J	A	CCU
Carcharhinus limbatus	blacktip shark		J	A	CCU
Carcharhinus plumbeus	sandbar shark		J	A	CCU
Carcharhinus obscurus	dusky shark		J		
Ginglymostomacirratum	nurse shark				CCU
Negaprion brevirostris	lemon shark		J	A	CCU
Rhizoprionodon terraenovae	Atlantic sharpnose shark		J	A	CCU
Squalidae - dogfish sharks					
Mustelus canis	smooth dogfish			A	CCU
Squalus acanthias	spiny dogfish			A	
Sphyrnidae - hammerhead sharks					
Sphyrna lewini or S. gilberti	scalloped hammerhead		J	A	CCU
Sphyrna tiburo	bonnethead		J	A	CCU
Rajidae - rays or skates					
Raja eglanteria	clearnose skate			A	MRRI
Dasyatidae - stingrays					
Dasyatis americana	southern stingray			A	CEIP
Dasyatis centroura	roughtail stingray			A	CEIP
Dasyatis sabina	Atlantic stingray		J	A	CEIP, MRRI
Dasyatis say	bluntnose stingray			A	p
Gymnuridae - butterfly rays					
Gymnura micrura	smooth butterfly ray		J	A	p
Myliobatidae - eagle rays					
Aetobatus narinari	spotted eagle ray		J		CCU
Rhinoptera bonasus	cownose ray		J	A	CEIP

		North Inlet			Winyah Bay
Scientific Name	**Common Name**	**L**	**J**	**A**	
Acipenseridae - sturgeons					
Acipenser oxyrinchus	Atlantic sturgeon		J		MRRI
Acipenser brevirostrum	shortnose sturgeon				MRRI
Lepisosteidae - gars					
Lepisosteus osseus	longnose gar		J	A	CEIP, MRRI
Elopidae - ladyfishes and tarpons					
Elops saurus	ladyfish	L	J	A	CEIP
Megalops atlanticus	tarpon	L	J	A	CEIP
Albulidae - bonefishes					
Albula vulpes	bonefish		J		
Anguillidae - freshwater eels					
Anguilla rostrata	American eel		J	A	CEIP, MRRI
Muraenidae - moray eels					
Gymnothorax nigromarginatus	blackedge moray		J		
Ophichthidae - worm and snake eels					
Bascanichthys sp.	eel		J		CEIP
Myrophis punctatus	speckled worm eel	L	J	A	CEIP, MRRI
Ophichthus gomesii	shrimp eel		J	A	CEIP
Congridae - conger eels					
Conger oceanicus	conger eel		J		
Ariosoma balearicum	bandtooth conger				MRRI
Clupeidae - herrings, shads, menhadens, and sardines					
Alosa aestivalis	blueback herring		J		CEIP, MRRI
Alosa mediocris	hickory shad		J		
Alosa sapidissima	American shad		J	A	MRRI
Brevoortia tyrannus	Atlantic menhaden	L	J	A	CEIP, MRRI
Dorosoma cepedianum	gizzard shad		J		CEIP, MRRI
Dorosoma petenense	threadfin shad		J		CEIP, MRRI
Opisthonema oglinum	Atlantic thread herring		J		
Sardinella aurita	Spanish sardine		J		
Engraulidae (syn. Engraulididae) - anchovies					
Anchoa hepsetus	striped anchovy	L	J	A	CEIP, MRRI
Anchoa mitchilli	bay anchovy	L	J	A	CEIP, MRRI
Cyprinidae - carps and minnows					
Cyprinus carpio	common carp				MRRI
Synodontidae - lizardfishes					
Synodus foetens	inshore lizardfish		J	A	CEIP
Ariidae - sea catfishes					
Ariopsis (Arius) felis	hardhead catfish		J	A	CEIP, MRRI
Bagre marinus	gafftopsail catfish			A	CEIP, MRRI

Scientific Name	Common Name	North Inlet L	North Inlet J	North Inlet A	Winyah Bay
Ictaluridae - freshwater and bullhead catfishes					
Ameiurus natalis	yellow bullhead		J	A	
Ameiurus (Ictalurus) catus	white or bullhead catfish				MRRI
Ameiurus (Ictalurus) platycephalus	flat bullhead				MRRI
Ameiurus (Ictalurus) nebulosus	brown bullhead				MRRI
Ictalurus punctatus	channel catfish				MRRI
Ictalurus furcatus	blue catfish				DNR
Gobiesocidae - clingfishes					
Gobiesox strumosus	skilletfish	L	J	A	CEIP, MRRI
Batrachoididae - toadfishes					
Porichthys plectrodon	Atlantic midshipman			A	
Opsanus tau	oyster toadfish		J	A	CEIP, MRRI
Antennariidae - frogfishes					
Antennarius ocellatus	ocellated frogfish			A	
Histrio histrio	sargassumfish		J		
Gadidae - codfishes					
Urophycis floridana	southern hake		J	A	CEIP, MRRI
Urophycis regia	spotted hake		J	A	CEIP, MRRI
Ophidiidae - cusk-eels					
Ophidion marginatum	striped cusk-eel		J	A	CEIP, MRRI
Hemiramphidae - halfbeaks					
Hyporhamphus unifasciatus	silverstripe halfbeak		J		
Belonidae - needlefishes					
Strongylura marina	Atlantic needlefish		J	A	p
Tylosurus crocodilus	houndfish		J		
Cyprinodontidae - killifishes and pupfishes					
Cyprinodon variegatus	sheepshead minnow		J	A	CEIP
Fundulidae - killifishes and topminnows					
Fundulus confluentus	marsh killifish		J	A	
Fundulus heteroclitus	mummichog	L	J	A	CEIP
Fundulus luciae	spotfin killifish		J	A	
Fundulus majalis	striped killifish	L	J	A	
Lucania parva	rainwater killifish		J	A	
Poeciliidae - livebearers					
Gambusia affinis	western mosquitofish		J	A	p
Poecilia latipinna	sailfin molly		J	A	p
Atherinopsidae - new world silversides					
Membras martinica	rough silverside		J	A	CEIP
Menidia beryllina	inland or tidewater silverside		J	A	
Menidia menidia	Atlantic silverside	L	J	A	CEIP

Scientific Name	Common Name	North Inlet L	North Inlet J	North Inlet A	Winyah Bay
Fistulariidae - cornetfishes					
Fistularia tabacaria	bluespotted cornetfish		J		
Syngnathidae - pipefishes and seahorses					
Hippocampus erectus	lined seahorse		J	A	
Syngnathus floridae	dusky pipefish		J	A	CEIP
Syngnathus fuscus	northern pipefish		J	A	CEIP, MRRI
Syngnathus louisianae	chain pipefish		J	A	CEIP
Dactylopteridae - flying gurnards					
Dactylopterus volitans	flying gurnard		J		
Scorpaenidae - scorpionfishes					
Scorpaena brasiliensis	barbfish		J	A	
Scorpaena calcarata	smoothhead scorpionfish				MRRI
Centropomidae - snooks					
Centropomus undecimalis	common snook		J		
Moronidae - temperate basses					
Morone americana	white perch		J	A	MRRI
Morone chrysops	white bass				MRRI
Morone saxatilis	striped bass		J	A	MRRI
Serranidae - sea basses and groupers					
Centropristis philadelphica	rock sea bass		J	A	CEIP, MRRI
Centropristis striata	black sea bass		J	A	MRRI
Diplectrum formosum	sand perch		J		
Epinephelus morio	red grouper		J		
Mycteroperca bonaci	black grouper		J		
Mycteroperca phenax	scamp		J		
Mycteroperca microlepis	gag	L	J		CEIP
Rypticus maculatus	whitespotted soapfish		J		
Centrarchidae - sunfishes					
Centrarchus maculatus	flier		J		
Chaenobryttus (Lepomis) gulosus	warmouth				MRRI
Lepomis auritus	redbreast sunfish				MRRI
Lepomis microlophus	redear sunfish				MRRI
Lepomis punctatus	spotted sunfish				MRRI
Micropterus salmoides	largemouth bass				MRRI
Priacanthidae - bigeyes					
Pristigenys alta	short bigeye		J		
Pomatomidae - bluefishes					
Pomatomus saltatrix	bluefish		J	A	CEIP, MRRI
Rachycentridae - cobias					
Rachycentron canadum	cobia		J		CEIP

Scientific Name	Common Name	North Inlet L	North Inlet J	North Inlet A	Winyah Bay
Echeneidae (Echeneididae) - remoras					
Remora remora	remora		J		
Echeneis naucrates	sharksucker		J		
Carangidae - jacks and pompanos					
Caranx hippos	crevalle jack		J	A	CEIP
Caranx latus	horse-eye jack		J	A	
Chloroscombrus chrysurus	Atlantic bumper	L	J	A	CEIP, MRRI
Selene vomer	lookdown		J	A	CEIP, MRRI
Trachinotus carolinus	Florida pompano		J		
Trachinotus falcatus	permit		J		
Oligoplites saurus	leatherjacket		J		
Lutjanidae - snappers					
Lutjanus analis	mutton snapper		J		
Lutjanus apodus	schoolmaster		J		
Lutjanus griseus	gray snapper		J		CEIP, MRRI
Lutjanus synagris	lane snapper		J		
Lobotidae - tripletails					
Lobotes surinamensis	tripletail		J		p
Gerreidae - mojarras					
Diapterus auratus	Irish pompano		J		CEIP
Eucinostomus argenteus	spotfin mojarra	L	J		CEIP
Eucinostomus gula	silver jenny	L	J		CEIP
Haemulidae - grunts					
Haemulon plumieri	white grunt		J		
Orthopristis chrysoptera	pigfish	L	J	A	CEIP
Sparidae - porgies					
Archosargus probatocephalus	sheepshead	L	J	A	CEIP, MRRI
Diplodus holbrookii	spottail pinfish		J		
Lagodon rhomboides	pinfish	L	J	A	CEIP, MRRI
Pagrus pagrus	red porgy		J		
Kyphodsidae - sea chubs,rudderfishes					
Kyphosus sp.	Bermuda or yellow chub		J		
Sciaenidae - drums and croakers					
Bairdiella chrysoura	silver perch	L	J	A	CEIP, MRRI
Cynoscion nebulosus	spotted seatrout	L	J	A	CEIP, MRRI
Cynoscion arenarius	sand seatrout		J		
Cynoscion regalis	weakfish	L	J	A	CEIP, MRRI
Larimus fasciatus	banded drum	L	J	A	MRRI
Leiostomus xanthurus	spot	L	J	A	CEIP, MRRI
Menticirrhus americanus	southern kingfish	L	J	A	CEIP, MRRI

		North Inlet			Winyah
Scientific Name	**Common Name**	**L**	**J**	**A**	**Bay**
Sciaenidae - drums and croakers (continued)					
Menticirrhus littoralis	Gulf kingfish				CEIP
Menticirrhus saxatilis	northern kingfish	L	J		CEIP
Micropogonias undulatus	Atlantic croaker	L	J	A	CEIP, MRRI
Pogonias cromis	black drum	L	J		CEIP, MRRI
Sciaenops ocellatus	red drum	L	J	A	CEIP, MRRI
Stellifer lanceolatus	star drum	L	J		CEIP, MRRI
Ephippidae (Ephippididae) - spadefishes					
Chaetodipterus faber	Atlantic spadefish	L	J		CEIP, MRRI
Chaetodontidae - butterflyfishes					
Chaetodon ocellatus	spotfin butterflyfish		J		
Pomacanthidae - Angelfishes					
Pomacanthus paru	French angelfish		J		
Pomacentridae - damselfishes					
Abudefduf saxatilis	sergeant major		J		
Mugilidae - mullets					
Mugil cephalus	striped mullet		J	A	CEIP, MRRI
Mugil curema	white mullet		J	A	CEIP
Sphyraenidae - barracudas					
Sphyraena barracuda	great barracuda		J		
Sphyraena borealis	northen sennet		J		
Labridae - wrasses					
Tautoga onitis	tautog		J		
Uranoscopidae - stargazers					
Astroscopus guttatus	northern stargazer		J	A	
Astroscopus y-graecum	southern stargazer		J	A	MRRI
Blenniidae - combtooth blennies					
Chasmodes bosquianus	striped blenny	L	J	A	CEIP
Hypleurochilus geminatus	crested blenny	L	J	A	
Hypsoblennius hentz	feather blenny	L	J	A	CEIP, MRRI
Hypsoblennius ionthas	freckled blenny		J	A	MRRI
Eleotridae (Eleotrididae) - sleepers					
Dormitator maculatus	fat sleeper		J	A	
Elotris pisonis	spinycheek sleeper		J	A	
Gobiidae - gobies					
Ctenogobius boleosoma	darter goby	L	J	A	CEIP
Ctenogobius shufeldti	freshwater goby	L	J	A	CEIP, MRRI
Evorthodus lyricus	lyre goby	L	J	A	
Gobionellus oceanicus	highfin or sharptail goby	L	J	A	CEIP
Gobiosoma bosc	naked goby	L	J	A	CEIP
Gobiosoma ginsburgi	seaboard goby	L	J	A	CEIP

Scientific Name	Common Name	North Inlet L	North Inlet J	North Inlet A	Winyah Bay
Gobiidae - gobies (continued)					
Microgobius gulosus	clown goby	L	J	A	CEIP
Microgobius thalassinus	green goby	L	J	A	CEIP
Microdesmidae - wormfishes					
Microdesmus longipinnis	pink wormfish			A	
Trichiuridae - ribbonfishes and cutlassfishes					
Trichiurus lepturus	Atlantic cutlassfish		J	A	p
Scombridae - mackerels, tunas, albacores, and bonitos					
Scomberomorus cavalla	king mackerel			A	
Scomberomorus maculatus	Spanish mackerel		J	A	CEIP
Stromateidae - butterfishes, harvestfishes, and rudderfishes					
Peprilus paru	harvestfish	L	J		CEIP, MRRI
Peprilus triacanthus	butterfish		J		CEIP, MRRI
Triglidae - searobins					
Prionotus carolinus	northern searobin	L	J		MRRI
Prionotus evolans	striped searobin	L	J		MRRI
Prionotus scitulus	leopard searobin		J	A	MRRI
Prionotus tribulus	bighead searobin	L	J	A	CEIP, MRRI
Paralichthyidae - lefteye flounders and sand flounders					
Ancylopsetta ommata	ocellated flounder	L	J	A	CEIP, MRRI
Citharichthys macrops	spotted whiff	L	J	A	
Citharichthys spilopterus	bay whiff	L	J	A	CEIP, MRRI
Etropus crossotus	fringed flounder	L	J	A	CEIP, MRRI
Etropus cyclosquamus	shelf flounder		J		
Etropus rimosus	gray flounder				
Hippoglossina oblonga	four spot flounder		J	A	
Paralichthys albigutta	Gulf flounder	L	J	A	
Paralichthys dentatus	summer flounder	L	J	A	CEIP, MRRI
Paralichthys lethostigma	southern flounder	L	J	A	CEIP, MRRI
Scophthalmidae - turbots					
Scophthalmus aquosus	windowpane	L	J	A	MRRI
Cynoglossidae - tonguefishes					
Symphurus civitatium	offshore tonguefish		J	A	
Symphurus plagiusa	blackcheek tonguefish	L	J	A	CEIP, MRRI
Achiridae - American and scrawled soles					
Trinectes maculatus	hogchoker	L	J	A	CEIP, MRRI
Monacanthidae - filefishes					
Aluterus schoepfii	orange filefish		J		
Stephanolepis hispidus	planehead filefish	L	J	A	CEIP, MRRI

Scientific Name	Common Name	North Inlet L	 J	 A	Winyah Bay
Diodontidae - burrfishes and porcupinefishes					
Chilomycterus schoepfii	striped burrfish		J	A	MRRI
Tetraodontidae - blowfishes, rabbitfishes, and puffers					
Lagocephalus laevigatus	smooth puffer		J	A	
Sphoeroides maculatus	northern puffer		J	A	CEIP
Sphoeroides spengleri	bandtail puffer		J		

Appendix F

Amphibian and Reptile List for Hobcaw Barony and Adjacent Estuarine Habitats

Amphibian and Reptile List for Hobcaw Barony and Adjacent Estuarine Habitats

Scientific Name	Common Name
CLASS: AMPHIBIA - Amphibians	
Sirenidae - Sirens	
Siren lacertina	Greater Siren
Salamandridae - Newts & Salamanders	
Notophthalmus viridescens	Eastern Newt
Amphiumidae - Amphiuma	
Amphiuma means	Two-Toed Amphiuma
Ambystomatidae - Mole Salamanders	
Ambystoma cingulatum	Flatwoods Salamander
Ambystoma mabeei	Mabee's salamander
Ambystoma opacum	Marbled Salamander
Plethodontidae - Lungless Salamanders	
[1]*Desmognathus auriculatus*	Southern Dusky Salamander
[1]*Eurycea cirrigera*	Southern Two-lined Salamander
Eurycea quadridigitata	Dwarf Salamander
Pseudotriton montanus	Mud Salamander
Scaphiopodidae - Spadefoots	
Scaphiopus holbrookii	Eastern Spadefoot
Bufonidae - Toads	
Bufo quercicus	Oak Toad
Bufo terrestris	Southern Toad
Hylidae - Tree Frogs	
Acris gryllus	Southern Cricket Frog
Hyla chrysoscelis	Cope's Gray Treefrog
Hyla cinerea	Green Treefrog
Hyla femoralis	Pine Woods Treefrog
Hyla gratiosa	Barking Treefrog
Hyla squirella	Squirrel Treefrog
Pseudacris crucifer	Spring Peeper
Pseudacris ocularis	Little Grass Frog
Ranidae - True Frogs	
Rana catesbeiana	American Bullfrog
Rana clamitans	Green Frog
Rana grylio	Pig Frog
Rana palustris	Pickerel Frog
Rana sphenocephala	Southern Leopard Frog

Scientific Name	Common Name
Microhylidae - Narrow-mouthed Toads	
Gastrophryne carolinensis	Eastern Narrow-mouthed Toad
CLASS: REPTILIA - Reptiles	
Alligatoridae - Alligators & Caimans	
Alligator mississippiensis	American Alligator
Chelydridae - Snapping Turtles	
Chelydra serpentina	Snapping Turtle
Kinosternidae - Mud & Musk Turtles	
Kinosternon baurii	Striped Mud Turtle
Kinosternon subrubrum	Eastern Mud Turtle
Sternotherus odoratus	Common Musk Turtle
Emydidae - Pond Turtles & Terrapins	
Trachemys scripta	Common Slider
Clemmys guttata	Spotted Turtle
Deirochelys reticularia	Chicken Turtle
Terrapene carolina	Eastern Box Turtle
Malaclemys terrapin	Diamondback Terrapin
Trionychidae - Softshell Turtles	
Apalone spinifera	Spiny Softshell
Cheloniidae - Marine Turtles	
Caretta caretta	Loggerhead
Chelonia mydas	Green Sea Turtle
Polychrotidae - Anoloid Lizards	
Anolis carolinensis	Green Anole
Phrynosomatidae - North American Spiny Lizards	
Sceloporus undulatus	Eastern Fence Lizard
Scincidae - Skinks	
Eumeces fasciatus	Five-lined Skink
Eumeces inexpectatus	Southeastern Five-lined Skink
Eumeces laticeps	Broad-head Skink
Scincella lateralis	Ground Skink
Teiidae - Ground Lizards, Racerunners & Whiptails	
[2]*Aspidoceles sexlineatus*	Six-Lined Racerunner
Anguidae - Alligator & Glass Lizards	
Ophisaurus ventralis	Eastern Glass Lizard
Colubridae - Typical Snakes	
Carphophis amoenus	Eastern Worm Snake
Cemophora coccinea	Scarlet Snake
Coluber constrictor	Racer

Scientific Name	Common Name
Colubridae - Typical Snakes (continued)	
Coluber constrictor priapus	Southern Black Racer
Diadophis punctatus	Ringneck Snake
Elaphe guttata	Corn Snake
Elaphe obsoleta	Rat Snake
Farancia abacura	Mud Snake
Farancia erytrogramma	Rainbow Snake
Heterodon platirhinos	Eastern Hog-nose Snake
Heterodon simus	Southern Hog-nose Snake
Lampropeltis getula getula	Eastern Kingsnake
Lampropeltis triangulum elapsoides	Scarlet Kingsnake
Masticophis flagellum flagellum	Eastern Coachwhip
Nerodia erythrogaster erythrogaster	Redbelly Water Snake
Nerodia fasciata confluens	Broad-banded Water Snake
Nerodia taxispilota	Brown Water Snake
Opheodrys aestivus	Rough Green Snake
Rhadinaea flavilata	Pine Woods Snake
Storeria dekayi	Brown Snake
Storeria occipitomaculata	Redbelly Snake
Tantilla coronata	Southeastern Crowned Snake
Thamnophis sauritus	Eastern Ribbon Snake
Thamnophis sirtalis	Common Garter Snake
Virginia valeriae	Smooth Earth Snake
Elapidae - Cobras & Coral Snakes	
Micrurus fulvius	Northern Coral Snake
Viperidae - (Pit) Vipers	
Agkistrodon contortrix contortrix	Southern Copperhead
Agkistrodon piscivorus piscivorus	Eastern Cottonmouth
[3]*Crotalus horridus (atricaudatus)*	Timber Rattlesnake (Canebrake)
[4]*Crotalus adamanteus*	Eastern Diamondback Rattlesnake
Sistrurus miliarius miliarius	Carolina Pigmy Rattlesnake

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[1] These individuals were observed & collected in 1965

[2] Original genus *Cnemidophorus* changed to *Aspidoceles*.

[3] Subspecies is not recognized by the Integrated Taxonomic Information System

Appendix G

Mammal List for Hobcaw Barony and Adjacent Estuarine Habitats

Mammal List for Hobcaw Barony and Adjacent Estuarine Habitats

Scientific Name	Common Name
Didelphidae	
Didelphis virginiana	Virginia Opossum
Soricidae	
Sorex longirostris	Southeastern Shrew
Blarina carolinensis	Southern Short-Tailed Shrew
Cryptotis parva	Least Shrew, Little Short-Tailed Shrew
Talpidae	
Scalopus aquaticus	Eastern Mole
Condylura cristata	Star-nosed Mole
Vespertilionidae	
Eptesicus fuscus	Big Brown Bat
Lasionycteris noctivagans	Silver-Haired Bat
Pipistrellus subflavus	Eastern Pipistrelle
Lasiurus borealis	Red Bat
Lasiurus seminolus	Seminole Bat
Lasiurus cinereus	Hoary Bat
Nycticeius humeralis	Evening Bat
Plecotus rafinesquii	Rafinesque's Big-Eared Bat
Molossidae	
Tadarida brasiliensis	Brazilian Free-Tailed Bat
Leporidae	
Sylvilagus palustris	Marsh Rabbit
Sylvilagus floridanus	Eastern Cottontail
Sciuridae	
Sciurus carolinensis	Gray Squirrel
Sciurus niger	Eastern Fox Squirrel
Glaucomys volans	Southern Flying Squirrel
Castoridae	
Castor canadensis	American Beaver
Cricetidae	
Oryzomys palustris	Marsh Rice Rat
Peromyscus gossypinus	Cotton Mouse
Sigmodon hispidus	Cotton Rat
Neotoma floridana	Eastern Woodrat
Reithrodontomys humulis	Eastern Harvest Mouse
Ochrotomys nuttalli	Golden Mouse
Microtus pennsylvanicus	Meadow Vole

Scientific Name	Common Name
Muridae	
Rattus rattus	Black Rat
Rattus norvegicus	Norway Rat
Mus musculus	House Mouse
Canidae	
Canis latrans	Coyote
Urocyon cinereoargenteus	Gray Fox
Vulpes vulpes	Red Fox
Ursidae	
Ursus americanus	Black Bear
Procyonidae	
Procyon lotor	Raccoon
Mustelidae	
Mustela frenata	Long-tailed weasel
Mustela vison	Mink
Mephitis mephitis	Striped skunk
Lontra (Lutra) canadensis	River Otter
Felidae	
Lynx (Felis) rufus	Bobcat
Delphinidae	
Tursiops truncatus	Bottle-Nosed Dolphin
Trichechidae	
Trichechus manatus	West Indian Manatee
Suidae	
Sus scrofa	Wild boar, Feral Pig
Cervidae	
Odocoileus virginianus	White-Tailed Deer

Appendix H

Bird Species Observed in North Inlet-Winyah Bay Area

Bird Species Observed in North Inlet-Winyah Bay Area

Common name	**Scientific name**
Snow Goose	*Chen caerulescens*
Brant	*Branta bernicla*
Canada Goose	*Branta canadensis*
Wood Duck	*Aix sponsa*
Gadwall	*Anas strepera*
Eurasian Wigeon	*Anas penelope*
American Wigeon	*Anas americana*
American Black Duck	*Anas rubripes*
Mallard	*Anas platyrhynchos*
Mottled Duck	*Anas fulvigula*
Blue-winged Teal	*Anas discors*
Cinnamon Teal	*Anas cyanoptera*
Northern Shoveler	*Anas clypeata*
Northern Pintail	*Anas acuta*
Green-winged Teal	*Anas crecca*
Canvasback	*Aythya valisineria*
Redhead	*Aythya americana*
Ring-necked Duck	*Aythya collaris*
Greater Scaup	*Aythya marila*
Lesser Scaup	*Aythya affinis*
Common Eider	*Somateria mollissima*
Surf Scoter	*Melanitta perspicillata*
White-winged Scoter	*Melanitta fusca*
Black Scoter	*Melanitta americana*
Long-tailed Duck	*Clangula hyemalis*
Bufflehead	*Bucephala albeola*
Common Goldeneye	*Bucephala clangula*
Hooded Merganser	*Lophodytes cucullatus*
Red-breasted Merganser	*Mergus serrator*
Ruddy Duck	*Oxyura jamaicensis*
Northern Bobwhite	*Colinus virginianus*
Wild Turkey	*Meleagris gallopavo*
Red-throated Loon	*Gavia stellata*
Common Loon	*Gavia immer*
Pied-billed Grebe	*Podilymbus podiceps*
Horned Grebe	*Podiceps auritus*
Eared Grebe	*Podiceps nigricollis*
Great Shearwater	*Puffinus gravis*
Wilson's Storm-Petrel	*Oceanites oceanicus*
Wood Stork	*Mycteria americana*
Magnificent Frigatebird	*Fregata magnificens*
Northern Gannet	*Morus bassanus*
Double-crested Cormorant	*Phalacrocorax auritus*
Great Cormorant	*Phalacrocorax carbo*

Common name	Scientific name
Anhinga	*Anhinga anhinga*
American White Pelican	*Pelecanus erythrorhynchos*
Brown Pelican	*Pelecanus occidentalis*
American Bittern	*Botaurus lentiginosus*
Least Bittern	*Ixobrychus exilis*
Great Blue Heron	*Ardea herodias*
Great Egret	*Ardea alba*
Snowy Egret	*Egretta thula*
Little Blue Heron	*Egretta caerulea*
Tricolored Heron	*Egretta tricolor*
Reddish Egret	*Egretta rufescens*
Cattle Egret	*Bubulcus ibis*
Green Heron	*Butorides virescens*
Black-crowned Night-Heron	*Nycticorax nycticorax*
Yellow-crowned Night-Heron	*Nyctanassa violacea*
White Ibis	*Eudocimus albus*
Glossy Ibis	*Plegadis falcinellus*
Roseate Spoonbill	*Platalea ajaja*
Black Vulture	*Coragyps atratus*
Turkey Vulture	*Cathartes aura*
Osprey	*Pandion haliaetus*
Swallow-tailed Kite	*Elanoides forficatus*
Mississippi Kite	*Ictinia mississippiensis*
Bald Eagle	*Haliaeetus leucocephalus*
Northern Harrier	*Circus cyaneus*
Sharp-shinned Hawk	*Accipiter striatus*
Cooper's Hawk	*Accipiter cooperii*
Red-shouldered Hawk	*Buteo lineatus*
Broad-winged Hawk	*Buteo platypterus*
Red-tailed Hawk	*Buteo jamaicensis*
Golden Eagle	*Aquila chrysaetos*
Yellow Rail	*Coturnicops noveboracensis*
Black Rail	*Laterallus jamaicensis*
Clapper Rail	*Rallus longirostris*
King Rail	*Rallus elegans*
Virginia Rail	*Rallus limicola*
Sora	*Porzana carolina*
Common Gallinule	*Gallinula galeata*
American Coot	*Fulica americana*
Black-bellied Plover	*Pluvialis squatarola*
American Golden-Plover	*Pluvialis dominica*
Snowy Plover	*Charadrius nivosus*
Wilson's Plover	*Charadrius wilsonia*
Semipalmated Plover	*Charadrius semipalmatus*
Piping Plover	*Charadrius melodus*
Killdeer	*Charadrius vociferus*
American Oystercatcher	*Haematopus palliatus*
Black-necked Stilt	*Himantopus mexicanus*

Common name	Scientific name
American Avocet	*Recurvirostra americana*
Spotted Sandpiper	*Actitis macularius*
Solitary Sandpiper	*Tringa solitaria*
Greater Yellowlegs	*Tringa melanoleuca*
Willet	*Tringa semipalmata*
Lesser Yellowlegs	*Tringa flavipes*
Upland Sandpiper	*Bartramia longicauda*
Whimbrel	*Numenius phaeopus*
Long-billed Curlew	*Numenius americanus*
Marbled Godwit	*Limosa fedoa*
Ruddy Turnstone	*Arenaria interpres*
Red Knot	*Calidris canutus*
Sanderling	*Calidris alba*
Semipalmated Sandpiper	*Calidris pusilla*
Western Sandpiper	*Calidris mauri*
Least Sandpiper	*Calidris minutilla*
White-rumped Sandpiper	*Calidris fuscicollis*
Baird's Sandpiper	*Calidris bairdii*
Pectoral Sandpiper	*Calidris melanotos*
Purple Sandpiper	*Calidris maritima*
Dunlin	*Calidris alpina*
Stilt Sandpiper	*Calidris himantopus*
Buff-breasted Sandpiper	*Tryngites subruficollis*
Ruff	*Philomachus pugnax*
Short-billed Dowitcher	*Limnodromus griseus*
Long-billed Dowitcher	*Limnodromus scolopaceus*
Wilson's Snipe	*Gallinago delicata*
American Woodcock	*Scolopax minor*
Wilson's Phalarope	*Phalaropus tricolor*
Red-necked Phalarope	*Phalaropus lobatus*
Red Phalarope	*Phalaropus fulicarius*
Sabine's Gull	*Xema sabini*
Bonaparte's Gull	*Chroicocephalus philadelphia*
Laughing Gull	*Leucophaeus atricilla*
Ring-billed Gull	*Larus delawarensis*
Herring Gull	*Larus argentatus*
Great Black-backed Gull	*Larus marinus*
Least Tern	*Sternula antillarum*
Gull-billed Tern	*Gelochelidon nilotica*
Caspian Tern	*Hydroprogne caspia*
Black Tern	*Chlidonias niger*
Common Tern	*Sterna hirundo*
Forster's Tern	*Sterna forsteri*
Royal Tern	*Thalasseus maximus*
Sandwich Tern	*Thalasseus sandvicensis*
Black Skimmer	*Rynchops niger*
Razorbill	*Alca torda*
Rock Pigeon	*Columba livia*

Common name	Scientific name
Eurasian Collared-Dove	*Streptopelia decaocto*
Mourning Dove	*Zenaida macroura*
Common Ground-Dove	*Columbina passerina*
Yellow-billed Cuckoo	*Coccyzus americanus*
Barn Owl	*Tyto alba*
Eastern Screech-Owl	*Megascops asio*
Great Horned Owl	*Bubo virginianus*
Barred Owl	*Strix varia*
Short-eared Owl	*Asio flammeus*
Northern Saw-whet Owl	*Aegolius acadicus*
Common Nighthawk	*Chordeiles minor*
Chuck-will's-widow	*Antrostomus carolinensis*
Eastern Whip-poor-will	*Antrostomus vociferus*
Chimney Swift	*Chaetura pelagica*
Ruby-throated Hummingbird	*Archilochus colubris*
Rufous Hummingbird	*Selasphorus rufus*
Belted Kingfisher	*Megaceryle alcyon*
Red-headed Woodpecker	*Melanerpes erythrocephalus*
Red-bellied Woodpecker	*Melanerpes carolinus*
Yellow-bellied Sapsucker	*Sphyrapicus varius*
Downy Woodpecker	*Picoides pubescens*
Hairy Woodpecker	*Picoides villosus*
Red-cockaded Woodpecker	*Picoides borealis*
Northern Flicker	*Colaptes auratus*
Pileated Woodpecker	*Dryocopus pileatus*
American Kestrel	*Falco sparverius*
Merlin	*Falco columbarius*
Peregrine Falcon	*Falco peregrinus*
Eastern Wood-Pewee	*Contopus virens*
Acadian Flycatcher	*Empidonax virescens*
Least Flycatcher	*Empidonax minimus*
Eastern Phoebe	*Sayornis phoebe*
Great Crested Flycatcher	*Myiarchus crinitus*
Eastern Kingbird	*Tyrannus tyrannus*
Gray Kingbird	*Tyrannus dominicensis*
Scissor-tailed Flycatcher	*Tyrannus forficatus*
Loggerhead Shrike	*Lanius ludovicianus*
White-eyed Vireo	*Vireo griseus*
Yellow-throated Vireo	*Vireo flavifrons*
Blue-headed Vireo	*Vireo solitarius*
Red-eyed Vireo	*Vireo olivaceus*
Blue Jay	*Cyanocitta cristata*
American Crow	*Corvus brachyrhynchos*
Fish Crow	*Corvus ossifragus*
Purple Martin	*Progne subis*
Tree Swallow	*Tachycineta bicolor*
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*
Bank Swallow	*Riparia riparia*

Common name	Scientific name
Cave Swallow	*Petrochelidon fulva*
Barn Swallow	*Hirundo rustica*
Carolina Chickadee	*Poecile carolinensis*
Tufted Titmouse	*Baeolophus bicolor*
Red-breasted Nuthatch	*Sitta canadensis*
White-breasted Nuthatch	*Sitta carolinensis*
Brown-headed Nuthatch	*Sitta pusilla*
Brown Creeper	*Certhia americana*
House Wren	*Troglodytes aedon*
Winter Wren	*Troglodytes hiemalis*
Sedge Wren	*Cistothorus platensis*
Marsh Wren	*Cistothorus palustris*
Carolina Wren	*Thryothorus ludovicianus*
Blue-gray Gnatcatcher	*Polioptila caerulea*
Golden-crowned Kinglet	*Regulus satrapa*
Ruby-crowned Kinglet	*Regulus calendula*
Eastern Bluebird	*Sialia sialis*
Swainson's Thrush	*Catharus ustulatus*
Hermit Thrush	*Catharus guttatus*
Wood Thrush	*Hylocichla mustelina*
American Robin	*Turdus migratorius*
Gray Catbird	*Dumetella carolinensis*
Northern Mockingbird	*Mimus polyglottos*
Brown Thrasher	*Toxostoma rufum*
European Starling	*Sturnus vulgaris*
American Pipit	*Anthus rubescens*
Cedar Waxwing	*Bombycilla cedrorum*
Ovenbird	*Seiurus aurocapilla*
Worm-eating Warbler	*Helmitheros vermivorum*
Louisiana Waterthrush	*Parkesia motacilla*
Northern Waterthrush	*Parkesia noveboracensis*
Black-and-white Warbler	*Mniotilta varia*
Prothonotary Warbler	*Protonotaria citrea*
Swainson's Warbler	*Limnothlypis swainsonii*
Orange-crowned Warbler	*Oreothlypis celata*
Kentucky Warbler	*Geothlypis formosa*
Common Yellowthroat	*Geothlypis trichas*
Hooded Warbler	*Setophaga citrina*
American Redstart	*Setophaga ruticilla*
Cape May Warbler	*Setophaga tigrina*
Northern Parula	*Setophaga americana*
Bay-breasted Warbler	*Setophaga castanea*
Yellow Warbler	*Setophaga petechia*
Blackpoll Warbler	*Setophaga striata*
Black-throated Blue Warbler	*Setophaga caerulescens*
Palm Warbler	*Setophaga palmarum*
Pine Warbler	*Setophaga pinus*
Yellow-rumped Warbler	*Setophaga coronata*

Common name	Scientific name
Yellow-throated Warbler	*Setophaga dominica*
Prairie Warbler	*Setophaga discolor*
Black-throated Green Warbler	*Setophaga virens*
Yellow-breasted Chat	*Icteria virens*
Eastern Towhee	*Pipilo erythrophthalmus*
Bachman's Sparrow	*Peucaea aestivalis*
Chipping Sparrow	*Spizella passerina*
Clay-colored Sparrow	*Spizella pallida*
Savannah Sparrow	*Passerculus sandwichensis*
Nelson's Sparrow	*Ammodramus nelsoni*
Saltmarsh Sparrow	*Ammodramus caudacutus*
Seaside Sparrow	*Ammodramus maritimus*
Fox Sparrow	*Passerella iliaca*
Song Sparrow	*Melospiza melodia*
Swamp Sparrow	*Melospiza georgiana*
White-throated Sparrow	*Zonotrichia albicollis*
White-crowned Sparrow	*Zonotrichia leucophrys*
Dark-eyed Junco	*Junco hyemalis*
Summer Tanager	*Piranga rubra*
Scarlet Tanager	*Piranga olivacea*
Northern Cardinal	*Cardinalis cardinalis*
Rose-breasted Grosbeak	*Pheucticus ludovicianus*
Blue Grosbeak	*Passerina caerulea*
Indigo Bunting	*Passerina cyanea*
Painted Bunting	*Passerina ciris*
Bobolink	*Dolichonyx oryzivorus*
Red-winged Blackbird	*Agelaius phoeniceus*
Eastern Meadowlark	*Sturnella magna*
Rusty Blackbird	*Euphagus carolinus*
Common Grackle	*Quiscalus quiscula*
Boat-tailed Grackle	*Quiscalus major*
Brown-headed Cowbird	*Molothrus ater*
Orchard Oriole	*Icterus spurius*
Baltimore Oriole	*Icterus galbula*
Purple Finch	*Haemorhous purpureus*
House Finch	*Haemorhous mexicanus*
Pine Siskin	*Spinus pinus*
American Goldfinch	*Spinus tristis*
Evening Grosbeak	*Coccothraustes vespertinus*
House Sparrow	*Passer domesticus*

Total species: 276

Appendix I

Species List and State Records of Insects Collected from Hobcaw Barony, South Carolina

Species List and State Records of Insects Collected from Hobcaw Barony, South Carolina*

University of Guelph Field Entomology Class, Spring of 2004.
Gard Otis, Instructor; Steve Paiero, Assistant Instructor

ORDER	FAMILY	Genus/Species
Coleoptera	Buprestidae	*Acmaeodera*
Coleoptera	Buprestidae	*Brachys*
Coleoptera	Buprestidae	*Buprestis salisburyensis* Herbst, 1801
Coleoptera	Buprestidae	*Haplanthaxia*
Coleoptera	Buprestidae	*Haplanthaxia quercata* (Fabricius)
Coleoptera	Buprestidae	*Taphrocerus*
Coleoptera	Carabidae	*Calybe sallei* (Chev.)
Coleoptera	Carabidae	*Panagaeus crucigerus* Say
Coleoptera	Elateridae	*Alaus myops* (Fabricius)
Coleoptera	Elateridae	*Cardiophorus*
Coleoptera	Elateridae	*Melanotus*
Coleoptera	Eucnemidae	*Dirrhagofarsus lewisi* Reitter
Coleoptera	Monommidae	*Hyporhagus*
Coleoptera	Oedemeridae	*Xanthochroa erythrocephala* (Germar)
Coleoptera	Scarabaeidae	*Canthon laevis* (Drury)
Coleoptera	Scarabaeidae	*Melanocanthon bispinatus* (Robinson)
Coleoptera	Trogossitidae	*Tenebroides bimaculata* Melsheimer
Dermaptera	Labiidae	*Labia*
Dermaptera	Labiidae	*Labia cf. curvicauda* (Motschulsky)
Dermaptera	Labiidae	*Vostox brunneipennis* (Audinet-Serville, 1839)
Diptera	Asilidae	*Laphria saffrana*
Diptera	Chloropidae	*Ectecephala*
Diptera	Lauxaniidae	*Trigonometopus*
Diptera	Micropezidae	*Grallipeza nebulosa* (Loew)
Diptera	Micropezidae	*Taeniaptera*
Diptera	Otitidae	*Chaetopsis*
Diptera	Otitidae	*Delphinia picta* (Fabricius)
Diptera	Otitidae	*Euxesta*
Diptera	Otitidae	*Zacompsia fulva* Coquillett
Diptera	Psilidae	*Loxocera cylindrica* Say, 1823
Diptera	Pyrgotidae	*Boreothrinax*
Diptera	Syrphidae	*Milesia virginiensis* (Drury)

ORDER	FAMILY	Genus/Species
Hemiptera	Achilidae	*Epiptera*
Hemiptera	Aradidae	*Mezira*
Hemiptera	Aradidae	*Proxius gypsatus* Bergroth
Hemiptera	Belostomatidae	*Abedus immaculatus* (Say)
Hemiptera	Belostomatidae	*Lethocerus uhleri* (Montandon)
Hemiptera	Berytidae	*Jalysus*
Hemiptera	Caliscelidae	*Bruchomorpha oculata* Newman
Hemiptera	Cercopidae	*Aphrophora*
Hemiptera	Cercopidae	*Clastoptera*
Hemiptera	Cicadellidae	*Draeculacephala*
Hemiptera	Cicadellidae	*Gyponana*
Hemiptera	Cicadellidae	*Homalodisca*
Hemiptera	Cicadellidae	*Norvellina*
Hemiptera	Cicadellidae	*Oncometopia*
Hemiptera	Cicadellidae	*Osbornellus*
Hemiptera	Cicadellidae	*Penthimia americana* Fitch
Hemiptera	Cicadellidae	*Ponana*
Hemiptera	Cicadellidae	*Scaphytopius*
Hemiptera	Cicadellidae	*Texananus*
Hemiptera	Cicadellidae	*Tylozygus bifidus* (Say)
Hemiptera	Cixiidae	*Oecleus*
Hemiptera	Cixiidae	*Oliarus*
Hemiptera	Cixiidae	*Pintalia delicata* (Fowler)
Hemiptera	Coreidae	*Althos obscurator* (Fabricius)
Hemiptera	Coreidae	*Euthochtha galeator* (Fabricius)
Hemiptera	Coreidae	*Leptoglossus phyllopus* (Linnaeus)
Hemiptera	Cydnidae	*Amnestus spinifrons* (Say)
Hemiptera	Cydnidae	*Pangaeus bilineatus* (Say)
Hemiptera	Cymidae	*Cymus*
Hemiptera	Delphacidae	*Delphacodes*
Hemiptera	Delphacidae	*Pissonotus aphidioides* VanDuzee
Hemiptera	Derbidae	*Cedusa*
Hemiptera	Derbidae	*Otiocerus degeeri* Kirby
Hemiptera	Derbidae	*Otiocerus stolli* Kirby
Hemiptera	Flatidae	*Anormenis septentrionalis* (Spinola)
Hemiptera	Flatidae	*Cyarda melichari* Van Duzee
Hemiptera	Gelastocoridae	*Gelastocoris oculatus* (Fabricius)

ORDER	FAMILY	Genus/Species
Hemiptera	Geocoridae	*Geocoris uliginosus* (Say)
Hemiptera	Hydrometridae	*Hydrometra*
Hemiptera	Largidae	*Largus succinctus* (Linnaeus)
Hemiptera	Lyctocoridae	*Lyctocoris stali* (Reuter)
Hemiptera	Membracidae	*Archasia auriculata* (Fitch)
Hemiptera	Membracidae	*Archasia pallida* (Fairmaire)
Hemiptera	Membracidae	*Ceresa*
Hemiptera	Membracidae	*Cyrtolobus*
Hemiptera	Membracidae	*Glossonotus*
Hemiptera	Membracidae	*Micrutalis calva* (Say)
Hemiptera	Membracidae	*Ophiderma*
Hemiptera	Membracidae	*Platycotis vittata* (Fabricius)
Hemiptera	Membracidae	*Smilia camelus* (Fabricius)
Hemiptera	Membracidae	*Telamona*
Hemiptera	Membracidae	*Tylopelta americana* (Goding)
Hemiptera	Mesoveliidae	*Mesovelia mulsanti* White
Hemiptera	Miridae	*Corticoris*
Hemiptera	Miridae	*Poecilocapsus lineatus* (Fabricius)
Hemiptera	Miridae	*Pseudoxenetus regalis* (Uhler)
Hemiptera	Miridae	*Sixeonotus*
Hemiptera	Miridae	unidentified Miridae
Hemiptera	Pachygronthidae	*Oedancala*
Hemiptera	Pentatomidae	*Banasa dimidiata* (Say)
Hemiptera	Pentatomidae	*Banasa euchlora* Stål
Hemiptera	Pentatomidae	*Banasa packardi* Stål
Hemiptera	Pentatomidae	*Dendrocoris*
Hemiptera	Pentatomidae	*Euschistus*
Hemiptera	Pentatomidae	*Hymenarcys nervosa* (Say)
Hemiptera	Pentatomidae	*Mormidea lugens* (Fabricius)
Hemiptera	Pentatomidae	*Oebalus pugnax* (Fabricius)
Hemiptera	Pentatomidae	*Parabrochymena arborea* (Say)
Hemiptera	Pentatomidae	*Thyanta calceata* (Say)
Hemiptera	Reduviidae	*Apiomerus crassipes* (Fabricius)
Hemiptera	Reduviidae	*Empicoris*
Hemiptera	Reduviidae	*Melanolestes picipes* (Herrich-Schaffer)
Hemiptera	Reduviidae	*Microtomus purcis* (Drury)
Hemiptera	Reduviidae	*Oncerotrachelus acuminatus* (Say)

ORDER	FAMILY	Genus/Species
Hemiptera	Reduviidae	*Ploiaria carolina* (Herrich-Schaffer)
Hemiptera	Reduviidae	*Pnirontis cf. languida* Stal
Hemiptera	Reduviidae	*Pnirontis modesta* Banks
Hemiptera	Reduviidae	*Pselliopus cinctus* (Fabricius)
Hemiptera	Reduviidae	*Repipta taurus* (Fabricius)
Hemiptera	Reduviidae	*Sirthenea carinata* (Fabricius)
Hemiptera	Reduviidae	*Zelus*
Hemiptera	Rhyparochromidae	*Cnemodus mavortius* (Say)
Hemiptera	Rhyparochromidae	*Neopamera albocincta* (Barber)
Hemiptera	Rhyparochromidae	*Ozophora*
Hemiptera	Rhyparochromidae	*Paromius longulus* (Dallas)
Hemiptera	Saldidae	*Saldula*
Hemiptera	Saldidae	*Saldoida*
Hemiptera	Scutelleridae	*Diolcus chrysorrhoeus* (Fabricius)
Hemiptera	Scutelleridae	*Tetyra bipunctata* (H.S.)
Hemiptera	Thyreocoridae	*Galgupha*
Hymenoptera	Andrenidae	*Andrena*
Hymenoptera	Andrenidae	*Perdita bradleyi* Viereck
Hymenoptera	Andrenidae	*Perdita halictoides* Smith, 1853
Hymenoptera	Andrenidae	*Perdita novae-angliae* Viereck
Hymenoptera	Anthophoridae	*Ceratina*
Hymenoptera	Anthophoridae	*Florilegus condiguus* (Cresson)
Hymenoptera	Apidae	*Xylocopa micans* Lepeletier
Hymenoptera	Chrysididae	*Chrysis conica* Brullé, 1846
Hymenoptera	Chrysididae	*Neochrysis alabamensis* (Mocsáry, 1914)
Hymenoptera	Colletidae	*Hylaeus schwarzii* (Cockerell, 1896)
Hymenoptera	Halictidae	*Dialictus*
Hymenoptera	Halictidae	*Lasioglossum*
Hymenoptera	Megachilidae	*Heriades variolosa variolosa* (Cresson)
Hymenoptera	Megachilidae	*Megachile*
Hymenoptera	Megachilidae	*Osmia*
Hymenoptera	Sphecidae	*Prionyx parkeri* Bohart & Menke, 1963
Hymenoptera	Vespidae	*Ancistrocerus campestris* (Saussure, 1852)
Hymenoptera	Vespidae	*Ancistrocerus unifasciatus seminole* Bequaert, 1943
Hymenoptera	Vespidae	*Eumenes fraternus* Say, 1824
Hymenoptera	Vespidae	*Euodynerus bidens* (Saussure, 1870)
Hymenoptera	Vespidae	*Euodynerus boscii* (Lepeletier, 1841)

ORDER	FAMILY	Genus/Species
Hymenoptera	Vespidae	*Euodynerus megaera* (Lepeletier, 1841)
Hymenoptera	Vespidae	*Euodynerus parvirudis* (Bohart, 1948)
Hymenoptera	Vespidae	*Euodynerus schwarzi* (Krombein, 1962)
Hymenoptera	Vespidae	*Parancistrocerus fulvipes rufovestis* (Bohart, 1948)
Hymenoptera	Vespidae	*Stenodynerus ammonia paraensis* (Saussure, 1855)
Hymenoptera	Vespidae	*Stenodynerus histrionalis histrionalis* (Robertson, 1901)
Hymenoptera	Vespidae	*Stenodynerus krombeini* Bohart, 1953
Hymenoptera	Vespidae	*Symmorphus canadensis* (Saussure, 1855)
Neuroptera	Berothidae	*Lomamyia banksi* Carpenter
Neuroptera	Sisyridae	*Climacia aerolaris* (Hagen)
Neuroptera	Sisyridae	*Sisyra fuscata* (Fabricus)
Neuroptera	Sisyridae	*Sisyra vicaria* (Walker)
Orthoptera	Batrachidae	*Tettigidea armata* Morse
Orthoptera	Batrachidae	*Tettigidea lateralis lateralis* (Say)
Orthoptera	Gryllidae	*Eunemobius*
Orthoptera	Tetrigidae	*Nomotettix cristatus cristatus* (Scudder)
Orthoptera	Tridactylidae	*Ellipes minutus minutus* (Scud.)

*Note: This is not a complete list in that it is only the material that was collected by some of the instructors, been mounted, identified and had the identification databased. Some additional material has yet to be mounted and student material is not included in this list. Also, they did not collect any Lepidoptera, so there are no butterflies or moths listed. As our interest at the University of Guelph Insect Collection is focused largely on acalyptrate Diptera (a subset of flies), with a bit of interest in aculeate Hymenoptera (the stinging wasps), bugs (Hemiptera) and certain beetles (Coleoptera), many of the other groups were not sampled.

Below Steve Paiero, Assistant Instructor, University of Guelph, has discussed several state records in groups that he is familiar with (they may have been recently recorded but his available literature indicates that they are otherwise unrecorded). Additional ones might exist but they do not have enough literature available to them on the SC fauna to fully determine what new records occur in these other groups.

STATE RECORDS

Panagaeus crucigerus (Carabidae) is a beautiful ground beetle that is known from both NC and FL but had yet to be found in SC.

Dirrhagofarsus lewisi (Eucnemidae) was known from nearby GA, NY, WV and MA, so it too was not surprising to find this species in SC. It apparently develops on beech trees.

Abedus immaculatus (Belostomatidae) is an aquatic predator that had previously been known from nearby Georgia (south to Florida). Several specimens were found in the creek/run-off ditch near the visitors centre.

Proxius gypsatus (Aradidae) appears to be rare (or rarely collected) and was previously recorded in North America only from Florida. One specimen was collected from the lights at the cabins. No hosts plants are recorded.

Otiocerus degeeri (Derbidae) is also newly recorded from SC, but it is not surprising to find it here as it is recorded from almost everywhere else in the eastern USA. It was found feeding on oaks along the roadway.

Otiocerus stolli (Derbidae) is known from NY south to FL but had not previously been recorded to SC. It was found feeding on oaks along the roadway.

Cyarda melichari (Flatidae) is known from as far north as DC and south to FL but has not yet been recorded to SC. This species was found in relatively large numbers along the road in the salt marsh (Clambank Road near the observation tower). It is recorded on several shrubs and on *Juncus*.

The reduviids *Apiomerus crassipes, Melanolestes picipes, Pnirontis modesta, Pselliopus cinctus,* and *Repipta taurus* are all new state records. Most of these species were collected in the vicinity of the cabins, with the exception of *P. modesta*, which was taken near the salt marsh

Appendix J

Butterfly Species Observed on Hobcaw Barony and the North Inlet-Winyah Bay NERR

Butterfly Species Observed on Hobcaw Barony and the North Inlet-Winyah Bay NERR

Common Name	Scientific Name
SWALLOWTAILS	
Pipevine Swallowtail	*Battus philenor*
Zebra Swallowtail	*Eurytides marcellus*
Black Swallowtail	*Papilio polyxenes*
Giant Swallowtail	*Papilio cresphontes*
Eastern Tiger Swallowtail	*Papilio glaucus*
Spicebush Swallowtail	*Papilio troilus*
Palamedes Swallowtail	*Papilio palamedes*
WHITES & SULPHURS	
Cabbage White	*Pieris rapae*
Falcate Orangetip	*Anthocharis midea*
Southern Dogface	*Colias cesonia*
Cloudless Sulphur	*Phoebis sennae*
Little Yellow	*Eurema lisa*
Sleepy Orange	*Eurema nicippe*
COPPERS, HAIRSTREAKS, & BLUES	
Banded Hairstreak	*Satyrium calanus*
Striped Hairstreak	*Satyrium liparops*
Henry's Elfin	*Callophrys henrici*
"Olive" Juniper Hairstreak	*Callophrys gryneus gryneus*
White M Hairstreak	*Parrhasius m-album*
Gray Hairstreak	*Strymon melinus*
Red-banded Hairstreak	*Calycopis cecrops*
Eastern Pygmy-Blue	*Brephidium isophthalma*
Ceraunus Blue	*Hemiargus ceraunus*
Eastern Tailed-Blue	*Everes comyntas*
Spring Azure	*Celastrina ladon*
BRUSHFOOTS	
American Snout	*Libytheana carinenta*
Gulf Fritillary	*Agraulis vanillae*
Zebra Heliconian	*Heliconius charithonia*

Common Name	Scientific Name
BRUSHFOOTS (continued)	
Variegated Fritillary	*Euptoieta claudia*
Phaon Crescent	*Phyciodes phaon*
Pearl Crescent	*Phyciodes tharos*
Question Mark	*Polygonia interrogationis*
Mourning Cloak	*Nymphalis antiopa*
American Lady	*Vanessa virginiensis*
Painted Lady	*Vanessa cardui*
Red Admiral	*Vanessa atalanta*
Common Buckeye	*Junonia coenia*
White Peacock	*Anartia jatrophae*
Red-spotted Purple	*Limenitis arthemis astyanax*
Viceroy	*Limenitis archippus*
SATYRS & WOOD NYMPHS	
Southern Pearly-eye	*Enodia portlandia*
Creole Pearly-eye	*Enodia creola*
Appalachian Brown	*Satyrodes appalachia*
Gemmed Satyr	*Cyllopsis gemma*
Carolina Satyr	*Hermeuptychia sosybius*
Little Wood-Satyr	*Megisto cymela*
Common Wood-Nymph	*Cercyonis pegala*
MILKWEED BUTTERFLIES	
Monarch	*Danaus plexippus*
Queen	*Danaus gilippus*
SKIPPERS	
Silver-spotted Skipper	*Epargyreus clarus*
Long-tailed Skipper	*Urbanus proteus*
Hoary Edge	*Achalarus lyciades*
Southern Cloudywing	*Thorybes bathyllus*
Northern Cloudywing	*Thorybes pylades*
Confused Cloudywing	*Thorybes confusis*
Hayhurst's Scallopwing	*Staphylus hayhurstii*
Horace's Duskywing	*Erynnis horatius*
Zarucco Duskywing	*Erynnis zarucco*
Common Checkered-Skipper	*Pyrgus communis*

Common Name	Scientific Name
SKIPPERS (continued)	
Tropical Checkered-Skipper	*Pyrgus oileus*
Common Sootywing	*Pholisora catullus*
Swarthy Skipper	*Nastra lherminier*
Clouded Skipper	*Lerema accius*
Least Skipper	*Ancyloxypha numitor*
Southern Skipperling	*Copaeodes minimus*
Fiery Skipper	*Hylephila phyleus*
Crossline Skipper	*Polites origenes*
Whirlabout	*Polites vibex*
Southern Broken-Dash	*Wallengrenia ortho*
Northern Broken-Dash	*Wallengrenia egeremet*
Little Glassywing	*Pompeius verna*
Sachem	*Atalopedes campestris*
Delaware Skipper	*Anatrytone logan*
Byssus Skipper	*Problema byssus*
Rare Skipper	*Problema bulenta*
Zabulon Skipper	*Poanes zabulon*
Yehl Skipper	*Poanes yehl*
Broad-winged Skipper	*Poanes viator*
Palatka Skipper	*Euphyes pilatka*
Dion Skipper	*Euphyes dion*
Dun Skipper	*Euphyes vestris*
Lace-winged Roadside-Skipper	*Amblyscirtes aesculapius*
Reversed Roadside-Skipper	*Amblyscirtes reversa*
Dusky Roadside-Skipper	*Amblyscirtes alternata*
Eufala Skipper	*Lerodea eufala*
Twin-spot Skipper	*Oligoria maculata*
Salt Marsh Skipper	*Panoquina panoquin*
Ocola Skipper	*Panoquina ocola*