RESEARCH PLAN

Defense Coastal/Estuarine Research Program 2 (DCERP2)

SERDP Project RC-2245

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RTI International

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Acronyms and Abbreviations

°C	degree Celsius
°F	degree Fahrenheit
µatm	microatmosphere
µg L^{-1}	micrograms per liter
µm	micrometer
ΔpCO_2	difference in carbon dioxide partial pressure between water and air (µatm)
U_{10}	hourly wind speed
1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
A/E	Aquatic/Estuarine
A.D.	Anno Domini
ADCIRC	Advanced Circulation (model)
AFB	Air Force Base
AutoMEDS	Automated Model Evaluation and Diagnostics System (software)
AVP	Autonomous Vertical Profiler
AquaCo	Aquatic Analysis and Consulting, LLC
AWAC	acoustic wave and current (recorder)
BMA	benthic microalgae
BMP	best management practice
C	carbon
CB	Coastal Barrier
CC	Climate Change
CCFHR	Center for Coastal Fisheries and Habitat Research
CDIP	Coastal Data Information Program
CDOM	chromophoric dissolved organic matter
CEQ	White House Council on Environmental Quality
CH_4	methane
CHN	carbon, hydrogen, and nitrogen
chl *a*	chlorophyll *a*
CHL-ERDC	Coastal and Hydraulics Laboratory-Engineer Research and Development Center
CLARIS	Coastal LIDAR (Light Detection and Ranging) and Radar Imaging System
cm	centimeter
cm^2	square centimeter
cm h^{-1}	centimeters per hour
CMIP5	Coupled Model Intercomparison Project
CO_2	carbon dioxide
CO-OPS	Center for Operational Oceanographic Products and Services
CW	Coastal Wetlands
C_{WC}	water column of labile organic carbon
C_{SED}	sediment pools of labile organic carbon
dbh	diameter at breast height
DCERP	Defense Coastal/Estuarine Research Program

DCERP1	first cycle of DCERP
DCERP2	second cycle of DCERP
DEM	Digital Elevation Model
DIC	dissolved inorganic carbon
DIMS	Data and Information Management System
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DNF	denitrification
DoD	U.S. Department of Defense
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DON	dissolved organic nitrogen
EA-IRMS	elemental analyzer–isotope ratio mass spectrometer
EC	Executive Committee
EDD	Electronic Data Delivery
EMD	Environmental Management Division
ESM	Estuarine Simulation Model
ESTCP	Environmental Security Technology Certification Program
FC	Freeman Creek
Fert	fertilized site
FN	French Creek
FNS	French Creek Shore
FNU	French Creek Upper
ft	foot, feet
FY	Fiscal Year
g	gram
GC-IRMS	gas chromatography–isotope ratio mass spectrometry
GEOMBEST	Geomorphic Model of Barrier, Estuarine, and Shoreface Translations
GFF	glass fiber filter
GIS	geographic information systems
GM/WC	Gottshalk Marina/Wallace Creek
GPP	gross primary production
GPS	global positioning system
GUI	graphical user interface
ha	hectare
H_3PO_4	phosphoric acid
HAB	harmful algal bloom
HCl	hydrochloric acid
HPLC	high-performance liquid chromatography
ICW	Intracoastal Waterway
IMEDS	Interactive Model Evaluation and Diagnostics System (software)
IPCC	Intergovernmental Panel on Climate Change
IRMS	isotope ratio mass spectrometer
IT	Information Technology
ITS	Information Technology Services

k	gas-exchange coefficient (cm h^{-1})
KeV	kiloelectron volt
K_0	carbon dioxide solubility coefficient
km	kilometer
km/h	kilometers per hour
L	liter
L min^{-1}	liters per minute
LIDAR	Light Detection and Ranging
m	meter
m/yr	meters per year
m s^{-1}	meters per second
m^{-2} yr^{-1}	square meters per year
m^2	square meter
m^2/ha	square meter per hectare
m^3	cubic meter
mm	millimeter
mm/y	millimeters per year
MARDIS	Monitoring and Research Data Information System
MARS	Merrick Advanced Remote Sensing (software package)
MCAS	Marine Corps Air Station
MCBCL	Marine Corps Base Camp Lejeune
MDOE	maximum depth of erosion
MEM	Marsh Equilibrium Model
MHB	Mile Hammock Bay
MHHW	mean higher high water
MHW	mean high water
MHz	megahertz
MIN	gross nitrogen mineralization
mL	milliliter
mm y^{-1}	millimeters per year
msl	mean sea level
N	nitrogen
NAD 83	North American Datum of 1983
NAM	North American Mesoscale (model)
NARCCAP	North American Regional Climate Change Assessment Program
NAVD 88	North American Vertical Datum of 1988
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NCA	National Climate Assessment
NCSU	North Carolina State University
NEE	net ecosystem exchange
NEM	net ecosystem metabolism
NEP	net ecosystem production
Nfix	nitrogen fixation
NH_4^+–N	ammonium-nitrogen (referred to as NH_4)
NMS	nonmetric multidimensional scaling
NO_2	nitrogen dioxide

$NO_3^- + NO_2^-$	nitrate- plus nitrite-nitrogen (referred to as NO_x)
NO_x	nitrate plus nitrite
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NRE	New River Estuary
NTU	Nephelometric Turbidity Unit
O^2	oxygen
OB	Onslow Beach
OBB	Onslow Back Barrier
OC	organic carbon
OSC	On-site Coordinator
P	phosphorus
PB	prescribed burning
pCO_2	partial pressure of carbon dioxide
P_{EST}	probability of establishment
PHYTO	phytoplankton
PI	Principal Investigator
P versus I	production versus irradiance (relationships)
PO_4^{3+}–P	orthophosphate (referred to as PO_4)
POC	particulate organic carbon
POS-LV	Positron and Orientation System for Land Vehicles
PP	primary production, Pollocks Point
PPS	Pollocks Point Shore
PPU	Pollocks Point Upper
ppmv	parts per million by volume
ppt	parts per thousand
P/R	ratio of production to respiration
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
R	respiration
R^2	R squared value
RCC	Regional Coordinating Committee
RCCC	Resource Conservation and Climate Change
RCW	red-cockaded woodpecker
RDBMS	Relational Database Management System
ReNuMa	Regional Nutrient Management (model)
RTK-GPS	real-time kinematic global positioning system
SAB	Scientific Advisory Board
SAV	submerged aquatic vegetation
Sc_{SST}	Schmidt number for carbon dioxide at ambient sea-surface salinity and sea-surface temperature
SSC	suspended sediment concentration
SDS/FIE	Spatial Data Standards/Facilities, Infrastructure, and Environment
SDSS	Spatial Decision-Support System
SEM	structural equation modeling

SERDP	Strategic Environmental Research and Development Program
SET	surface elevation table
SSL	Secure Sockets Layer
SSS	sea-surface salinity
SST	sea-surface temperature
SWAN	Simulating Waves Nearshore (model)
T	Terrestrial
TAC	Technical Advisory Committee
TBB	Traps Bay Bridge
TBC	Traps Bay Creek
TCAT	Terrestrial Carbon Assessment Decision-Support Tool
TDN	total dissolved nitrogen
TELSA	Tool for Exploratory Landscape Scenario Analyses
TLS	terrestrial laser scanner
TOC	total organic carbon
TSG	thermosalinograph
TSP	Translating Science into Practice
TSS	total suspended solids
UCONN	University of Connecticut
UNC-CH	University of North Carolina at Chapel Hill
UNC-IMS	University of North Carolina Institute of Marine Sciences
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VA Tech	Virginia Polytechnic Institute and State University
VIMS	Virginia Institute of Marine Science
WL	water level (stations)
WSM	Watershed Simulation Model

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1.0 Introduction

1.1 Background to DCERP

Critical military training and testing on lands along the nation's coastal and estuarine shorelines are increasingly placed at risk because of development pressures in surrounding areas, impairments due to other anthropogenic disturbances, and increasing requirements for compliance with environmental regulations. The U.S. Department of Defense (DoD) intends to enhance and sustain its training and testing assets and to optimize its stewardship of natural resources through the development and application of an ecosystem-based management approach on DoD facilities. DoD's policy has established ecosystem-based management as the preferred approach for military lands (Goodman, 1996). This management approach focuses on sustaining and enhancing military training and testing activities by monitoring and managing the interdependent natural resource assets on which the future of these activities depend. To expand its commitment to improving military readiness while demonstrating the science behind this approach, the Strategic Environmental Research and Development Program (SERDP) funds research and monitoring projects that support the sustainability of military training and testing in ecologically and economically important ecosystems.

To accomplish this goal, especially for coastal environments, SERDP launched the Defense Coastal/Estuarine Research Program (DCERP) at Marine Corps Base Camp Lejeune (MCBCL) in North Carolina (**Figure 1-1**) in 2006. As a U.S. Marine Corps installation, MCBCL has a single and exclusive mission: military preparedness. MCBCL provides an ideal platform for DCERP because it integrates coastal barrier, aquatic/estuarine, coastal wetland, and terrestrial ecosystems, all within the boundaries of DoD properties.

DCERP was designed to provide relevant research and monitoring data, develop and apply environmental indicators, and provide MCBCL's natural resources managers with assessment tools and models in support of ecosystem-based management. DCERP was implemented in two contract periods. The first cycle of DCERP, referred to as DCERP1, was conducted from July 2006–January 2013 and included a 9-month planning period and 6-year implementation period for research and monitoring activities. The specific objectives of DCERP1 were to: (1) develop appropriate conceptual and mechanistic ecological models to guide research, monitoring, and adaptive management feedback loops; (2) identify significant ecosystem stressors, their sources (on and off MCBCL), and their level of impact on MCBCL's ecological systems, and (3) incorporate stressor and other ecological indicator information into the models, with an aim to develop more effective management guidelines for sustainable ecosystems.

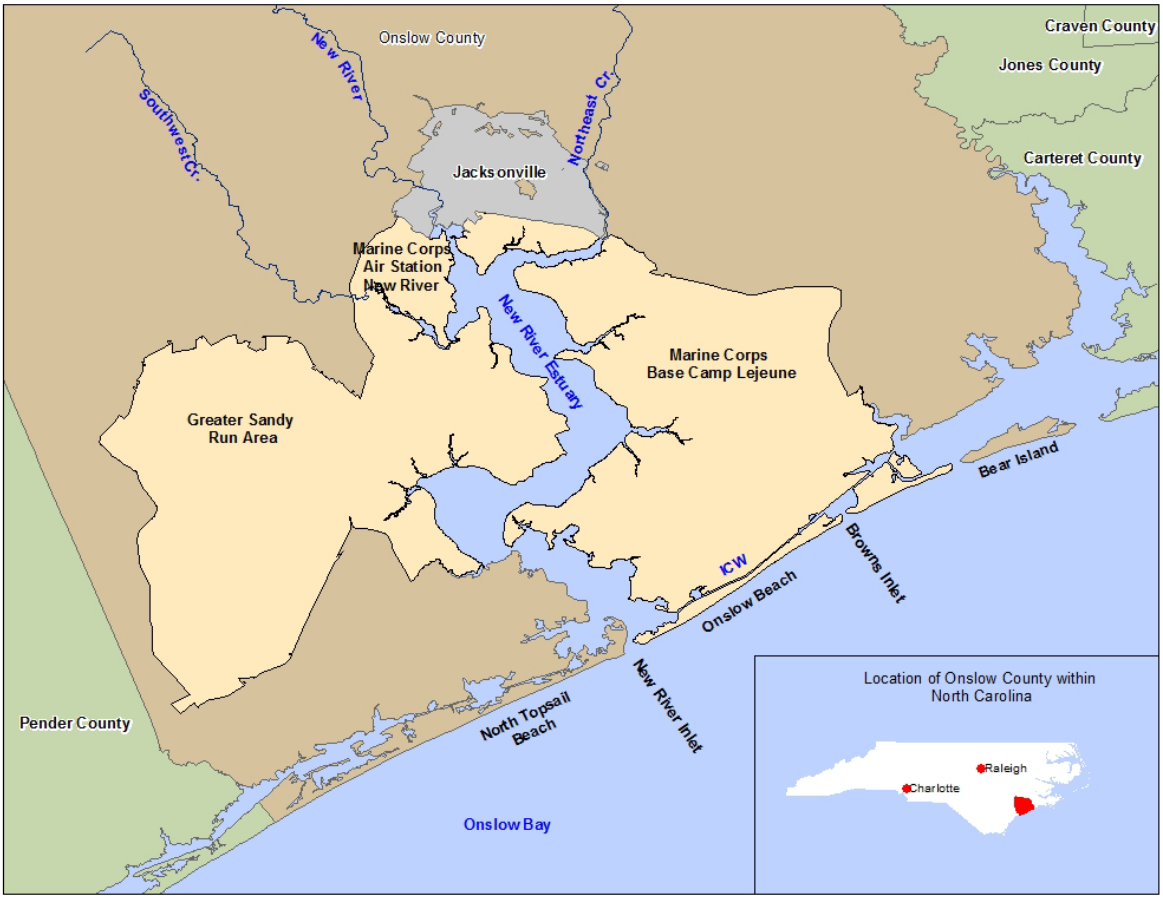

Figure 1-1. Site map of MCBCL.

Since DCERP1 was implemented, the potential impacts of climate change on military training have been identified as a growing challenge to our nation's military readiness. DoD facilities in coastal/estuarine areas are at additional risk from climate change, including rising sea level and extreme weather conditions (i.e., severe droughts, heavy rainfall events, warming temperatures, and increased magnitude of storms). In addition, installation managers need to understand the tradeoffs between carbon management and other adaptive management decisions under future climate change conditions. To balance military training needs and sustainable natural resource management, installation managers need easy-to-use decision-support tools, models, and other products to assist them in making often complex management decisions.

The second cycle of DCERP, referred to as DCERP2, had a 3-month planning period and will be implemented in over 5 years. The specific objectives of DCERP2 include the following:

1. Determine how ecosystem processes (within military training environments) respond to climate change to understand the resiliency and adaptive capacity of these ecosystems
2. Build on DCERP1 findings to identify additional thresholds that can serve as indicators of tipping point conditions that could threaten sustainability of the military training mission

3. Assess opportunities for adaptive management of estuarine, coastal, and terrestrial ecosystems to enhance carbon storage at MCBCL and other installations in similar coastal settings
4. Convey results of scientific studies to installation managers and decision makers by developing clearly written products and easy-to-use decision-support tools and models hosted on a readily accessible Web-based platform.

This document is the *DCERP2 Research Plan*, and it will serve as a guide throughout program implementation. A companion document, the *DCERP2 Monitoring Plan,* will provide a summary of the monitoring program to be used by the Aquatic/Estuarine and Coastal Wetlands modules. The *DCERP2 Research Plan* builds upon the scientific framework established during DCERP1 and describes the 13 research projects to be conducted during DCERP2 and follow-on work to one project (Research Project T-1) carried over from DCERP1. This Research Plan also serves as a reference for documenting specific research objectives, research questions, and hypotheses; technical approaches and methodologies; and milestones for major research outcomes and deliverables developed for each of the 13 research projects. This Research Plan also discusses the ways in which research efforts are communicated among the RTI DCERP Team, SERDP staff, DoD installation managers, and other interested stakeholders.

1.2 Literature Cited

Goodman, S.W. 1996. Ecosystem management at the Department of Defense. *Ecological Applications 6*(3):706–707.

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2.0 Program Organization

RTI International is leading the DCERP2 research and monitoring effort and has assembled a diverse team of experts, henceforth referred to as the RTI DCERP2 Team. DCERP is a collaborative effort between SERDP, the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC), MCBCL, and the RTI DCERP2 Team.

2.1 Management Team

SERDP is an environmental research and development program that is planned and carried out by DoD in full partnership with the U.S. Department of Energy and the U.S. Environmental Protection Agency. The SERDP Resource Conservation and Climate Change (RCCC) Program Manager, Dr. John Hall, ensures that DCERP activities provide for the enhanced knowledge of ecosystem and military interactions within approved Scopes of Work and budgets (**Figure 2-1**). The overarching federal management for DCERP is assigned to the NAVFAC EXWC. The DCERP PI, Dr. Patricia Cunningham of RTI, is responsible for the overall scientific quality, cohesiveness, and relevance of the DCERP2 Monitoring and Research Plans. The DCERP PI is also the primary point of contact for SERDP and MCBCL and coordinates all DCERP activities conducted at MCBCL through the DCERP On-site Coordinator (OSC), Dr. Susan Cohen.

At MCBCL, the DCERP OSC and the Director of the MCBCL Environmental Management Division (EMD), Mr. John Townson, will assist the DCERP PI with coordinating the environmental monitoring and research activities on the Base. The DCERP OSC is the primary point of contact between MCBCL and the RTI DCERP2 Team.

Dr. Cunningham will manage DCERP2 with support from a three-person Executive Committee (EC), including Drs. Norman Christensen (Duke University), Michael Piehler (University of North Carolina at Chapel Hill [UNC-CH]), and Craig Tobias (University of Connecticut [UCONN]), who will provide their expertise for the different ecosystem modules. The EC will meet regularly with the DCERP PI to discuss ongoing research and monitoring activities and ensure that DCERP2 is meeting the goal of providing ecosystem-based management recommendations to DoD. The EC members will also assist the DCERP PI with integrating the scientific findings from the RTI DCERP2 Team. In addition, the EC members will review documents from the RTI DCERP2 Team members and will provide recommendations for modifications as necessary to ensure that integration of the scientific findings of the individual research projects is also accomplished at both the module and programmatic levels and that this integration is maintained throughout the conduct of the program.

Two additional committees provide guidance and input to DCERP. The first, the Technical Advisory Committee (TAC), is a group of discipline experts from academia, industry, government, and the military that was assembled by the DCERP OSC to provide scientific and technical review and guidance to ensure the quality and relevance of DCERP. The second committee, the Regional Coordinating Committee (RCC), is a group of local and regional stakeholders that serves as one of the recipients of outreach from MCBCL, the DCERP PI, the DCERP OSC, and the SERDP RCCC Program Manager, thereby fostering relationships among

the representative organizations and DCERP. The RTI DCERP2 Team provides a summary of research findings to both the TAC and RCC at annual meetings.

Figure 2-1 illustrates the overall organization and lines of communication of DCERP2.

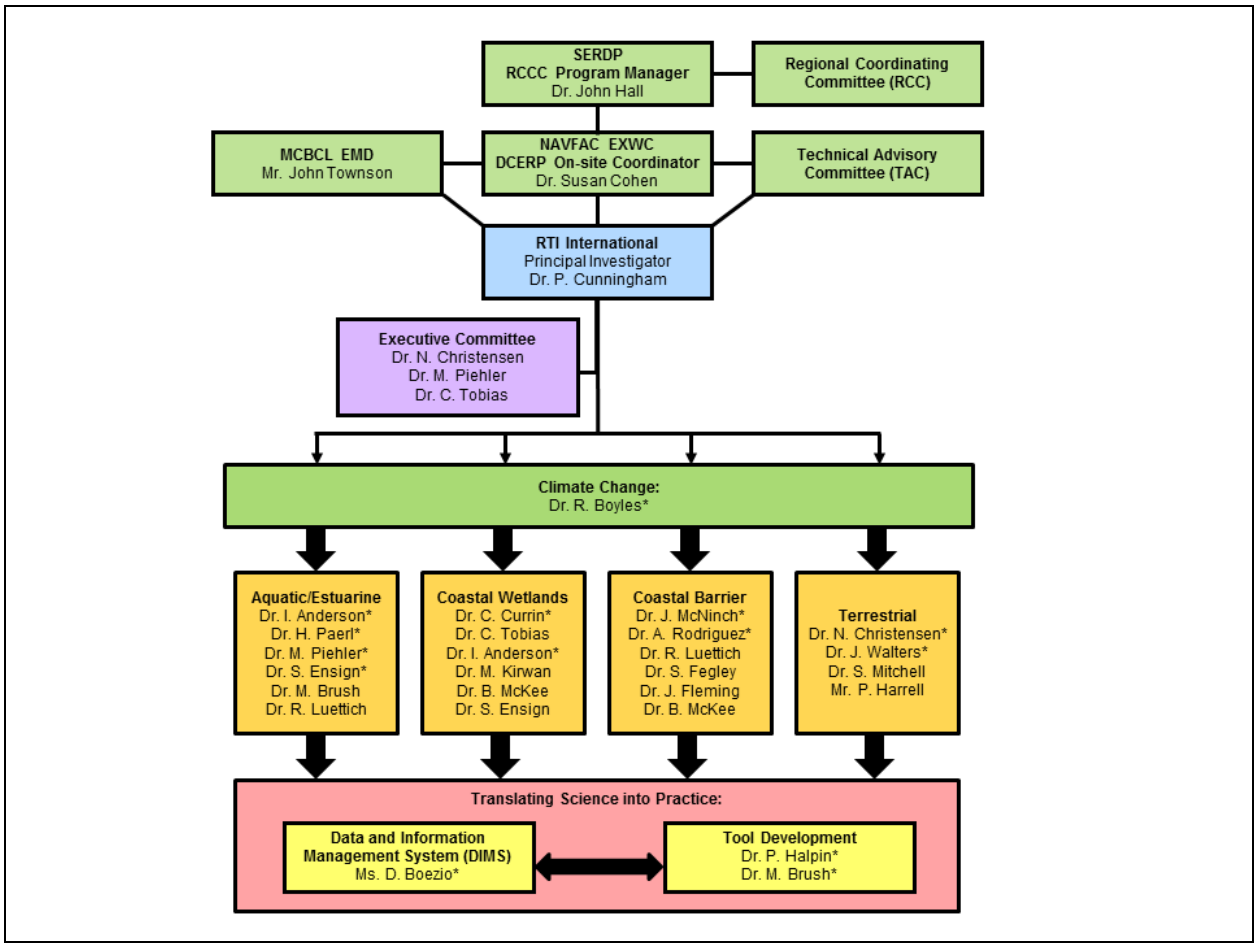

Figure 2-1. Organization of DCERP2.

Note: Asterisks denote Lead Investigators.

In addition, DCERP2's progress will be annually reviewed by SERDP's In-Progress Review Committee comprised of representatives of the various military service branches, the U.S. Environmental Protection Agency, and the U.S. Department of Energy. The SERDP Scientific Advisory Board (SAB), comprised of various discipline experts, will also assess progress and make recommendations for program improvements throughout the implementation period.

2.2 RTI DCERP2 Team

The RTI DCERP2 Team remains organized around four interconnected ecosystem modules established in DCERP1 (i.e., Aquatic/Estuarine [AE], Coastal Barrier [CB], Coastal Wetlands [CW], and Terrestrial [T], as shown in **Figure 2-1)**. Because climate change has a central role on ecosystem function and services, a fifth cross-cutting Climate Change (CC) Module will link the ecosystem modules to a central suite of local and regional-scale climate forcings. Finally, data

and outcomes from all of our integrated research and monitoring efforts will be managed within the new Translating Science into Practice (TSP) Module, which incorporates many elements of the DCERP1 Data Management Module.

The RTI DCERP2 Team includes the DCERP PI, environmental scientists from RTI, and researchers from academic institutions, governmental agencies, and private companies. The academic institutions supporting DCERP2 are Duke University in Durham, NC; North Carolina State University (NCSU) in Raleigh; UNC-CH; UCONN in Groton, CT; the Virginia Institute of Marine Science (VIMS) in Gloucester Point, VA; and Virginia Polytechnic Institute and State University (VA Tech) in Blacksburg, VA. The team also includes researchers from governmental agencies: the National Oceanic and Atmospheric Administration's (NOAA's) Center for Coastal Fisheries and Habitat Research (CCFHR) in Beaufort, NC; and the U.S. Army Corps of Engineers' (USACE's) Field Data Collection and Analysis Branch in Duck, NC, and Construction and Engineering Research Laboratory in Champaign, IL. Private companies supporting DCERP2 are from Aquatic Analysis and Consulting (AquaCo), LLC, in Wilmington, NC; Geodynamics, LLC, in Pine Knoll Shores, NC; and Seahorse Coastal Consulting in Morehead City, NC.

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3.0 DCERP Overarching Strategy

DCERP2 builds on the previous 6 years of research at MCBCL (i.e., DCERP1) and adapts the program to the new priorities of climate change, carbon cycling, and translating science into practice. DCERP2 is based on integrated research and monitoring activities that flow directly from the process that was successfully used in DCERP1 (**Figure 3-1**). The program is structured to use measurements and develop conceptual and mechanistic models and tools that inform science-based adaptive management at MCBCL and that can be easily transferred to other DoD installations. The monitoring program is designed to document trends, but to be sufficiently adaptive to capture extremes and ecosystem threshold events and to support the Research Plan by satisfying fundamental data needs. Together, these research and monitoring activities represent an integrated continuum of ecosystem response to changing climate, with respect to carbon cycling, nutrient utilization, sediment loading, and ecosystem services and sustainability.

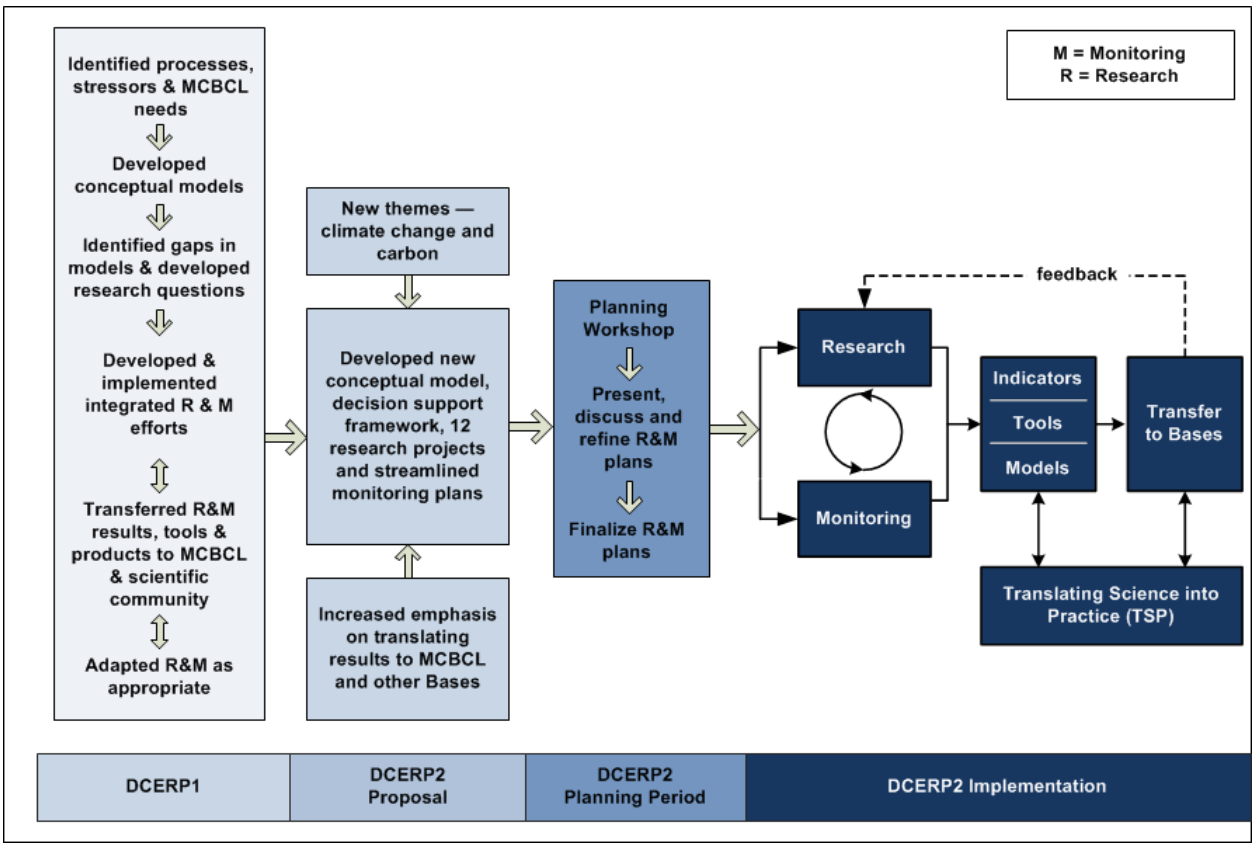

Figure 3-1. The overarching strategy for DCERP.

Measurements, models, and management are the foundation for the new DCERP2 effort. Measurements provide calibration, constraints, and mechanisms behind models. Models synthesize, extrapolate spatially and temporally, and provide platforms for scenario testing at the appropriate scales to analyze the effects of climate change and ecosystem response. Models also assess response to multiple stressors (including regional-scale climate trends), local extreme events, and localized anthropogenic modification of the coastal zone. Management support is an extension of the modeling such that the model output informs decision making, but changing

management needs also guide subsequent measurements and modeling simulations. This integrated tripartite approach is, therefore, not strictly hierarchical, but is characterized by feedback among the component parts. The approach is wholly adaptive, and its plasticity lends to transferability to other military installations.

3.1 Conceptual Models

Conceptual models are used to illustrate the key biological processes (e.g., primary production), chemical processes (e.g., nutrient cycling), and physical processes (e.g., hydrodynamics, sedimentation) of the ecosystem, as well as the key stressors that alter natural ecological processes. The RTI DCERP2 Team developed an overarching conceptual model that links ecosystem level processes in the aquatic/estuarine, coastal barrier, coastal wetlands, and terrestrial ecosystems as is shown in **Figure 3-2**. This overarching conceptual model highlights the interconnections among the various ecosystem modules in examining the estuarine and coastal processes that are affected by climate change and that drive carbon cycling.

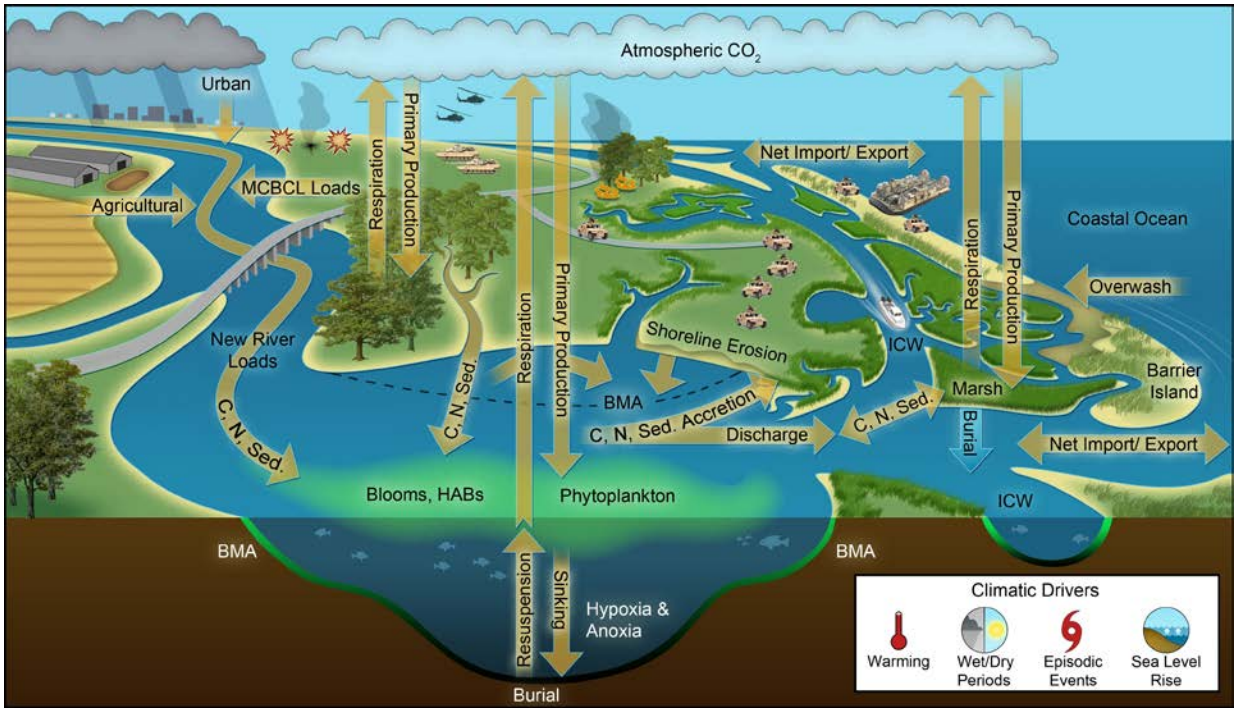

Figure 3-2. The overarching conceptual model for DCERP2.

Detailed, module-specific (i.e., Aquatic/Estuarine, Coastal Wetlands, Coastal Barrier, and Terrestrial) conceptual models were also developed that highlight individual ecosystem-level processes with a focus on DCERP2's thematic areas of climate change, carbon cycling, and translating science into practice. As new understanding of these ecosystem processes is gained during the course of DCERP2, the module-level conceptual models will be revised. For more information about the module-specific models, see Sections 5.0 through 9.0 of this Research Plan. In addition, research project–level conceptual models may be developed to highlight processes at a more detailed scale than can be shown at the module level, particularly in those modules where diverse research is being conducted. The DCERP2 Team will revisit the

conceptual models at the programmatic, module, and research project levels and will work on refining the models. The purpose of refining the models is to provide a clearer representation of the current understanding of each ecosystem at the appropriate level of detail to clearly explain the ecological processes, stressors, and research focus of each module and research project to a wider audience.

3.2 Integrated Ecosystem-Based Management Approach

DCERP2 is designed to be a research-initiated process; therefore, it is distinct from other ecosystem-based programs that are driven by specific regulatory or management objectives. The *DCERP2 Research Plan* is supported by the *DCERP2 Monitoring Plan*, which is designed to gather basic environmental data and to support the research projects. Results from research projects feed back into the adaptive Monitoring Plan so that changes in the frequency of sampling, spatial scale of sampling locations, or parameters to be sampled can be modified as necessary. The RTI DCERP2 Team will use results from the monitoring and research efforts to identify ecosystem indicators and develop associated threshold values, tools, or design models that address installation management needs. Team members will then communicate this information to MCBCL and more broadly to other DoD installations to assist in the decision-making process (for more information on the user engagement process, see Section 10.4 of this Research Plan). This information transfer may occur rapidly for some management needs or may require longer periods for the collection of research and monitoring data to provide appropriate indicators, models, or other decision-support tools. Once this information is transitioned to the installation, the DoD's natural resources managers will be able to make decisions as to what type of management action should be taken and to implement appropriate physical or military operational changes. After implementing these changes, the RTI DCERP2 Team can continue monitoring (via feedback loop) to ensure that the desired management outcomes are achieved (**Figure 3-1**). In addition, the RTI DCERP2 Team created module-based roadmaps to illustrate and track all monitoring and research activities and their interrelationships to ensure within and among module integration of research and monitoring data collection activities (see **Appendix A** of this Research Plan).

3.3 DCERP2 Themes

SERDP identified three major themes to be addressed in DCERP2: climate change, the carbon cycle, and translating science into practice. These three themes span the four ecosystem modules and 13 research projects of DCERP2. DoD lands in the United States and abroad include a large number of installations in coastal settings that are most vulnerable to climatic drivers (e.g., rising sea level, increased temperatures, extended periods of drought or flood conditions, extreme storm events [i.e., hurricanes, cyclones, Nor'easters]). To better manage DoD lands and their infrastructure and natural assets, it is imperative that installation managers have accurate research findings to inform their management decision and prepare for future contingencies necessitated by changed climates. In addition, the carbon cycle is inextricably linked to climate change and its association with increasing concentrations of greenhouse gases (e.g., carbon dioxide [CO_2], methane) generated from the use of fossil fuels. DoD is a major consumer of fossil fuels used for military training and actual military engagements across the globe. The U.S. Congress has set targets for reducing energy use and for increasing use of renewable energy for all federal agencies, including DoD under Section 203 of the Energy Policy Act of 2005; Section

2852 of the National Defense Authorization Act of 2006; and Section 431 of the Energy Independence and Security Act of 2007 (Schwartz et al., 2012). As a result of this legislation, DoD is concerned about reducing its carbon footprint through the use of alternative energy sources, improvements in energy conservation and efficiency, and resource management activities that address carbon management. Examples of resource management activities include enhancements of carbon sinks, as an important ecosystem service consideration. Findings that result from these two thematic areas of research need to be communicated broadly not only to the scientific community, but also to installation managers to help them understand and assess potential vulnerabilities of coastal installations and prepare contingencies to ensure sustainability of the military mission under future climate conditions.

3.3.1 Climate Change

The DoD recognizes that projected changes in climate will impact installations, operations, and missions in the United States and globally. The *2010 DoD Quadrennial Defense Review* (U.S. DoD, 2010a) requires that "The Department must complete a comprehensive assessment of all installations to assess the potential impacts of climate change on its missions and adapt as required." DoD's *Strategic Sustainability Performance Plan* (U.S. DoD, 2010b) mandated by Executive Order 13514 (October 5, 2009) identifies climate change as one of four major challenges to sustainability for DoD installations and their missions. As part of DoD's response to Executive Order 13514, the draft *DoD Fiscal Year (FY) 2012 Climate Change Adaptation Roadmap* (U.S. DoD, 2012) was approved in September 2012 for inclusion as an appendix to DoD's *Strategic Sustainability Performance Plan*. At the national scale, the Climate Change Adaptation Task Force, co-chaired by the White House Council on Environmental Quality (CEQ), NOAA, and the Office of Science and Technology Policy, has provided guiding principles and recommended actions for federal agencies to better understand, prepare for, and respond to climate change (White House CEQ, 2010). On March 4, 2011, this interagency task force released implementation instructions for federal climate change adaptation planning. These instructions tasked federal agencies to conduct high-level analyses and report to the CEQ on agency vulnerability to climate change.

DoD installations have a significant footprint in the southeastern United States that includes major coastal installations such as Naval Base Norfolk (in Virginia), the world's largest Naval Base; Eglin Air Force Base (AFB; in Florida), the largest AFB in land area in the United States; and MCBCL (in North Carolina), the largest Marine Corps Base in the eastern United States. Many of the largest and most important U.S. Army Bases are also in the southeastern United States. These Bases include Fort Bragg (in North Carolina) and Fort Stewart and Fort Benning (both in Georgia). DoD installations in the Southeast support all of the major DoD land, air, and sea training; operations; and testing missions and are major support facilities for U.S. contingency operations. A significant theme in DCERP2 is climate change, and the DCERP2 Team will be looking specifically at four climatic drivers: rising temperatures, change in precipitation patterns, increasing storm intensity, and rising sea level. The DCERP Team will examine the potential impacts of these drivers on ecosystem processes and the training mission. A summary of the climatic drivers and their potential impacts (both detrimental and beneficial) on ecosystems and the military mission on MCBCL and other DoD installations in the Southeastern United States is provided in **Table 3-1**. Although impacts from each of the individual climatic drivers are summarized in **Table 3-1**, there also may be more severe impacts that result from a combination of

two or more of these climatic drivers acting in concert. For example, flooding resulting from an extreme rainfall event coupled with rising sea level may result in a larger areal impact of water damage to installation property in low-lying coastal areas. Changes in frequency, magnitude, and storm track of extreme events such as hurricanes are also considered to be an interactive effect of temperature and precipitation patterns.

Table 3-1. Relationships of climatic drivers, ecosystem impacts, and potential DoD mission impacts relevant to DCERP2[a]

Climatic Drivers	Potential Ecosystem Impacts	Potential Military Mission Impacts
Changes in trajectory and variability related to temperature	*Detrimental impacts* could include heat stress, soil warming, vegetation transition (species range and biome shifts), and increased wildfire risk; waterbody warming with loss of habitat for coldwater species; and changes in migration patterns. *Beneficial impacts* could include increased vegetation growth rates and growing season because of warmer temperatures, which could support more rapid range restoration and revegetation.	*Detrimental impacts* could include a shift in viable training mission; reduced human activity levels, airlift capacity, and live-fire training; and increased equipment and infrastructure maintenance costs; electrical grid stress and energy costs for building and installation operations; and change in operational parameters for weapons and equipment.
Changes in trajectory and variability related to precipitation	*Detrimental impacts* could include increased wildfire risk, dust, air quality impairment, loss of vegetative cover and soil (wind and/or water erosion), altered burn regimes, impacted surface and groundwater quality, soil function and resilience (desertification), and protected species stress. *Beneficial impacts* could include reduced erosion due to less rainfall.	*Detrimental impacts* could include reduced land-carrying capacity for vehicle maneuvers, live-fire training, and low-level rotary wing flight operations; and increased infrastructure damage, equipment maintenance costs, constraints on water supply, and regulatory constraints on training land access. *Beneficial impacts* could include greater off-road access for vehicles and dismounted personnel due to less rainfall.
Changes in frequency, magnitude, and track of extreme events (e.g., storms)	*Detrimental impacts* could include flooding; an increase in overwash on barrier islands, surface water quality degradation, and soil and vegetation loss (wind and water damage and erosion); and impacts to soil function and carbon and nutrient cycling.	*Detrimental impacts* could include an inundation of and damage to coastal infrastructure; increased flood control and erosion prevention measures, maintenance costs, and transportation infrastructure damage; and reduced off-road maneuver capacity and access to military water crossings and river operations.
Changes in sea level	*Detrimental impacts* could include loss of coastal land and protected ecosystem resources, land subsidence, drowning of coastal marshes, and increased incidents of overwash on barrier islands, disintegration of low-lying coastal barrier islands, and extent of saltwater intrusion.	*Detrimental impacts* could include degradation or loss of coastal areas and infrastructure, damage to physical infrastructure (roads, targets, ranges), impacts to littoral and shore training and to the supply chain from potential shipping interruptions (roadways and rail systems), increased cost of infrastructure reinforcement, and modification and regulatory constraints on training land access.

[a] Information in this table was adapted from DoD (2012) and augmented with information from Burkett and Davidson (2012) and Parris et al. (2012).

Land-based military training operations in the southeastern region of the United States include road and off-road maneuver training by dismounted troops and tracked and wheeled vehicles to simulate real-world combat operations. These operations are inherently subject to the effects of the prevailing climate and weather conditions. Air operations conducted by all the DoD services (i.e., combat support training, flight training, personnel transport, and logistical support) are also subject to prevailing weather and climate conditions (DoD, 2012). Naval ship operations include near-shore combat training operations, sea-based training operations, and logistical support functions, which all depend upon access to port facilities and coastal environments. Amphibious training operations require access to beach and near-shore environments for landing operations, which can be impacted by sea level, storm surge, overwash, and other conditions of extreme weather events (RTI, 2013).

The built infrastructure required to support military operations at DoD installations is extensive and includes air fields, port facilities, and the associated supporting infrastructure comparable to that of small cities. Supporting infrastructure may consist of commercial buildings, medical facilities, public safety facilities, housing, and supporting utilities such as power, water, sewer, communication networks, roads, and railways (DoD, 2012). This extensive DoD installation infrastructure is subject to the same climate conditions and vulnerabilities identified for comparable civilian infrastructure and is interdependent with many civilian regional services (public utilities, transportation systems, and communications networks).

DoD installations in the southeastern United States also have significant responsibilities for managing natural resources for maintenance and sustainability of lands and vegetative cover for training operations and for meeting environmental regulatory requirements, including the Endangered Species Act, the Clean Air Act, and the Clean Water Act (Goodman,1996; SERDP, 2005). Climate and weather conditions that affect the physical features and natural resource assets of DoD installations have major implications for both sustainability of military training missions and environmental compliance.

DCERP2 approaches under the climate change theme are consistent with and support the *Department of Defense FY 2012 Climate Change Adaptation Roadmap* (DoD, 2012). The RTI DCERP2 Team understands that climate change will be interactive with and a catalyst for other system stressors currently under study in coastal/estuarine and terrestrial environments on MCBCL and that consideration of climate change impacts must be integrated with recommended management strategies and decision-support capabilities developed under DCERP2. These integrated capabilities will be of particular relevance to other DoD coastal facilities in the southeastern United States. In addition, SERDP initiated a suite of research projects during FY 2012 to support the development of a climate change decision framework, and work under DCERP2 will build upon climate change-related products and information provided by other SERDP–funded work, such as Research Projects RC-1702 and RC-2206. DCERP2 and associated SERDP research projects will also assist in meeting DoD's goals under the draft *DoD FY 2012 Climate Change Adaptation Roadmap* (DoD, 2012). These goals are to: (1) establish processes for obtaining updated climate change data, (2) use future climate scenarios to understand potential ecosystem impacts, (3) develop guidance for assessments at the appropriate spatial and temporal scales, and (4) demonstrate applications for adaptation planning and use of down-scaled climate information.

3.3.2 Carbon Cycle

The enhanced radiative forcing due to increasing atmospheric CO_2 is the principal cause of rising global mean temperatures over the past century. Approximately half of the anthropogenic CO_2 emissions contribute to rising atmospheric concentrations, and the other half is attenuated by terrestrial and oceanic carbon sinks. The magnitude of open-ocean carbon sequestration is reasonably well-constrained by elemental stoichiometry resolved in the surface and bottom waters and by deep-sea burial estimates (Denman et al., 2007). In contrast, the contribution of coastal ecosystems to carbon burial and to atmospheric carbon exchanges is not well constrained. Some estimated carbon sequestration rates in coastal ecosystems are of the same order of magnitude as deep-ocean burial (Chmura et al., 2003; Crooks et al., 2011; Duarte et al, 2005; Laffoley and Grimsditch, 2009; Mcleod et al., 2011; Nellemann et al., 2009). These habitats may also represent carbon reservoirs large enough to affect global carbon balances should they be lost and their carbon stores released through decomposition (Forqurean et al., 2012; Hopkinson and Cai, 2012). Therefore, loss of such coastal habitats equates with a loss of active carbon fixation and burial and with a release of stored carbon back to the atmosphere on annual to decadal timescales (Kirwan and Mudd, 2012; Kirwan et al., 2010). Despite uncertainties in assessing the carbon sequestration rates of intact ecosystems and the carbon release potential associated with habitat loss, it is likely that coastal carbon burial is globally significant (Sifleet et al., 2011). This carbon storage may, in some regions, be large enough to warrant assessment within the context of carbon emissions offsets (Murray et al., 2011).

The wide range in coastal carbon sequestration rates can be traced to uncertainty in area assessments of specific habitat coverage, carbon density (mass of carbon buried per volume of buried sediment), net ecosystem production, and longer term respiration rates of carbon (Duarte et al., 2005). Most current assessments of carbon cycling in the coastal landscape are typically conducted piecemeal and are habitat specific. For example, atmospheric CO_2 fluxes or carbon burial rates might be measured in an intertidal marsh or estuary, but are quantified in the absence of measuring carbon exchanges between these habitats. This type of existing approach in which carbon cycling estimates are uncoupled from cross-habitat transport, or source determination, precludes full understanding of the source-sink nature of the habitat. This approach specifically confines interpretation to static mass balances and provides limited mechanistic understanding of underlying processes that are likely to drive altered patterns of carbon cycling in the future. Results from DCERP1, however, delineated the biogeochemical connections between coastal habitats within MCBCL and their sensitivity to physical drivers such as seasonal and pulsed delivery of freshwater and nutrients. This previous work also characterized the influence of tidal forcings on marsh-estuary exchanges, identified the effects of storm-driven overwash of the backbarrier marsh, and defined the linkages between land-use and watershed loadings. The system-scale knowledge acquired during DCERP1 helped shape the structure of how carbon cycling is approached in DCERP2. The DCERP2 approach equally weights intra-habitat mass balancing with inter-habitat exchanges to yield an integrated picture at the landscape scale. This “big picture” approach uniquely allows assessment of carbon (re)distribution at expanded spatial and temporal scales.

Because of their position in the landscape, the estuary, marshes, and barrier islands of MCBCL are sensitive to a changing climate as it imprints regionally. An altered hydrologic cycle, sea level rise, and more direct human modification of watersheds (e.g., nutrient delivery) will alter

patterns of carbon fixation, storage, and burial. Nitrogen and carbon in dissolved and particulate forms are delivered to the estuary from the New River and adjacent tributaries within MCBCL. During transit, the load is modified by fixed-carbon additions from primary production and by carbon removal via respiration and CO_2 evasion into the atmosphere. Net system metabolism (the balance between carbon fixed and carbon respired), including contributions from the benthos and the water column, largely govern the carbon balance in the estuary proper. This balance shifts as a function of river discharge and water residence time, nutrient and chromophoric dissolved organic matter (CDOM) inputs, as well as light limitation in the water column and benthic production. However, the overall carbon dynamics of the integrated coastal landscape (NRE + marshes + barrier island + Intracoastal Waterway [ICW]) are modified further by the transport of carbon and nitrogen between these habitats. Net carbon turnover and storage depends upon the balance between the respiration, fixation, watershed loadings, dissolved inputs from intertidal marshes, sediment burial rates within the estuarine basin and contiguous marshes, and the export of dissolved and particulate carbon to the coastal ocean (Cai, 2011; **Figure 3-3**). Inputs of marsh carbon may support estuary to atmosphere CO_2 fluxes (Cai, 2011; Neubauer and Anderson, 2003) in some systems, but it is unclear whether this is the case in the NRE or ICW. Order of magnitude calculations from DCERP1 place estuarine shoreline erosion rates in approximately the same range as NRE marsh sediment accretion rates, although the actual source of sediments (and associated carbon) supporting marsh accretion is both unresolved and fundamentally important. Other data generated during DCERP1 indicate that one of the largest potential carbon sinks (marsh accretion) responds positively to nutrient additions. Yet altered marsh geomorphology and decreased marsh sustainability have been observed in other coastal marshes subject to high nitrogen additions (Deegan et al., 2012). Coastal barrier islands, the dominant feature along the southern boundary of MCBCL, have almost completely escaped characterization with respect to carbon cycling. Overwash of the barrier islands buries backbarrier marshes and dampens the carbon sequestration capacity of that habitat until macrophyte recolonization takes place. The shoreward island migration concurrently exposes previously buried peat carbon to high-energy oxidizing conditions on the seaward edge; potentially remobilizing and respiring large stores of carbon. However, the importance of these processes to overall carbon turnover and burial within the coastal landscape is currently unknown.

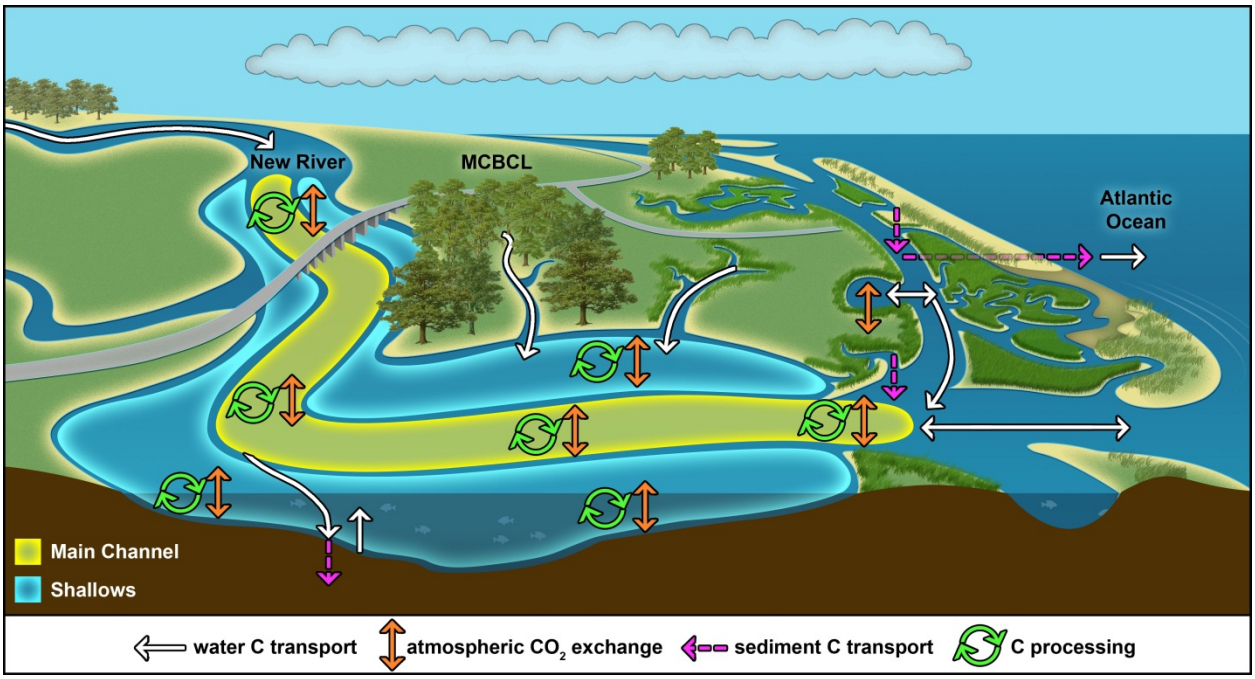

Figure 3-3. Carbon budget for the NRE and surrounding coastal area.

What then emerges from the compiled results of DCERP1 within the context of the broader coastal carbon literature are the following three major considerations:

1. *Generalize with caution*—The coastal landscape of the NRE may or may not fit existing, albeit few, models of coastal carbon cycling reported in other systems, particularly in response to global climate drivers or local anthropogenic modifications.
2. *Everything is connected*—Quantifying reactions within and transport exchanges among habitats is necessary for an integrated landscape view.
3. *Know the processes behind the mass balances*—A mechanistic understanding of the transport and reaction processes regulating carbon cycling, burial, and atmospheric exchanges is essential for inferring changes in future carbon allocation within the coastal landscape.

DCERP2 provides an integrated approach to quantifying carbon cycling throughout the coastal landscape bounded by MCBCL (**Figure 3-4**). Although each ecosystem module is assessed within discrete boundary fluxes and mass balances (e.g., fluvial delivery, atmospheric exchanges, burial), these habitats share boundary fluxes where appropriate to provide an integrated picture of carbon cycling (**Appendix B**). Although the overall effort is organized by ecosystem, DCERP2 combines carbon reactions within and transport among ecosystems. The DCERP2 team will use a common methodology that quantifies atmospheric carbon fluxes, burial, carbon exchanges, and attribution of carbon sources fueling respiration and burial across ecosystems. The symmetry of experimental approaches built into each module (i.e., common spatial and temporal scale or measurements, common units of flux) lead to a more seamless integration. This approach yields contemporaneous mass balances that serve as snapshots of carbon inventory and transformation rates and contributes to the mechanistic understanding of how probable changes in climatic and localized anthropogenic drivers will impact carbon cycling. The team's approach

enables scaling across modules, starting from the reaction scale, up to changes in the geomorphological distribution of habitats and their associated carbon-cycling characteristics within the landscape. The principal drivers of change include those extant to sea level rise and alteration of the hydrologic cycle. These factors are examined and constrained on regional scales (Research Project CC-1), and as boundary conditions in ecosystem simulations (Research Project TSP-2). Using the process-based understanding of carbon reactions and transport, landscape-scale sensitivity to these factors will be assessed. Specifically, the team will quantify marsh sustainability (Coastal Barrier and Coastal Wetlands Modules), shifting patterns of estuarine metabolism (Aquatic/Estuarine Module), carbon burial magnitude and distribution (Aquatic/Estuarine, Coastal Barrier, and Coastal Wetlands Modules), and net source/sink strength of carbon exchange with the atmosphere (Aquatic/Estuarine and Coastal Wetlands Modules). This integrated process-level approach provides an accounting of present-day carbon storage in MCBCL, enhances the understanding of how coastal carbon cycling may likely change on the decadal scale, and facilitates application of this knowledge and models to other regions.

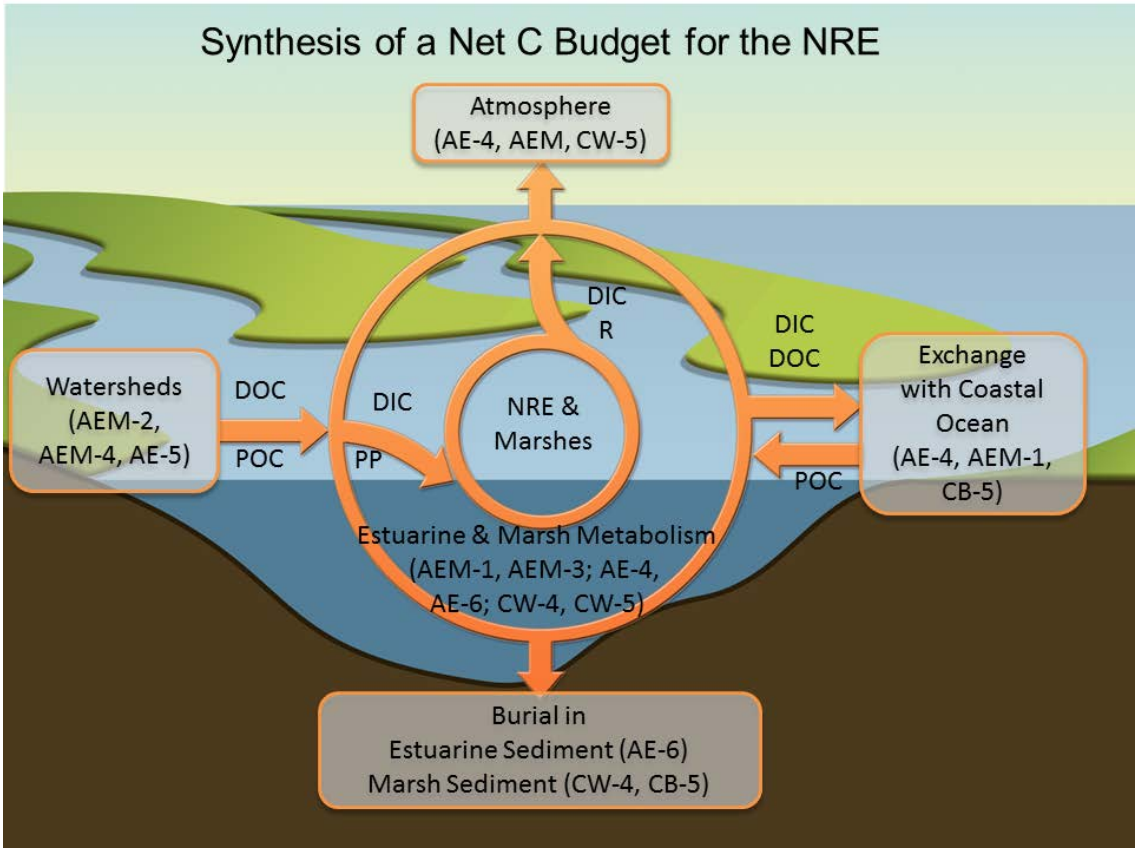

Figure 3-4. Synthesis of the carbon budget for the NRE.

Note: DIC = dissolved inorganic carbon; DOC = dissolved organic carbon; POC = particulate organic carbon; PP = primary production; R = respiration.

It should be noted that, although SERDP's major focus for DCERP2 is directed at research on the carbon cycle associated with the estuary and coastal areas, the terrestrial ecosystem's connection to the estuarine/coastal carbon budget comes predominantly from lands upstream of

MCBCL in the New River watershed and not from MCBCL forest lands. Carbon contributions from the upstream watershed will be captured by Aquatic/Estuarine Module water quality monitoring in the NRE. The Terrestrial Module will not be developing a terrestrial carbon budget per se; instead, it will estimate carbon storage at different locations through time across the MCBCL landscape. These estimates of carbon storage will be obtained by modeling the hypothetical effects of forest management alternatives, particularly at locations associated with various forest management practices used on longleaf and loblolly pine stands. The primary focus of the Terrestrial Module's research is thus associated with assessing the effects of a variety of different forest management strategies on carbon storage across the landscape. The Terrestrial Module will work with the Aquatic/Estuarine Module to identify forestry management areas with different management treatments to assess runoff of carbon, nutrients, and sediment from the MCBCL landscape.

3.3.3 Translating Science Into Practice

Translating scientific information into practice requires several different approaches to communicate information to reach a variety of target audiences (**Table 3-2**). The audiences that will be receiving information from DCERP2 include the following: the scientific community, DoD installation managers, and state, regional, and local managers and local stakeholders, including the general public. Communicating complex information to each of these diverse audiences requires that the product and message be crafted to the appropriate level of scientific detail and complexity for each target audience.

Table 3-2. Translating Science into Practice requires different modes of communication for each target audience.

Note: MARDIS = Monitoring and Research Data Information System.

Target Audience	Communication Mode
Scientific community	Peer-reviewed journal articles and books Presentations at national scientific conferences Other presentations and seminars at academic institutions
DoD Installation managers	Technical presentations or workshops for installation managers on specific technical and management topics Access to the MARDIS database: • Decision-support tools and models (with user guides) • Maps and analysis of GIS data layers • Technical reports
Other federal, state, regional, and local land managers and local stakeholders, including the general public	Presentations to managers and stakeholder groups Access to the DCERP public Web site • Factsheets • Brochures

The primary means of translating science to the scientific community is through publishing findings in peer-reviewed journal articles or books or presenting research at scientific meetings to inform and engage colleagues and obtain feedback. The DCERP1 Team published substantial work in the print media through refereed or peer-reviewed literature, including books, book chapters, and articles in major scientific journals. In addition, many of the researchers have

presented posters and papers at national and international scientific meetings; the team will continue to use these venues during DCERP2 to communicate results to the scientific community. As part of DCERP1, several researchers from the Aquatic/Estuarine and Coastal Wetlands Modules contributed four chapters to a special issue of *Estuaries and Coasts*. It is anticipated that the team could also prepare a similar contribution on the topic of the carbon cycling in estuarine/coastal areas as a special issue of a major scientific journal or as multiple chapters in book.

Although publishing results in scientific journals and presenting research at scientific conferences is vitally important to the scientific community, these activities often do not provide the scientific results in a format that is directly useable or understandable by DoD installation managers. Thus, a major effort of DCERP2 will be directed at providing the scientific research results in easy-to-understand documents, and via models and decision-support tools geared directly to address installation management needs. The DCERP2 Team has defined decision-support tools more broadly to include any product that can be used by an installation to inform the installation management and decision-making processes. These products may include mechanistic models, geographic information systems (GIS) data layers and associated analyses, and maps and reports that provide information needed by installation managers to make ecosystem-based management decisions. These products will be disseminated through various meetings with installation staff. These meetings can include the annual TAC meeting with MCBCL's Department of Environmental Management and other installation personnel, lunch and learn presentations to MCBCL natural resources staff, and topic-specific technical briefings with appropriate installation technical committees or staff from other installations.

To improve communication to MCBCL and to other DoD installations, the RTI DCERP2 Team will also invite managers from other installations such as Eglin AFB (in Florida), Marine Corps Air Station (MCAS) Cherry Point and Fort Bragg (both in North Carolina), and Ft. Stewart (in Georgia) to the annual DCERP2 TAC meeting at MCBCL. The purpose of this outreach effort will be to provide additional perspective on tool development needs and ways to craft research results into clear actionable statements for installation managers. These types of formal and informal meetings will continue as appropriate and as requested by the installation. In addition, researchers on the RTI DCERP2 Team will develop training workshops that show installation staff how to use the various tools and products.

At the April 2013 TAC meeting, Mr. John Towson presented the MCBCL management actions that have direct relevance to DCERP. These management actions are: (1) the shift to tracked vehicle training being conducted in off-road scenarios as opposed to being restricted to existing, delineated trails and (2) the red-cockaded woodpecker (RCW) Recovery and Sustainment Program (RASP) to accomplish RCW recovery, by providing a broader landscape in which to balance training and species needs. When possible, the RTI DCERP2 Team will use these actions as plausible future management scenarios to demonstrate the process of forecasting consequences and trade-offs of decisions that are meaningful to decision makers. Trade-offs associated with these two proposed actions could involve any number of decision support tools and other analyses being developed by DCERP2 researchers. For these analyses use of hypothetical scenarios are preferred as DCERP2's contribution should be to demonstrate the feasibility and utility of an approach versus assessing a specific installation action.

The DCERP2 researchers will also seek installation staff assistance in evaluating the resulting decision-support products (i.e., beta testing models and decision-support tools) and providing feedback through general survey questionnaires to be developed by the team on how these products can be improved to better address management needs. Dissemination of decision-support tools and other information to MCBCL and other installation staff will also be made available through the Spatial Decision-Support System (SDSS) developed as part of Research Project TSP-1 (see Section 10.2 of this Research Plan). The SDSS will house decision-support tools and models, and the Monitoring and Research Data Information System (MARDIS) will be used to access documents, maps, and GIS data layers (for more details, see Section 11.0 of this Research Plan).

Finally, the outreach efforts of the RTI DCERP2 Team will include communicating the information to other federal, state, regional, and local stakeholders and to the general public. This is likely the greatest communication challenge—to communicate complex ideas and concepts in clear, simple terms that are understood by stakeholders with and without scientific training. As was performed during DCERP1, the DCERP researchers have presented results to local stakeholders such as the DCERP RCC and to the New River Roundtable, Onslow Bight Conservation Forum, and Marine Science Education Partnership during their regularly scheduled meetings. Members of the RTI DCERP2 Team have also participated in events such as the New River Roundtable's annual State of the River Day held each spring in Jacksonville, NC. The team can develop other outreach products such as brochures or fact sheets on specific topics as appropriate to clearly and concisely explain the results of DCERP2 research to this target audience. These products can be posted and easily accessed via the DCERP2 public Web site.

3.4 Literature Cited

Burkett, V.R., and M.A. Davidson (Eds.). 2012. *Coastal Impacts, Adaptation, and Vulnerability: A Technical Input to the 2012 National Climate Assessment*. Cooperative Report to the 2013 National Climate Assessment. 150 pages.

Cai, W. 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? *Annual Review of Marine Science 3*:123–145.

Chmura, G., S.C. Anisfeld, D.R. Cahoon, and J.C. Lynch. 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles 17*(1111). 12 pages.

Crooks, S., D. Herr, J. Tamelander, D. Laffoley, and J. Vandever. 2011. *Mitigating Climate Change Through Restoration and Management of Coastal Wetlands and Near-Shore Marine Ecosystems: Challenges and Opportunities*. Environment Department Paper 121. World Bank, Washington, DC. Available at http://siteresources.worldbank.org/ENVIRONMENT/Resources/MtgtnCCthruMgtofCoastalWetlands.pdg.

Deegan, L.A., D.S. Johnson, R.S. Warren, J. Fleeger, S. Fagherazzi, and W. Wollheim. 2012. Coastal eutrophication as a driver of salt marsh loss. *Nature 490*:388–392.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciasis, P.M. Cox, R.E Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, and X. Zhang. 2007. Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press: Cambridge, United Kingdom and New York, NY.

Duarte, C.M., J.J. Middelburg, and N. Caraco. 2005. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences 2*:1–8.

Forqurean, J.W., C.M. Duarte, H. Kennedy, N. Marba, M. Holmer, M.A. Mateo, E.T. Apostolaki, G.A. Kendrick, D. Krause-Jensen, K. McGlathery, and O. Serrano. 2012. Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience 5*:505–509.

Hopkinson, C.S., and W. Cai. 2012. Carbon sequestration in wetland dominated coastal systems—A global sink of rapidly diminishing magnitude. *Current Opinions in Environmental Sustainability 4*:186–194.

Kirwan, M.L., and S.M. Mudd. 2012. Response of salt-marsh carbon accumulation to climate change. *Nature 489*:550–554.

Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters 37*, L23401. 5 pages.

Laffoley, D., and Grimsditch, G. (Eds.). 2009. The management of natural coastal carbon sinks. The International Union for Conservation of Nature, Gland, Switzerland. 53 pages. Available at http://www.iucn.org/knowledge/publications_doc/publications/?4229/The-Management-of-Natural-Coastal-Carbon-Sinks.

Mcleod, E., G. Chmura, S. Bouillon, R. Salm, M. Bjork, C. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman. 2011. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment 9*(10):552–560.

Murray, B.C., L. Pendleton, W.A. Jenkins, and S. Sifleet. 2011. *Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats*. Duke University's Nicholas Institute for Environmental Policy Solutions Report NI R 11-04. Available at http://nicholasinstitute.duke.edu/economics/naturalresources/blue-carbon-report.

Nellemann, C., E. Corcoran, C.M. Duarte, L. Valdes, C. De Young, L. Fonseca, and G. Grimsditch. (Eds.). 2009. *Blue Carbon. A Rapid Response Assessment*. United Nations

Environment Programme, GRID-Arendal. Available at http://www.grida.no/publications/rr/blue-carbon.

Neubauer, S.C., and I.C. Anderson. 2003. Transport of dissolved inorganic carbon from a tidal freshwater marsh to the York River Estuary. *Limnology and Oceanography 48*(1):299–307.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. Global Sea Level Rise Scenarios for the U.S. National Climate Assessment. NOAA Tech Memorandum OAR CPO-1. 37 pages.

RTI International. 2013. In preparation. *DCERP1 Data Management Report.* RTI, Research Triangle Park, NC.

Schwartz, M., K. Blakeley, and R. O'Rourke. 2012. Department of Defense Energy Initiatives: Background and Issues for Congress. CRS Report for Congress. Available at http://www.fas.org/sgp/crs/natsec/R42558.pdf.

Sifleet, S., L. Pendleton, and B.C. Murray. 2011. *State of the Science on Coastal Blue Carbon: A Summary for Policy Makers*. Duke University's Nicholas Institute for Environmental Policy Solutions Report NI R 11-06. Available at http://nicholasinstitute.duke.edu/economics/naturalresources/state-of-science-coastal-blue-carbon.

U.S. DoD (Department of Defense). 2012. *DoD Fiscal Year 2012 Climate Change Adaptation Roadmap.* Draft report. September.

U.S. DoD (Department of Defense). 2010a. *Quadrennial Defense Review Report*. February.

U.S. DoD (Department of Defense). 2010b. *DoD Strategic Sustainability Performance Plan.* August 26.

White House Council on Environmental Quality. 2010. *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy.* October 5.

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4.0 Purpose of the Research Plan

4.1 Objectives of the Research Plan

The *DCERP2 Research Plan* builds upon the scientific framework established during DCERP1 by describing the details of our planned DCERP2 research. In addition, this Research Plan is intended to serve as a mechanism for providing clear communication and coordination among the researchers on the RTI DCERP2 Team, SERDP staff, MCBCL and other DoD installation managers, and interested stakeholders.

The main purposes of this *DCERP2 Research Plan* are to provide a program overview, describe the 13 research projects to be conducted, discuss the measures of success for evaluating the program, and provide the final deliverables. Sections 5.0 through 10.0 of this Research Plan contain summaries of the planned research projects for each of the four ecological modules (i.e., Aquatic/Estuarine, Coastal Wetlands, Coastal Barrier, and Terrestrial) and two overarching modules (i.e., Climate Change and Translating Science into Practice). These sections include background information on the module, the knowledge gaps in the conceptual model that the research will fill, and the individual research projects that are proposed for implementation. Specific information is provided for each research project, including the names of the researchers on that Module Team, the hypotheses to be tested or research question, the technical goals and objectives, background, methods, assessment of climate change impacts, milestones, deliverables, and planned publications. A summary of the deliverables by research project in provided in **Appendix C**. The DCERP Data and Information Management System (DIMS) is described in Section 11.0, and the overall program measures of success are summarized in Section 12.0.

4.2 DCERP2 Overview

Although DCERP1 focused on nitrogen cycling rates and exchanges, DCERP2 emphasizes carbon cycling and exchanges between the estuary, marshes, coastal ocean, and the atmosphere, and will develop a carbon accounting for the terrestrial system. DCERP2 builds on information gained from DCERP1 regarding the importance of freshwater discharge, temperature, light availability, and salinity on both metabolic rates and nitrogen-cycling rates across the estuary. During DCERP2, team members will determine how episodic events affect metabolic and nutrient cycling rates with a new emphasis on carbon cycling. Team members will also improve and expand several tools and models developed during DCERP1. For example, the Marsh Equilibrium Model (MEM) will be refined to include both *Spartina*- and *Juncus*-dominated marshes, support the development of a new point-based model to predict marsh sustainability to sea level rise and carbon sequestration rates, and test adaptive management strategies for sustaining the coastal marshes. Similarly, the beach morphology model proposed for Research Project CB-4 will incorporate the overwash and run-up model developed during DCERP1 into the beach morphology model to provide insight on how barrier morphology will change as a result of sea level rise, as well as increased storminess and their combined impacts on processes affecting overwash. Some research projects, such as Research Project T-1 (initiated in DCERP1 , require more than 5 years to fully determine treatment effects of multiple forest management procedures (prescribed burning and mechanical thinning). Therefore, experimental treatment plots established in DCERP1 for determining impacts of alternative restoration strategies in

loblolly pine forests will be reassessed in 2015 to evaluate longer term vegetation community changes.

Throughout this effort, we will ensure close coordination with MCBCL military training and infrastructure development activities through frequent communication with the DCERP OSC. The DCERP OSC will inform the team of any changes in large-scale military training and testing activities, including activity levels and duration, temporal and spatial changes in training area use, and the introduction of new equipment and/or new training practices. In addition, the DCERP OSC will inform the team of Base planning for major infrastructure development projects or other land management projects on MCBCL that might impact DCERP research or monitoring efforts negatively. Because of our finding in DCERP1 that direct military training activities at their current level (2007–2012) were not significantly affecting MCBCL ecosystems, DCERP2 research projects do not currently plan to directly measure military training impacts with the exception of Research Project AE-5, which will continue to study the impacts of various land uses associated with increased loadings of nutrients, carbon, and sediment to the MCBCL tributary creeks.

4.3 Research Objectives and Projects of DCERP2

Research objectives of the DCERP2 effort are summarized in **Table 4-1**. To achieve these objectives, DCERP2 will implement 13 integrated research projects that will: (1) measure current ecosystem processes (with a focus on carbon measurements); (2) model ecosystem responses to specific disturbances resulting from climate change, land management, and infrastructure development at both local and regional scales; and (3) provide broad-based decision-support tools and models that can be adapted to other DoD installations.

Table 4-1. Research objectives of DCERP2

Determine the likely effects of current and projected climate scenarios on key ecosystem processes (e.g., carbon and nutrient cycling, sediment transport) and associated ecosystem services, with a central focus on quantifying carbon sources, fluxes, and sinks, including development of an estuarine/coastal carbon budget
Evaluate the impacts of land management, and infrastructure development (e.g., land-use change) within a military training environment coupled with climate change (i.e., temperature, drought/rainfall, storminess, and sea level rise) on the carbon cycle in estuarine/coastal systems
Develop effective adaptive management guidelines and tools and assess opportunities for restoration of aquatic/estuarine, coastal barrier, coastal wetlands, and terrestrial ecosystems to enhance carbon storage and long-term sustainability at MCBCL and other DoD installations in similar ecological settings
Translate the scientific results of integrated research and modeling activities into decision-support tools for natural resource managers that are easy to understand, can be broadly applied in making informed management decisions, and are readily accessible to MCBCL staff and other DoD installations via a decision-support framework housed in MARDIS

Thirteen individual research projects form the core of the *DCERP2 Research Plan* (**Table 4-2**). Ten projects are distributed among the four ecosystem modules (i.e., Aquatic/Estuarine, Coastal Wetlands, Coastal Barrier, and Terrestrial). Although each of these research projects addresses questions unique to its ecosystem, all of them are designed to serve the common goal of defining the changing interactions among climate, carbon cycling, and ecosystem-based management decisions. A new Climate Change Module will link the ecosystem modules by providing locally scaled climate forecasts for warming temperatures and multiple perturbations of an accelerating

hydrologic cycle (e.g., precipitation intensity and frequency, drought prevalence) and for interpreting future storminess (frequency, magnitude, and path of storms); the latter will be based on results of other SERDP–funded projects (i.e., Research Project RC-1702). Guidance on regional sea level rise assumptions will be obtained in consultation with SERDP. Reflecting the importance of data translation and application, two research projects are proposed for the new Translating Science into Practice Module. Research Project TSP-1 involves the development and transitioning of a decision-support framework into MARDIS to house a variety of tools and models developed by the DCERP researchers with links to some tools and models hosted on the DCERP researchers' Web sites. Research Project TSP-2 focuses on the development of an expanded Estuarine Simulation Model (ESM), which will integrate results from the Aquatic/Estuarine, Coastal Wetlands, and Coastal Barrier Module carbon and ecosystem processes studies and will test carbon, nutrient cycling, and sediment transport under current and climate conditions projected for the future.

Table 4-2. Research projects to be conducted during DCERP2 (2013–2017)

Project	Research Project Title[a]	Senior Researchers
AE-4	Nutrient–Driven Eutrophication and Carbon Flux Modulated by Climate Change in the NRE	Hans Paerl
AE-5	Climate and Land Use Impacts on Exports of Carbon, Sediments, and Nutrients from Coastal Subwatersheds	Michael Piehler
AE-6	Climatic Drivers Regulating Benthic-Pelagic Carbon and Associated Nutrient Exchanges in the NRE	Iris Anderson
CW-4	Improving Model Predictions for Marsh Response to Sea Level Rise and Implications for Natural Resource Management	Carolyn Currin
CW-5	Marsh–Atmosphere and Marsh–Creek Exchanges of Carbon	Iris Anderson
CB-4	Predicting Sustainability of Coastal Military Training Environments: Developing and Evaluating a Simplified, Numerical Morphology Model	Jesse McNinch
CB-5	Linking Barrier Island Transgression Induced by Storms and Sea Level Rise to the Carbon Cycle	Tony Rodriguez
T-1 Supple-mental	Effects of Different Understory/Midstory Restoration Management Options on Terrestrial Ecosystem Plant and Arthropod Communities	Norman Christensen
T-3	Forest Management, Species Habitat, and Implications for Carbon Flux and Storage	Norman Christensen and Steve Mitchell
T-4	Impacts of Climate Change on Management of Red-Cockaded Woodpeckers at MCBCL	Jeffrey Walters
CC-1	Development of Uniform Historical and Projected Climate to Support Integrated Coastal Ecosystem Research	Ryan Boyles
TSP-1	Development of a Common Spatial Decision Support System (SDSS) Framework	Patrick Halpin
TSP-2	Coupled Ecosystem Modeling of the NRE for Research, Synthesis, and Management	Mark Brush

4.4 Integrating DCERP Research and Monitoring

The team's ecosystem-based approach integrates the *DCERP2 Monitoring and Research Plans*. The research projects will incorporate data from DCERP's monitoring program, MCBCL environmental monitoring activities, and other local, state, federal, and private monitoring activities to provide an integrated approach to ecosystem-based management and to alleviate redundancy in data collection activities. The team can also use the monitoring data to develop, refine, and verify the models, tools, and indicators created as part of the research effort.

Schedules and site locations for all DCERP monitoring activities will ensure that linkages between the monitoring and research project sampling sites are maintained whenever possible. Information derived from research projects will aid in adapting elements of the *DCERP2 Monitoring Plan*. For example, initial monitoring activities may need to change (i.e., adding or deleting parameters being sampled, increasing or decreasing sampling frequencies of some parameters, or increasing or decreasing spatial extent of sampling locations) in response to results obtained from research projects. In this way, the monitoring program will be adaptive in nature to respond to new information on environmental parameters being monitored.

Specific roadmaps for each of the four ecosystem modules illustrate the linkages among monitoring and research activities and summarize the models, decision-support tools, and indicators that will be developed from these activities and the information that will be disseminated to MCBCL and other stakeholders. These roadmaps illustrate how information from the research projects and outcomes will be used to refine the monitoring activities before these activities are transitioned to MCBCL at the completion of DCERP2. The roadmaps for the four ecosystem modules are presented in **Appendix A** of this Research Plan.

The models, decision-support tools, and indicators that are designed, developed, tested, and verified will be transitioned to MCBCL and to other DoD installations as appropriate to assist in monitoring and forecasting ecosystem changes. The models, decision-support tools, and indicators developed from the research projects should also help to streamline the monitoring program to a limited set of key parameters that will be easily transitioned to MCBCL at the end of DCERP2. As previously mentioned, a goal of DCERP2 is to disseminate monitoring and research results and information from associated models, decision-support tools, and indicators to MCBCL and to other users groups, including other DoD installations in similar ecological settings, the scientific community, other stakeholders (e.g., New River Roundtable, Onslow Bight Conservation Forum), and the general public.

4.5 Programmatic Approach to Review Comments

During the Planning Period (November 2012 through February 2013) and continuing through the first DCERP2 TAC meeting in April 2013, the DCERP2 Team received three sets of comments from SERDP and the TAC on the draft versions of the DCERP2 Research and Monitoring Plans. Four major comments emerged regarding overarching topics that need to be considered throughout program's implementation. These comments included concerns about the development and use of conceptual models and scaling up of field measurements to watershed and climate change scales. The comments also included concerns about uncertainty and propagation of error in models and differences in data needs for constructing empirical nutrient

and carbon budgets and for populating associated simulation models. These issues were discussed at length at the 2013 TAC meeting, and some progress toward their resolution was made. However, because of the complexity of these issues, these will be ongoing topics for discussion at future TAC meetings. The following discussion describes the specific concerns of the SERDP and TAC reviewers, and briefly outlines the team's response to these issues, the initial progress made in addressing these issues, and subsequent steps that will be taken to resolve each issue.

4.5.1 Conceptual Models

As discussed in Section 3.1 of this Research Plan, conceptual models were developed at both the programmatic and module levels for each of the four ecosystem modules. However, the reviewers indicated that, although the models were attractive and may serve the Research Team as shorthand graphical lists of ecosystem processes and potential flows and connections, these conceptual models do not communicate information well to other audiences. Furthermore, the reviewers believed that the conceptual models do not indicate which processes are insufficiently known, yet are key to understanding the respective ecosystem; which processes are dominant or less important; and where the strength of the team's knowledge and understanding is currently. Because the module-level conceptual models must address a large number of ecological processes associated with diverse research projects being conducted within each module, even module-level conceptual models are often inappropriate for providing the detailed information that the SERDP and TAC reviewers recommended. In response to this concern, the Research Team has developed additional graphic and/or tabular information at the research project–level to help differentiate the complexities of the ecosystem processes being studied. For example, Research Project T-3 developed a conceptual framework to describe the different forest management treatments and their anticipated impact on carbon storage across the landscape, while Research Project T-4 used a flow chart to show the integration of the landscape and RCW population models. During Year 1 of program implementation, the DCERP2 Team will revisit the conceptual models at both the programmatic, module, and research project levels and will work on refining relationships among ecosystem processes and stressors so as to provide a clearer representation of their current understanding of each ecosystem at the appropriate level of detail to clearly explain the ecological processes, stressors, and research focus of each research project to a wider audience. The conceptual models will likely undergo some modifications as the researchers gain a better understanding of the processes associated with their respective ecosystems.

4.5.2 Data Scaling

Scaling up from in situ field measurements of relatively small dimensions (e.g., mL to L, cm^2 to m^2, and seconds to decades) to watershed and climate change scales is not a trivial matter. This scaling becomes more complex when budgets require integration and mathematical manipulations of values based on different sampling methods and data are collected by multiple researchers. The SERDP and TAC reviewers recommended that a facilitated brainstorming session was needed to focus attention of all researchers, especially the modelers, on general rules and expectations for scaling data. The reviewers suggested that this session should be held before sampling was initiated rather than afterwards to help redirect efforts if necessary. At the November 2012 planning meeting, members of the DCERP2 Team discussed how they would

scale up field measurements to a landscape or watershed scale and for projecting future climate change scenarios. Specifically for carbon, each researcher provided an inventory of the inputs and outputs he or she planned to measure, the sampling methodology to be used, and the units in which these inputs and outputs would be measured. In addition, the researchers responsible for modeling or scaling up the results indicated their data needs. The issue of standardization is very important to all researchers, but especially to the modelers. Further discussions were held at the 2013 TAC meeting to ensure that all research and monitoring data are collected appropriately to be able to scale up the plot-level values. The team has planned an All Scientists Meeting for fall 2014 to scale up a draft carbon budget for the entire estuarine/coastal area of MCBCL. The scaling issue will continue to be a topic of discussion among the team researchers during the implementation period and will be discussed at subsequent TAC meetings. However, the team believes that the use of standardized methods and reporting of results in standard units will go a long way to improving data precision, accuracy, and comparability and the associated scaling up of field measurement data.

4.5.3 Uncertainty of Data and Propagation of Error

Uncertainty of data and propagation of error need to be considered when interpreting data from both budget and simulation of scenario responses. SERDP and TAC reviewers believed that this issue was not thoroughly discussed in draft versions of the Research Plan. The DCERP2 Team agreed with this comment and addressed this comment within each research project description as appropriate. In summary, when constructing the empirical carbon budget, researchers will use accepted error propagation methods in estuarine science as demonstrated by Boynton et al. (2008), Lehrter and Cebrian (2010), and Smith and Kemp (1995). For model scenarios, they will employ simulations with stochastically varying parameters, which propagate error through model calculations to account for imprecisely known and temporally variable parameter values (Kremer, 1983). At the 2013 TAC meeting, numerous methods were discussed, including the use of sensitivity analyses and Monte Carlo bootstrapping methods to determine uncertainty and propagate error. As the team develops models and conducts their analyses, they will determine which methods are most appropriate and will provide a level of uncertainty with their final measurements and model projections, particularly for the net carbon budget projections for the estuarine/coastal region.

4.5.4 Data Needs for Budget and Model Simulations

The requirements for constructing nutrient and carbon budgets and for populating the equations of simulation models are different. Nutrient and carbon budgets often provide the basis for validating the simulation models. The SERDP and TAC reviewers indicated that the draft versions of the Research Plan did not clearly illustrate that the needs of simulation models were being met, specifically for the ESM's development of a net carbon budget. Dr. Mark Brush (developer of the ESM associated with Research Project TSP-2) has closely coordinated with DCERP researchers collecting field data on carbon. Dr. Brush is confident that sufficient data are being collected on major ecosystem pathways in the estuarine/coastal carbon budget to provide a meaningful validation of the ESM–based carbon budget. The carbon cycle and the development of carbon budget are discussed in Section 3.3.2 of this Research Plan and a table of the carbon sources, sinks, and outflows presented in **Appendix B** further ensures that the appropriate data are being collected by the team.

4.6 Literature Cited

Boynton, W.R., J.D. Hagy, J.C. Cornwell, W.M. Kemp, S.M. Greene, M.S. Owens, J.E. Baker, and R.K. Larsen. 2008. Nutrient budgets and management actions in the Patuxent River Estuary, Maryland. *Estuaries and Coasts 31*:623–651.

Kremer, J.N. 1983. Ecological implications of parameter uncertainty in stochastic simulation. *Ecologlical Modeling 18*:187–207.

Lehrter, J.C., and J. Cebrian. 2010. Uncertainty propagation in an ecosystem nutrient budget. *Ecological Applications 20*(2):508–524.

Smith, R.E., and W.M. Kemp. 1995. Seasonal and regional variations in plankton community production and respiration for Chesapeake Bay. *Marine Ecology Progress Series 116*: 217–231.

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5.0 Aquatic/Estuarine Module

5.1 Introduction

Estuaries integrate inputs from terrestrial, freshwater, oceanic, and atmospheric systems (Day and Kemp, 1989; Hobbie, 2000; Valiela et al., 1997). Accurate assessment of ecosystem function and management of estuaries necessitate consideration of their connections to, and interactions with, these other systems. Estuaries also exist in regions of rapidly expanding and diversifying human activity (Boesch et al., 2001; Cloern, 2001; Nixon, 1995). One of the critical roles that estuaries play is transporting and transforming carbon. Photosynthetic organisms from algae to higher plants fix CO_2, some of which support highly productive estuarine food webs. Excessive allochthonous and autochthonous carbon inputs to estuaries, or eutrophication (Nixon, 1995), are a documented problem (as harmful algal blooms [HABs] and hypoxia or anoxia) in estuaries worldwide. **Figure 5-1** presents the conceptual model for the Aquatic/Estuarine Module, illustrating the complementary nature of the critical physical, chemical, and biotic processes and interactions. We will use this model to capture the complexity of the estuarine carbon cycle, among other processes (nutrient cycling and sediment transport). Understanding and sustaining the function of the New River Estuary (NRE) cannot occur without considering processes in the context of climate change, including warming, temperature regime, storm frequency and magnitude, sea level rise and hydrologic extremes (drought and floods). The fully integrated approach within the Aquatic/Estuarine Module and DCERP2 as a whole will permit a rigorous assessment of estuarine ecosystem function and translate that information to management decisions in coastal regions.

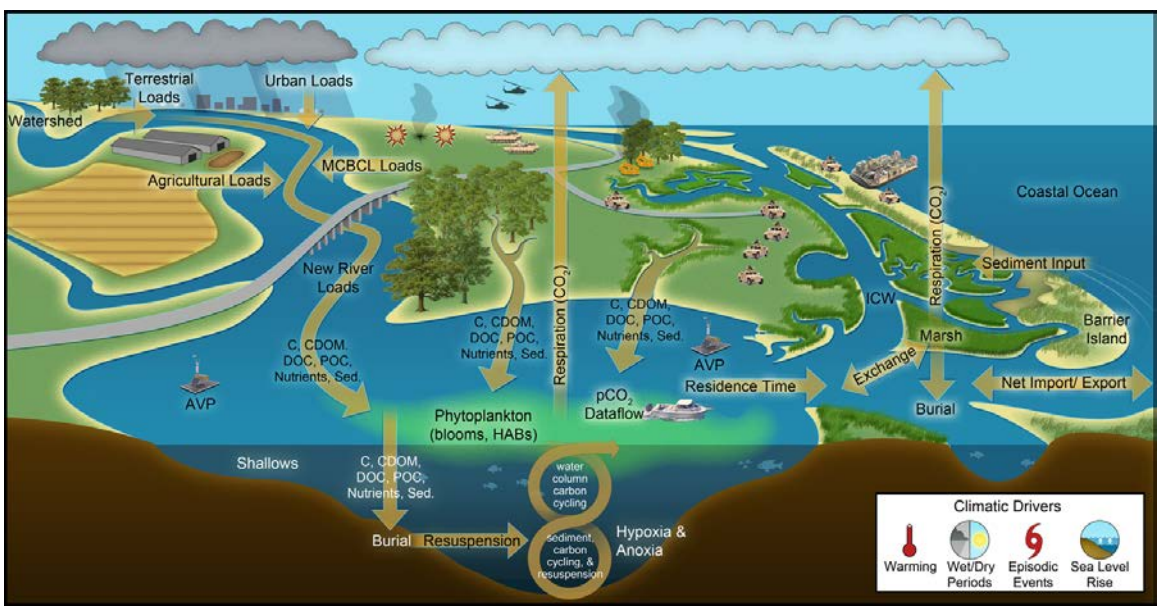

Figure 5-1. Conceptual model for the Aquatic/Estuarine Module.

Estuarine responses to physical, chemical, and biological processes serve as indicators of ecological change (Cloern, 2001; Neimi et al., 2004; NRC, 2000; Peierls et al., 2003). Inputs of carbon, nutrients, sediments, organic matter, and contaminants reach the NRE from multiple sources, including watershed inputs, precipitation and dry deposition from the atmosphere, and

tidal exchanges with Onslow Bay. Watershed inputs include sources from the New River at Jacksonville, NC; creeks that drain into the NRE; surface runoff; and groundwater as baseflow. These inputs influence the biological and chemical cycling within the NRE's water column and sediments (e.g., carbon and nutrient cycling and sediment transport; Anderson et al., 2003; Cloern, 2001). Nutrients stimulate phytoplankton and benthic microalgae (BMA; primary production), thereby providing food for zooplankton and benthic invertebrates (secondary production), respectively (Hobbie, 2000; Sundbäck et al., 2003). The zooplankton and benthic invertebrates provide food for fish, and phytoplankton is the primary food source for shellfish. Excessive phytoplankton production and sediment inputs, however, can reduce light penetration, leading to declines in important nursery area attributes, such as submerged aquatic vegetation (SAV) and BMA abundance (Gallegos et al., 2005), thereby reducing the food supply for benthic-feeding fish and interfering with the role of BMA in modulating water column nutrient enrichment. The NRE's response to human and climate impacts partly depends upon physical and biological interactions, such as wave activity, which leads to the resuspension of bottom sediments, and freshwater discharge and exchange, which affect the estuary's water residence time and degree of stratification (Luettich et al., 2000). These conditions strongly influence the biomass and composition of the autotrophic communities within the NRE, the estuary's susceptibility to hypoxia or anoxia, and the relative importance of microbial processes that may remove nutrients from both the water column and benthos. The research projects presented in **Table 5-1** address the challenges that are associated with stresses imposed as a consequence of MCBCL or other direct anthropogenic activities.

Table 5-1. Aquatic/Estuarine Module research projects, their outcomes and benefits to MCBCL, senior researchers, and duration of the projects

Project	Research Project Title	Senior Researchers and Duration
AE-4	*Nutrient-Driven Eutrophication and Carbon Flux Modulated by Climate Change in the New River Estuary: Application to Water Quality and Watershed Management*	**Senior Researcher:** Hans Paerl
	Outcomes and benefits: 1. Link estuarine planktonic primary production, respiration, and carbon flux dynamics to watershed, wetlands, and oceanic nutrient and hydrologic inputs and exchanges (Research Projects AE-5, AE-6, CB-5, CW-4, CW-5, and TSP-2) 2. Determine the tipping points that relate anthropogenic and climatic drivers to major shifts in phytoplankton community biomass (blooms), composition, production and respiration, and carbon flux dynamics 3. Determine the linkages between carbon fluxes and water column water quality conditions under hydrologically variable conditions throughout the NRE 4. Develop approaches and indicators for assessing human and climatic (change) perturbations impacting the NRE, MCBCL's training mission, and other MCBCL activities that use the NRE	**Duration:** 3/2013–7/2017

(continued)

Table 5-1. Aquatic/Estuarine Module research projects, their outcomes and benefits to MCBCL, senior researchers, and duration of the projects (continued)

Project	Research Project Title	Senior Researchers and Duration
AE-4 (continued)	**Outcomes and benefits (continued):** 5. In conjunction with Research Projects AE-5, AE-6, CB-5, CW-4, CW-5, and using the ESM (Research Project TSP-2), construct a carbon budget for the estuary that is sensitive to and incorporates climatic and anthropogenic drivers of change 6. Provide water column response parameters that go into the ESM for extrapolation to models at other coastal DoD installations. Lagoonal systems such as the NRE are representative of up to half of the estuarine surface area in the United States (Kennish and Paerl, 2010; NOAA, 2011); hence, results are broadly applicable to other key coastal habitats.	
AE-5	*Climate and Land-Use Affect Exports of Carbon, Sediments, and Nutrients from Coastal Subwatersheds*	**Senior Researcher:** Mike Piehler
	Outcomes and benefits: 1. Provide targeted information to decision makers on linking land-use activities and management choices to transport of carbon and other materials to the estuary 2. Provide information to decision makers on forestry and storm water management efforts and their impacts and effectiveness, respectively 3. Use GIS maps to capture research results tod transition to MCBCL managers 4. Support Research Projects AE-4 and AE-6 in developing a carbon budget for the NRE system.	**Duration:** 3/2013–7/2017
AE-6	*Climatic Drivers Regulating Benthic–Pelagic Carbon and Associated Nutrient Exchanges in the New River Estuary*	**Senior Researcher:** Iris Anderson
	Outcomes and benefits: 1. Compare Research Project AE-6 results with predictions by the ESM (Research Project TSP-2). 2. Develop a carbon budget for the NRE in conjunction with Research Projects AE-4, AE-5, CW-4, CW-5, and CB-5. 3. In conjunction with Research Projects AE-4 and AE-5, assess the effects of climate and land-use change on net carbon sequestration versus export of carbon by or from the system. Development of decision-support tools (Research Project TSP-2) using these data will better enable MCBCL to assess the ecological impacts of Base development and evaluate changes in water quality conditions in the context of climate change. 4. Establish generalized estuarine carbon model parameters for extrapolation to models at other coastal DoD installations.	**Duration:** 3/2013–10/2017

5.2 Knowledge Gaps in Conceptual Model and Research Needs

The overarching objective of the Aquatic/Estuarine Module Team is to develop a carbon budget for the NRE and to predict how the carbon cycle will vary in response to long-term anthropogenically and climatically induced changes in the NRE watershed and beyond (i.e., regional changes). Research performed during DCERP1 demonstrated that natural stressors, in particular those resulting from meteorological events, had greater ecological impacts on the NRE than local anthropogenic stressors. For example, the Aquatic/Estuarine Module Team determined that the factors that most control primary production and metabolism in the NRE (i.e., light and nutrient availability and residence time) responded strongly to meteorological and hydrological conditions. Higher freshwater discharge generally increased loads of nutrients while decreasing available light to both the water column and benthos, but especially to the benthos. These conditions exacerbated pelagic phytoplankton blooms, including harmful algae, and decreased the effectiveness of the benthic filter in removal of nutrients. The two important research priorities during DCERP1 were to obtain quantitative information on the allochthonous versus autochthonous loadings of nutrients, sediment, and pathogens from both regional and local watersheds and to determine the transformations of nutrients that occur within the NRE. Products of DCERP1 research included quantifying rates of benthic and pelagic primary production, respiration, and net metabolism and nutrient cycling; identifying indicators of benthic and pelagic productivity; developing a phytoplankton community structure; and assessing the estuarine-wide effectiveness of the benthic filter.

DCERP1 focused on nutrient dynamics, water quality, and coupling between the benthic and pelagic zones; however, DCERP2 will shift focus to the cycling of carbon in the context of changing climate and anthropogenic disturbances. We will examine responses to short-term drivers, including meteorological and hydrological, seasonality, nutrient pulses, and long-term climatic variables, including warming and changes in salinity in response to sea level rise. Studying the factors that modulate the residence time and light availability for this estuary and the role of physical processes involved in loading, transformation, exchange and fate of carbon, nutrients, sediments are of paramount importance to understanding ecosystem-based management options for the NRE.

There is a clear need to improve our understanding of estuarine ecosystem function in the face of changing climate. Monitoring and experimental components of the Aquatic/Estuarine Module will address many of these needs and will inform efforts to forecast future estuarine ecosystem function by providing data to the ESM (Research Project TSP-2). Just as critical is the need to transform the scientific and modeling products from research into forms that are useful to management. To ensure that the Aquatic/Estuarine Module's results will be of as much value as possible to decision makers, we will closely coordinate our research with the TSP Module. The informational and technical gaps that will be addressed by the Aquatic/Estuarine research projects are especially important to fill in this period of extreme climatic variability and change. In addition, as data gaps are filled, researchers will revise the conceptual models as appropriate to reflect the new understanding of ecosystem processes gained and will make the information more useful to a wider audience of users.

5.3 Research Project AE-4: Nutrient-Driven Eutrophication and Carbon Flux Modulated by Climate Change in the New River Estuary: Application to Water Quality and Watershed Management

Lead Investigator: Dr. Hans Paerl (UNC-IMS)

Supporting Researchers: Drs. Scott Ensign (AquaCo), Michael Piehler (UNC-IMS), Iris Anderson (VIMS), one Graduate Assistant (4 years); and half-time Research Technician

Technical Objectives/Goals: Quantify how nutrient inputs and climatically driven hydrologic variability interact to control primary production, microalgal composition and function, air-water CO_2 exchange, and carbon flux in the NRE. Determine the role that phytoplankton play as a carbon source and sink in the NRE carbon budget and how this is influenced by human perturbations and climatic change, building on nutrient and hydrologic input and water quality data collected during DCERP1.

Research Questions:

1. How do meteorological events such as high precipitation storms, tropical cyclones, and droughts modify phytoplankton community structure and function (rates of primary production and planktonic respiration) and will the changes significantly impact carbon flux and budgets for the NRE?
2. What is the relationship between allochthonous organic carbon loading from freshwater discharge events and respiration and heterotrophic conditions? This relationship will be compared to authochthonous phytoplankton-based production as a source of organic carbon. These sources are likely to vary depending on freshwater discharge, nutrient inputs, and residence time, which all jointly control phytoplankton community structure and production, as well as the fate of organic carbon produced by these sources.

   The frequency and intensity of these events will affect the overall net carbon balance (heterotrophic versus autotrophic) of the system. Atmospheric warming is taking place globally (IPCC, 2007 and 2012), regionally (Webster et al., 2005), and locally (Band and Salveston, 2009). North Carolina is experiencing record temperatures, droughts, and tropical cyclone frequencies (NOAA, National Hurricane Center; North Carolina Climate Office). More “extreme” heat waves and cold snaps are manifestations of climate change that strongly affect rates of primary production, respiration, and nutrient transformations in the estuary, all of which will alter community structure and function of algal communities (Hall et al., 2012; Paerl and Huisman, 2008 and 2009).
3. Do warmer conditions favor potentially harmful cyanobacterial, dinoflagellate, and raphidophyte HAB species over more desirable diatoms? If so, how will these changes impact NRE fertility, nutrient cycling, and carbon utilization and flux?

   From research and management perspectives, we need to distinguish and quantify climatically and anthropogenically driven changes in the NRE, so that we can realistically and accurately assess, model, and manage specific causes, mechanisms, and manifestations of environmental change affecting the NRE.

5.3.1 Background

The NRE is a highly productive lagoonal ecosystem and a dominant physiographic feature of MCBCL. The NRE is also the dominant processor of external sources of nutrients and organic matter originating in the watersheds and airsheds and internally produced. Prior research in the NRE system and the nearby North Carolina lagoonal estuarine system (Pamlico Sound System) have shown that nutrient and organic matter processing and resultant water quality and trophic state of these systems are strongly susceptible to and driven by hydrologic forcing. This type of forcing includes freshwater runoff from tropical and extra-tropical storm “events,” droughts, man-made discharge events (e.g., sewage spills), and flow alterations (e.g., upstream water diversions and withdrawal, irrigation; Hall et al., 2012; Paerl et al., 2007 and 2010b; Peierls et al., 2003 and 2012). Carbon is the currency of productivity and trophic state of the estuary.

Carbon inputs from external sources and internally generated from nutrient-driven (largely nitrogen) primary production, play integral roles in determining nutrient and oxygen cycling, which in turn determines the fertility (including excess fertility or eutrophication) and habitability (e.g., hypoxia potentials) of the estuary. Understanding and quantifying the interactions of contemporaneous carbon and nitrogen loading and cycling, as well as the role that the estuary plays as a carbon source or sink, will help clarify the sensitivity and susceptibility of the NRE to different conditions. Examples of these conditions include altered carbon and nitrogen inputs arising from current and future watershed development scenarios; climatic changes, including a well-documented increase in tropical cyclone activity and intensity in the Atlantic Ocean (Bender et al., 2010; Elsner et al., 2008; Holland and Webster, 2007; IPCC, 2007; Webster et al., 2005); and record droughts (Band and Salveston, 2009). This improved understanding will enhance the ability to forecast impacts of these changing climatic forcing features on carbon flux and budgets (Crosswell et al., 2012, in review). An improved understanding will also help identify the effective management steps needed to minimize risks to water quality and habitat degradation of this valuable component of MCBCL during a period of anthropogenic and climatically induced change.

Data collected during DCERP1 have shown that the NRE can process a large proportion of externally and internally supplied (recycled) nutrients (i.e., nitrogen, phosphorus, and carbon) via phytoplankton production, which accounts for at least half of the estuary's total primary production (Hall et al., 2012; Paerl et al., 2011). Phytoplankton can proliferate as highly visible and problematic (toxic, hypoxia-generating) blooms (Tomas et al., 2007), at times exceeding the State of North Carolina's "acceptable" chlorophyll *a* (chl *a*) standard of 40 $\mu g\ L^{-1}$ (Paerl et al., 2012). These blooms also represent a significant portion of overall primary production and carbon inventory of the NRE (Paerl et al., 2012). The composition, location, magnitude, and duration of blooms are controlled by nutrient-rich freshwater discharge from the New River and local tributary creeks that drain MCBCL. Therefore, changes in freshwater discharge, due to altered storm frequency and/or intensity in the Atlantic Ocean, that alter local precipitation patterns and/or droughts, modulate blooms (Paerl et al., 2011; Ramus et al., 2003; Wetz et al., 2011) and hence are a major factor controlling air–water CO_2 fluxes that define the role of the NRE as a carbon source or sink. Data collected during DCERP1 indicate that future growth and development within MCBCL may increase the importance of on-Base tributaries as sources of nutrients and organic matter that influence bloom dynamics, and the projected increase in climatic extremes will likely enhance the role of air–water exchanges in the estuarine carbon cycle (Crosswell et al., 2012 in press and in review).

Collection of high-resolution partial pressure of carbon dioxide (pCO_2) data using a flow-through monitoring system adapted for small boat use (Crosswell et al., 2012, in press) will be synchronized with carbon measurements of Research Projects AE-5 and AE-6 to optimize temporal and spatial coverage of carbon fluxes during regularly scheduled and episodic research activities. The DCERP2 Team will use data from these three Aquatic/Estuarine Module research projects to develop a comprehensive carbon budget to evaluate current land-water-atmosphere carbon fluxes. This comprehensive carbon budget produced from more than 4 years of field data will define the seasonal pattern of net carbon flux within the estuary. Event-scale dynamics due to floods or droughts are likely to produce significant deviations from this seasonal pattern (Crosswell et al., 2012). These deviations will be used to determine the absolute magnitude and relative importance of event-scale forcing on net carbon flux by subtracting observed fluxes

during events from the seasonal norm. Use of the data to properly parameterize the ESM will allow robust model determinations of changes in carbon fluxes across a range of future climate change scenarios.

Regional carbon exchanges among MCBCL ecosystems may undergo significant changes under the current climate projections, including an increase in tropical cyclone activity and/or intensity (Holland and Webster, 2007; IPCC, 2012; Webster et al., 2005) and more protracted droughts (Band and Salveston, 2009). The North Carolina Coastal Habitat Protection Plan (Deaton et al., 2010) has identified climate change as the most "cross-cutting" threat to estuarine and coastal habitat in North Carolina because it affects virtually all ecosystems, and it may also exacerbate or mitigate the individual impacts posed by other major threats. As described in Section 5.4, environmental data collected by Research Project AE-4 (with support from monitoring activity AEM-1) can be used to directly measure and assess five of the 10 top threats to coastal marine ecosystems, defined by Crain et al. (2009). These five threats are eutrophication and hypoxia, altered salinities, altered sedimentation, climate change, and ocean acidification. A major advantage of the diverse parameters measured by Research Project AE-4 is that they can be used collectively to assess the synergistic effects of multiple threats. A primary example of this is the recently added pCO_2 monitoring system, which, when paired with data from YSI sensors and discrete water quality samples, can be used to resolve how increased storminess and altered freshwater and seawater exchanges will influence the estuarine ecosystem (**Figure 5-2**).

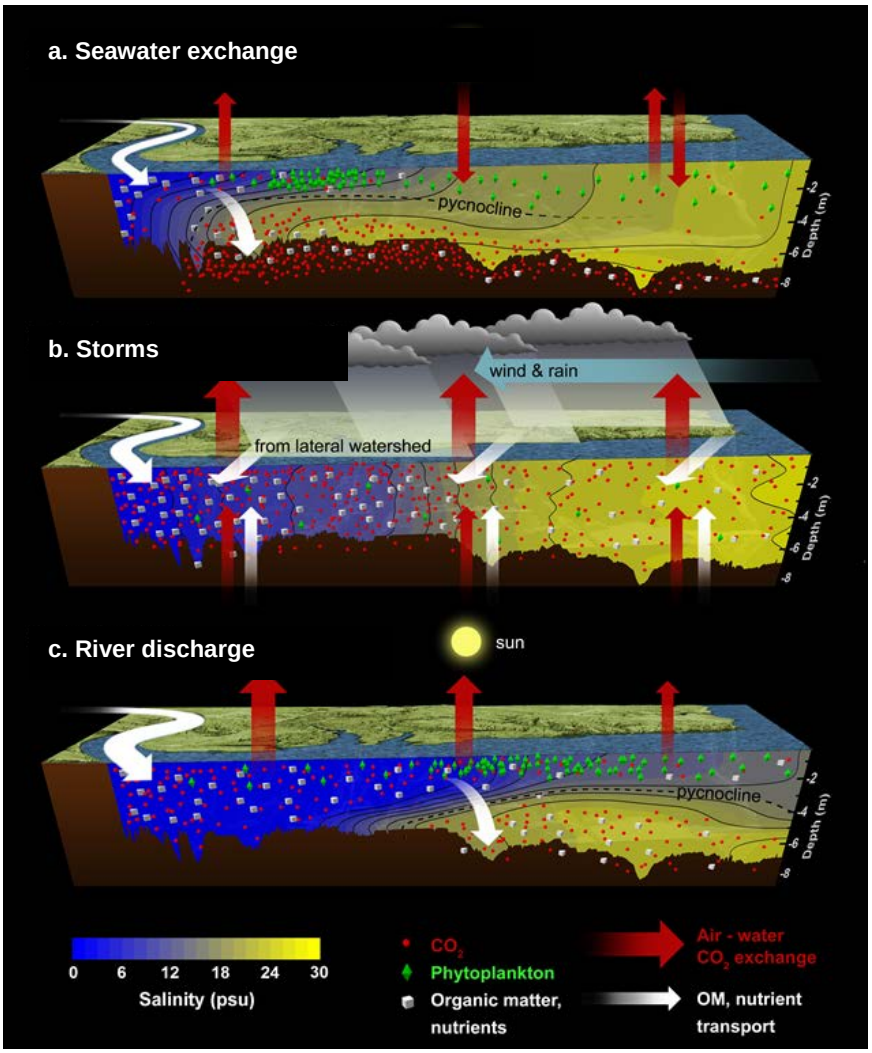

Figure 5-2. Estuarine conditions under projected climate change scenarios of (a) increased seawater exchange, (b) increased storminess, and (c) increased river discharge (from Crosswell et al., 2012, in review).

Water quality monitoring and assessment methods (e.g., transects, Dataflow, Autonomous Vertical Profilers [AVPs]; part of monitoring activity AEM-1) will be coupled to field-based approaches for measuring air–water and watershed–estuarine carbon and nitrogen fluxes, and recently developed bio-indicators (diagnostic photopigments, molecular probe indicators of HABs). This will help clarify, quantify, and characterize the interactive effects of externally supplied and internally generated carbon and nitrogen inputs that are mediated by freshwater discharge, tidal forcing, sediment–water column exchanges, and (linked with the stream and watershed component) lateral (streams and tributaries) exchanges. A key question (and objective) that will be addressed is how these exchanges and resultant fluxes are impacted by symptoms of climate change, including more frequent and extreme storm events, droughts, sea level rise, and warming. All of these factors are known to impact estuarine primary production, algal bloom, and hypoxia dynamics (Christian et al., 2004; Cloern et al., 2011; Kennish and Paerl, 2010; Paerl and Huisman, 2008 and 2009; Paerl et al., 2011; Peierls et al., 2003), which will, in turn, affect internal nutrient, carbon, and oxygen cycling, and water and habitat quality

and sustainability (Diaz and Rosenberg, 2008). This information, integrated with benthic and watershed inputs from Research Projects AE-5 and AE-6, will serve as the data source for developing, testing, and refining a carbon and nitrogen–based water quality model (i.e., the ESM) for the NRE (Research Project TSP-2, in conjunction with Research Projects AE-5 and AE-6). The ESM will be capable of gauging and evaluating what is manageable (i.e., man-made nutrient and carbon inputs) versus what is not manageable, at least not on a short-term (seasonal, multi-annual) scale. Research project AE-4 will be a critical part of MCBCL's ability to detect, quantify, and evaluate short-term and longer term trends in water quality and habitat condition mediated by the interactive effects of human activities and climatic changes taking place in the NRE watersheds and airsheds.

The products of this research will be transferrable and applicable to other military installations in similar estuarine and coastal settings impacted by the effects of extreme climatic variability and change. Lagoonal systems such as the NRE are representative of up to half of the estuarine surface area in the United States (Kennish and Paerl, 2010); hence, the results are broadly applicable to other key coastal habitats. Locally, these installations would include MCAS Cherry Point (on the Neuse River Estuary); regionally, these would include locations on the U.S. Atlantic, Gulf, and Pacific Coasts.

5.3.2 Methods

Central to Research Project AE-4 is the application of a small boat-based flow-through system that measures the pCO_2 in the water and air (Crosswell et al., 2012, in press) in parallel with multiparameter datasondes, to determine in situ CO_2 flux and physicochemical conditions in representative freshwater, microtidal, and tidal regions. During monthly mid-estuarine transects, we will continuously pump water from a through-hull fitting, located 0.4 m below the water line, at approximately 10 L min^{-1} through a thermosalinograph (TSG; Sea-Bird Electronics, SBE 45) followed by an air–water showerhead equilibration chamber. The TSG is used to measure sea-surface salinity (SSS) and sea-surface temperature. pCO_2 in the equilibration chamber is determined by recirculating a carrier gas at a flow of approximately 1.0 L min^{-1} through the equilibrator chamber and sending a small split (0.030 L min^{-1}) to a nondispersive infrared absorbance detection analyzer (Li-Cor, LI-840). At the beginning and end of each transect survey, ambient atmospheric air and two CO_2 gas standards (Scott-Marrin Inc.) are measured for calibration and verification of the absorbance detection analyzer. The extent of equilibration in the showerhead equilibrium chamber is verified using inlet and outlet gases. The calibrated detector xCO_2 is corrected for headspace pressure and temperature and is presented as pCO_2 at SST, with an attainable accuracy of ±4 µatm over the functional range of 149 to 5,050 ppmv. We will simultaneously pump water into a flow-through cell attached to a multiparameter datasonde (YSI, Model 6600) configured to measure chlorophyll fluorescence, dissolved oxygen (DO), pH, and turbidity (we refer to the flow-through system as Dataflow, after Madden and Day, 1992). All measurements are taken at 2-second intervals, and the lag time between Dataflow, the TSG, and CO_2 absorbance detection analyzer is measured and corrected for each sampling run. We will coordinate sampling efforts with Research Projects AE-5 and AE-6 (i.e., same day or within close-as-possible proximity) to minimize temporal and spatial uncertainties and thereby support the model projections of Research Project TSP-2 as a tool to guide management decisions.

Air-water-gas exchange is a function of complex underlying mechanisms, which include turbulence, bubble-mediated transfer, and the physicochemical properties of the relative waterbody (Smith et al., 2011). Most of these mechanisms are largely dependent upon wind stress, hence gas-transfer velocities are often empirically defined as a function of wind speed in open-water systems. However, the uncertainty of such parameterization is compounded in estuaries because the effect of wind speed and water currents can vary substantially along the estuarine continuum due to major changes in bathymetry and fetch (Alin et al., 2011). Recent compilations have shown that gas-transfer velocities within individual estuaries can vary as much, if not more, than the average gas-transfer velocities between different estuarine systems (Alin et al., 2011; Jiang et al., 2008). If we consider the large range of environmental conditions observed during DCERP1, the precise estimation of air-water CO_2 fluxes would require an equally exhaustive parameterization of gas transfer velocities in the NRE. However, most of these environmental conditions are represented in the collective body of literature on estuarine gas-transfer velocities. Currently, the regression equation proposed by Jiang et al. (2008; shown below as Equation 2) is the most comprehensive, and it is widely used in recent reviews of estuarine CO_2 fluxes (Chen and Borges, 2009; Laruelle et al., 2010). For this reason, we will apply this equation as described below to estimate air-water CO_2 fluxes in the NRE. We will calculate the magnitude of the air-water CO_2 fluxes in the NRE as shown in Equation 5-1:

$$flux\ (mmol\ C\ cm^{-2}h^{-1}) = kK_0(\Delta pCO_2) \qquad \text{(Eq. 5-1)}$$

where k (cm h^{-1}) is the gas-exchange coefficient, K_0 is the CO_2 solubility coefficient (Weiss, 1974), and ΔpCO_2 is the difference in CO_2 partial pressure between water and air (µatm). We will calculate k as shown in Equation 5-2 (Jiang et al., 2008):

$$k = (.314U_{10}^2 - .436U_{10} + 3.99) \times (Sc_{SST}/600)^{-0.5} \qquad \text{(Eq. 5-2)}$$

where U_{10} is the hourly wind speed and Sc_{SST} is the Schmidt number for CO_2 at ambient SST and SSS (Wanninkhof, 1992). We will obtain hourly wind speeds from two anemometers, one on each AVP. Wind speeds will be adjusted from the anemometer approximately 4 meters above the water surface to U_{10} following Large and Pond (1981) and validated with meteorological data from the New River MCAS weather station (WBAN 92727) 93727. For each survey, we will calculate air-water CO_2 fluxes using distance-weighted pCO_2 averages, integrated U_{10} data from both AVP stations and the average pCO_2 of the ambient air measured before and after each survey.

At bimonthly intervals and in conjunction with Research Project AE-6, we will run parallel transects along the estuarine shoreline (conducted by Research Project AE-6) and in the main channel (conducted by Research Project AE-4) using the pCO_2-Dataflow system to assess lateral variability in the measured parameters. We will conduct these transects at dawn, dusk, and the following dawn to assess diel variability. This is critical information needed for scaling instantaneous measurements to the daily and longer scale. In addition to the pCO_2 measurements, we will obtain the following information:

- Water column physical–chemical measurements from an eight station (see **Figure 5-3**) downstream transect along the NRE (also supported by monitoring activity AEM-1).

These measurements include all forms of dissolved and particulate carbon needed for budget calculations.

- ^{14}C primary productivity (Paerl, 2002; Paerl et al., 1995) and planktonic respiration measurements, using the open-water diel oxygen method and in conjunction with Research Project AE-6. Planktonic and benthic production and respiration measured at AVP stations and proximal shallow water stations (by Research Project AE-6) will be scaled to the estuarine surface area by distance-weighted linear interpolation between each model element and depth-weighted spatial interpolation within each element based on bathymetry.
- Determination of phytoplankton biomass (chl *a*) and specific phytoplankton functional groups responsible for blooms, using high-performance liquid chromatography (HPLC)–determined diagnostic photopigments (supported by monitoring activity AEM-1; for details please see Paerl et al., 2007; Pinckney et al., 2001).

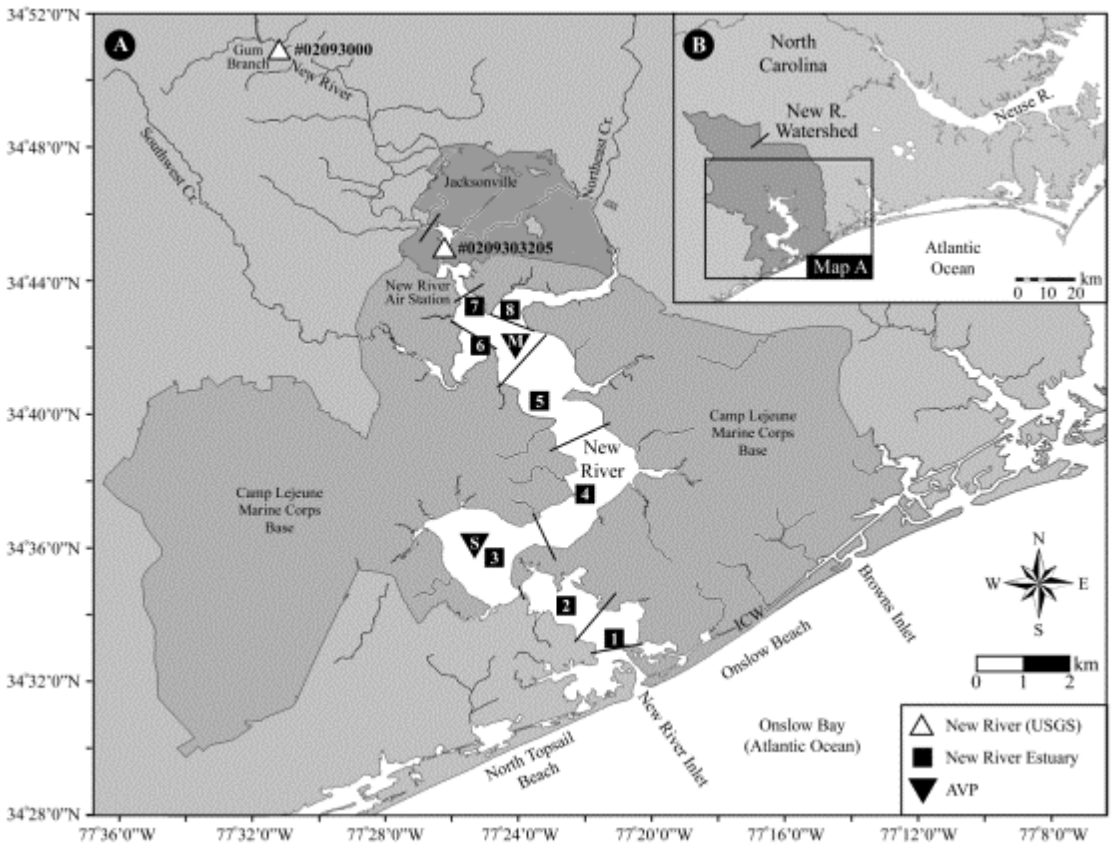

Figure 5-3. A map of the NRE showing the locations of the eight monthly sampling stations (1–8) and the locations of the two AVPs.

5.3.2.1 Linkage to Carbon Budget

We will use these measurements to calculate physical and biogeochemical water column carbon fluxes to assess the environmental controls on the carbon cycle of the NRE. We will collect a dual subset of carbonate chemistry samples to ensure methods and measurement continuity with

Research Projects AE-5 and AE-6. This quality analysis will facilitate integration of data from Research Projects AE-4, AE-5, and AE-6 into a unified carbon budget for the NRE.

We will link the carbon flux measurements from Research Project AE-4 to hydrologic and nutrient inputs from the New River and the tributary creeks (Research Project AE-5), as well as near-shore sediment-water column nutrient and carbon exchange (Research Project AE-6). We will use land-water-atmosphere carbon flux data in conjunction with monthly water-column profiles of nutrients, organic and inorganic carbon sources, and DO (in conjunction with Research Project AE-6) to determine carbon and oxygen balance (net heterotrophic versus autotrophic) conditions of the NRE. We will then integrate HPLC–based diagnostic pigment-based (Paerl et al., 2003) assessments of phytoplankton community responses to anthropogenic (nutrient, organic matter) and climatic drivers with previously mentioned carbon and nutrient budgets. In collaboration with Research Projects AE-5 and AE-6, we will compare these assessments to sediment core data and organic matter lability data (from Research Project AE-6) to hindcast prior conditions of the NRE and forecast ecosystem responses to prospective climatic change in the NRE (Research Project TSP-2; Crosswell et al., 2012, in press).

The previously described analyses will determine how the NRE "breathes" in response to the full range of nutrient and hydrologic drivers and will clarify short-term (diel), longer term (weekly–monthly and seasonal), and event-scale processes that define the role of the NRE as a source or sink of CO_2 that can be linked to MCBCL CO_2 emissions and budgets (as a possible offset). In addition, we will use data derived from these experiments to determine nutrient-driven and hydrologically driven "tipping points" for algal bloom formation and their impacts on carbon flux.

5.3.3 Assessment of Climate Change Impacts

Research Project AE-4 will measure the pCO_2 in the water and air to determine in situ CO_2 flux in parallel with phytoplankton production and planktonic respiration in representative freshwater, micro-tidal, and tidal regions of the estuary. We will collect measurements to assess the effects of nutrient-enriched freshwater inputs (and changes therein due to storms, floods, droughts, and seasonal hydrologic changes) on phytoplankton-mediated flux of CO_2 in the estuary. Evaluating parallel measurements of nutrient enrichment and residence time will enable us to distinguish the effects of eutrophication and flushing/residence time on phytoplankton composition and activity (CO_2 uptake) (Hall et al., 2012; Peierls et al., 2012). The previously mentioned variables reflect physical and chemical impacts of climatic variability and change on the estuarine carbon flux. Together with tributary input (Research Project AE-5) and benthic-water column nutrient and carbon exchange data (Research Project AE-6), these measurements will provide critical information for calibrating and validating the modeled carbon cycle of the ESM as part of Research Project TSP-2. Once validated for current conditions, future climate conditions can be used to forecast responses of NRE ecological responses through scenario testing using the ESM. These results will enable us to better estimate anthropogenic (nutrient) from climatic (hydrologic) impacts on phytoplankton-mediate carbon flux in the estuary now and under changed climate conditions.

5.3.4 Milestones

1.	Assess interactive impacts of carbon and nutrient loads, freshwater discharge, phytoplankton production, and biomass dynamics	3/2013–1/2016
2.	Assess the impacts of planktonic production and biomass dynamics on carbon flux	3/2013–1/2017
3.	In conjunction with Research Project AE-6, link water column to benthic nutrient and carbon flux measurements	3/2013–1/2016
4.	In conjunction with Research Projects AE-5, AE-6, and TSP-2, couple 1, 2, and 3 above to watershed nutrient input and estuarine response models	3/2013–10/2017
5.	Refine predictions of changes in carbon flux based on field measurements and modeling	3/2013–10/2017
6.	Along with Research Projects AE-5, AE-6, CB-5 and CW-4, develop a carbon flux model coupling the coastal marsh and barrier island with aquatic components of MCBCL	3/2013–10/2017
7.	Incorporate experimental and ESM results in carbon-flux decision-support tool for MCBCL	7/2016–10/2017
8.	Prepare and deliver final Research Report	10/2017

5.3.5 Deliverables

1.	Real-time, through-hull continuous pCO_2 monitoring system methodology for vessels conducting environmental monitoring and research on estuarine and coastal waters	6/2013
2.	Contribute to the development of a carbon budget for the estuarine/coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5)	Draft 3/2015; final 3/2017
3.	Annual and final reports	Draft 3/2017; final 9/2017

5.3.6 Planned Publications

Crosswell, J.R., et al. CO_2 flux dynamics in the anthropogenically and climatically impacted New River Estuary, NC. Implications for larger scale estuarine carbon cycling in an era of climatic change. Planned submission to *Global Biogeochemical Cycles* in 2014.

Paerl, H.W., et al. Interactive effects of anthropogenic nutrient loading and climatic perturbations on phytoplankton-mediated carbon flux in the New River Estuary, NC. Planned submission to *Limnology and Oceanography* in 2014.

Peierls, B.L., et al. Allochthonous versus authochthonous inputs of organic carbon mediated by climatic perturbations: Impacts on microbially mediated carbon cycling in the New River Estuary, NC. Planned submission to *Environmental Microbiology* in 2015.

5.4 Research Project AE-5: Climate and Land-use Impacts on Exports of Carbon, Suspended Solids, and Nutrients from Coastal Subwatersheds

Lead Investigator: Dr. Michael F. Piehler (UNC-IMS)

Supporting Researchers: One Research Technician, and one Graduate Research Assistant (Ph.D.)

Technical Objectives/Goals:

Research Project AE-5 builds on our understanding of the links between land-use activities and the tributary streams, with a focus on the impacts of climate change and climate variability on the processing and export of materials (particularly carbon) by coastal tributary creeks. We will convey this information to end users at MCBCL and at other installations in similar coastal environments. Specific objectives of Research Project AE-5 are to

1. Assess MCBCL land-use effects on tributary creek loading of carbon (both dissolved and particulate) and its delivery mechanism to the estuary (e.g., in baseflow or stormflow). We will measure carbon, nutrient, and sediment concentrations through baseflow and stormflow in five MCBCL tributaries to the NRE with representative land uses over a 2-year period (2013–2015). We will employ flow and water level from monitoring activity AEM-2 to calculate loading, and then will use these loads during Research Project AE-6 to assess in-stream attenuation of loading through deployments that they will conduct to assess flow and concentrations at the tributary creek mouths. We will conduct analyses to determine not only the quantity of carbon loaded, but also the type of carbon (e.g., labile versus refractory). We will use these data to determine the load of carbon from MCBCL lands through streams to the NRE with specific details on the effects of MCBCL land use.
2. Measure impacts of forestry management on exports of carbon, suspended solids, and nutrients. We will make targeted deployments in forestry management areas adjacent to streams in land areas subjected to midstory and understory thinning and prescribed burning in collaboration with Research Project T-3 (portions of 2015). We will collect similar measurements at a reference stream draining from a similar forest type that is not subject to active management.
3. Quantify the linkage between tributary creek temperature and MCBCL land use and determine the potential effects on the ecology of both the tributary creeks and the estuary. We will assess stream thermal loading through 2 years at five tributaries to the NRE (2013–2015). We will calculate the impacts of stream delivery of thermal energy on the overall thermal budget of the receiving waters to determine the extent to which patterns in thermal loading are ecologically relevant. Then, we will directly link these results to experiments planned for Research Project AE-6 and the ESM (Research Project TSP-2).
4. Determine the extent to which stormwater best management practices (BMPs) restore ecosystem function by decreasing subwatershed scale export of carbon, nutrients, and sediments through tributary streams. During recent construction activities at MCBCL, a significant number of stormwater management structures have been built on the installation. Through targeted deployments (portions of 2016), we will determine the mass balance of materials (nutrients, sediments, and carbon) entering and leaving several of these BMP structures. We will compare the loadings from the subwatersheds with BMPs to less developed reference sites to assess the extent to which the BMP engineering solution has reduced excessive loading of nutrients, suspended solids, and carbon to the levels observed in less developed watersheds.

Research Questions:

1. Will the intensity and type of watershed development alter stream loading of carbon, nutrients, and suspended solids? Will there be shifts in carbon forms (dissolved organic carbon [DOC] versus particulate organic carbon [POC]) related to watershed land cover?
2. Will forest management to enhance habitat for red-cockaded woodpeckers (RCWs; *Picoides borealis*) affect stream export of carbon relative to forested streams not being managed for RCWs?
3. Stormwater BMPs are generally designed to reduce nutrient, pathogen, and suspended material loading. How effective are the BMPs selected for this study and what are their impacts on the magnitude and type of carbon loading?
4. What are the impacts of variations in watershed land cover on thermal loading in coastal streams? Are there variable impacts on base- and storm-flow thermal loading? If observed, are distinctions in thermal loading ecologically significant for the streams and/or estuary?
5. How will predicted changes in air temperature and freshwater pulses affect the magnitude and patterns of stream loadings of carbon, nutrients, and sediments in these coastal creeks?

5.4.1 Background

Changes in watersheds associated with human development affect ecosystem function through impacts on both the hydrology and the sources and composition of materials (e.g., carbon, nitrogen, sediments; Paul and Meyer, 2001). The transition to a developed landscape results in increases in the amount of impervious cover and decreases in forested area, among other changes. These changes decrease infiltration of rainfall creating periods of increased peak stormflows of shorter duration and a corresponding potential for decreased baseflows. Some changes in land use, associated with development, likely increase sources of materials or decrease the effectiveness of sinks of materials.

In coastal regions, managing stream loading of nutrients and suspended matter can pose a challenge to managers because sufficient quantities of each are necessary for coastal wetlands ecosystem to function, but in excess, they are pollutants. Some proportional amount of nitrogen and phosphorus are necessary to support primary production to meet the consumptive needs of higher trophic levels in coastal ecosystems. Additionally, sea level rise is currently counteracted by accretion of mineral and organic materials in marshes, necessitating delivery of ample amounts of sediment to coastal areas, in part, via riverine networks (Morris et al., 2002). Balancing the need for some nutrients and suspended materials within coastal management programs generally designed to minimize loading requires reliable information about the magnitudes and timing of material loading from coastal streams.

A variety of modeling approaches have been used to estimate material loading by streams over a range of systems (Alexander et al., 2002; Seitzinger et al., 2005). The models reviewed by Alexander et al. (2002) predicted nitrogen export within 50% of measured export for large watersheds; however, this potential discrepancy may be too large if the information is being related to relatively small-scale changes in the landscape. One central challenge for modeling coastal stream loading is the tendency for a shallow water table, which significantly affects stream function.

The utility of directly measuring coastal stream material load is obvious, as is the need for standardized methods that enable cross-watershed comparisons. Several studies have used direct measurements of material concentration and discharge to calculate load (Birgand et al., 2006;

Kaushal et al., 2008; Sobota et al., 2009). Measuring discharge and multiple parameters of water chemistry is the most robust method and rigorously connect changes in the watershed to stream carbon, nutrient, and sediment loading. Natural coastal subwatersheds deliver high DOC loads due to the prevalence of wetlands (Mullholland and Kuenzler, 1979). Urbanization in coastal watersheds has been linked to changes in DOC loading (Hatt et al., 2004). Quantitative connections between the degree of development and patterns and the magnitudes of loading of dissolved carbon and other constituents (suspended materials, nutrients) require direct measurements of loading at several representative sites.

Recent increases in stream and river temperatures have been reported throughout the United States (Kaushal et al., 2010). Water temperatures affect the metabolic rates of organisms and the speed of chemical reactions (Harris et al., 2006; O'Connor et al., 2009) and water characteristics, including vapor pressure, surface tension, density, and viscosity (Stevens et al., 1975), that affect ecosystem function (Vogel, 1994). Metabolic rates are known to increase exponentially with temperature (Brown, 2004); however, the change in these rates is not uniform across all organisms. Harris et al. (2006) found that consumer (heterotrophic) respiration increases twice as rapidly as net primary production rates with temperature increases due to larger consumer biomass and a lower autotrophic activation energy. This difference could shift the ecosystem balance and impose limits on heterotrophic biomass or deplete autotrophic standing stock (O'Connor et al., 2009). Changes in temperature can also influence the organism's presence in an area as these organisms have certain temperature preferences and tolerances.

During DCERP1, we quantified the effects of MCBCL–associated land-use changes on delivery of nutrients and sediments through coastal creeks. Indicators of development such as percent imperviousness often increased both the total load and the proportion of nutrient or sediment load delivered during storms. Examination of patterns within storms revealed that although sediments were generally delivered early in the storm event, other materials such as nutrients were delivered throughout the storm event. We also determined that the tributary creeks in the NRE do not currently contribute a large proportion of the total annual load of nutrients; however, increased MCBCL development has the potential to significantly increase this contribution. Using the data gathered in DCERP1, we developed flow versus concentration models for the 10 tributaries we examined. These models permit a reasonable estimation of the annual load of nutrients and sediments if flow is known. An important finding from DCERP1 was that there appeared to be a threshold in impervious cover percentage in watersheds that led to significant increases in loading above 15% imperviousness (**Figure 5-4**). We also found that one watershed with a relatively high percent imperviousness had lower than expected nitrate loading in the stream that drained from it. During the DCERP1 study period, Tarawa Terrace was undergoing significant construction activities. Accompanying this construction was the installation of a stormwater BMP, which appeared to be the reason for the lower than expected nitrate loading. During DCERP2, we will build on our understanding of the links between land uses and the tributary creeks and focus on the impacts of climate change (i.e., changes in storminess, precipitation patterns, temperature, and sea level) and climate variability on the processing and export of materials (particularly carbon) by coastal tributary creeks. We will fully integrate Research Project AE-5 with the estuarine (Research Project AE-4), benthic (Research Project AE-6), and modeling (Research Project TSP-2) efforts proposed. We will also integrate Research Project AE-5 with the marsh carbon and sediment efforts (Research Projects CW-4 and CW-5). Finally, we will integrate with terrestrial (Research Project T-3) efforts to understand the

landscape impacts of forest management (e.g., prescribed burning, thinning, clearing regimes) through targeted deployments in tributary streams within forestry management areas. Finally, we will assess the extent to which stormwater BMPs can reduce export of excessive levels of nutrients and sediments.

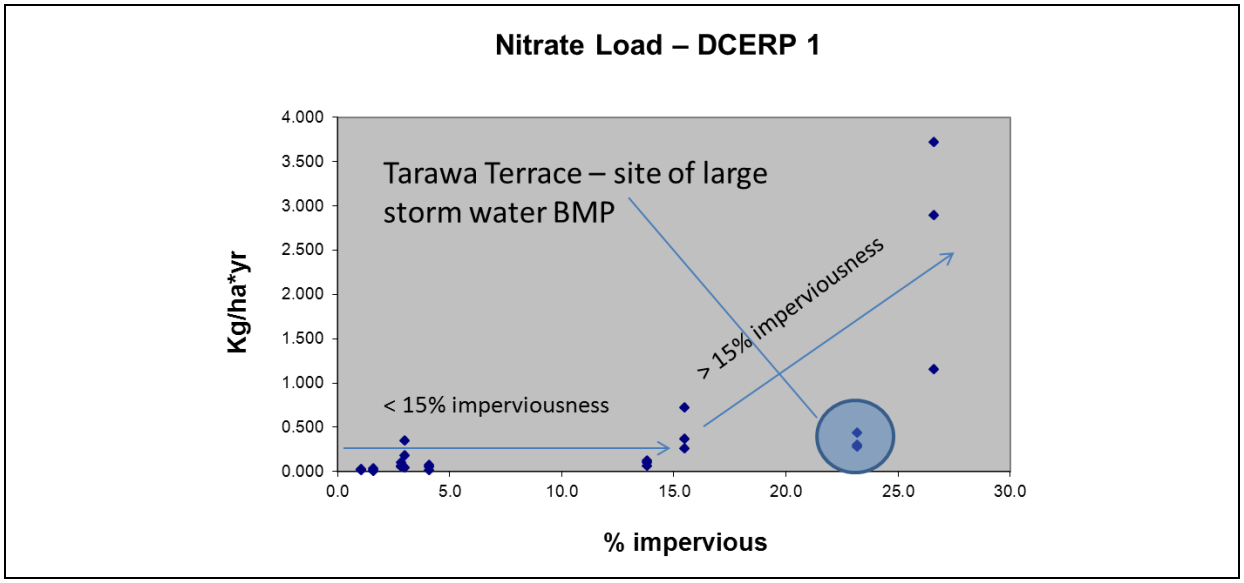

Figure 5-4. DCERP1 tributary creek loading of nitrate versus percent watershed imperviousness.

5.4.2 Methods

Using five creeks (see **Figure 5-5 and Table 5-2**) with watersheds on a development gradient from 3% to 63% developed and a wide range of imperviousness, we will measure sample concentration of carbon, nutrients, and suspended sediments for 2 years. We will deploy Teledyne Isco, Inc. automated water samplers equipped with YSI datasondes to continuously collect data. We will calculate loading of nutrients, sediments, and dissolved inorganic carbon (DIC) and DOC (including quantity of reactive carbon) from the sum of daily water volume based on 0.5-hour records of water velocity and level, which will be measured in monitoring activity AEM-2 and paired with nutrient, sediment, and carbon concentrations from monthly baseflow conditions and stormflow periods.

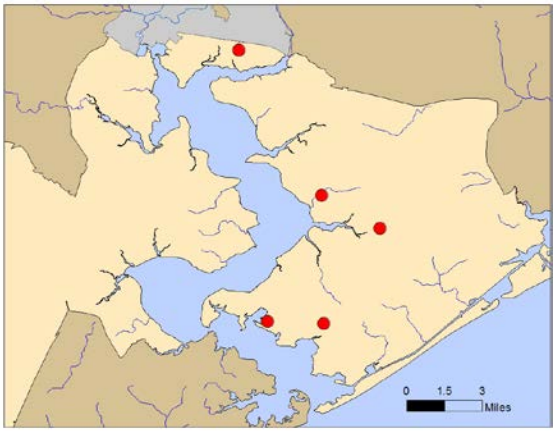

Figure 5-5. DCERP2 tributary creek research sites at MCBCL.

Water sampling will consist of manual sampling (water grab, water depth measurement, and water velocity confirmation using a Sontek Flowtracker Acoustic Doppler Velocimeter) every other week and after a rain event (defined as greater than 2.5 cm of rain in 24 hours). In addition, we will conduct more frequent automated sampling to enhance resolution during storm events

with automated samplers. We will program the samplers to trigger above a threshold stream velocity set for storms and at flow-paced intervals once enabled. We will collect automated grab samples as soon as possible after a rain event and will transport these on ice to the laboratory for processing. We will select water samples from the automated samplers to encompass a period, including before, rising, peak, and falling limbs of hydrographs, for each storm at each site. After we have collected the samples along those sections of the hydrograph, we will composite them (by equal volume) when multiples have been collected.

We will analyze all water samples collected for total suspended solids (TSS) and nutrients, including nitrate- plus nitrite-nitrogen (NO_3^-+NO_2^-, referred to as NO_x), ammonium-nitrogen (NH_4^+–N, referred to as NH_4), orthophosphate (PO_4^{3+}–P, referred to as PO_4), and total dissolved nitrogen (TDN). We will filter water samples through Whatman glass fiber filters (GF/F; 25 mm in diameter, 0.7-µm nominal pore size) and will analyze the filtrate with a Lachat Quick-Chem 8000 automated ion analyzer using standard protocols (Lachat Instruments, Milwaukee, WI NO_x Method 31-107-04-1-A; NH_4 Method 31-107-06-1-A; and PO_4 Method 31-115-01-3-G). We will filter additional water through pre-cleaned and dried Whatman glass fiber prefilters (GF/F; 47 mm in diameter, 0.7-µm nominal pore size) and will dry and weigh residue for measurement of TSS using standard protocols (Method 2540 D, 2-57 [APHA, 1998]). We will use a carbon, hydrogen, and nitrogen (CHN) analyzer to measure POC and will employ a total organic carbon (TOC) analyzer to measure DOC. For POC analysis, we will filter stormflow and baseflow water samples on 25-mm pre-combusted glass fiber filters and store the samples frozen in small, plastic Petri dishes. We will fume the filters with concentrated hydrochloric acid (HCl) for 6 hours and will allow them to dry before analyzing the filters on a CHN analyzer. For DOC analysis, we will filter water samples on 25-mm pre-combusted glass fiber filters. We will collect 5 mL of filtrate in a combusted glass scintillation vial and cap it with an acid rinsed, Teflon-lined cap. We will store the samples frozen on their side until analysis on a TOC analyzer. Quarterly, we will sample all streams for storm- and baseflow DIC concentrations. DIC samples will be acidified and analyzed on a Li-Cor CO_2 analyzer.

Table 5-2. Land Cover and Watershed Area Of Study Sites

Site	Forested Land (ha)	Impervious Surface (ha)	Developed Land (ha)	Total Area (ha)
Cogdel Creek	280.53	115.25 (13.8%)	209.16	835.83
French Creek	80.28	8.56 (1.1%)	27.72	807.30
Tarawa Terrace	24.48	32.28 (23.2%)	63.90	139.14
Courthouse Bay	3.06	4.85 (15.5 %)	19.62	31.32
Traps Bay	5.76	2.11 (4.13%)	6.39	51.03

We will separate stream loading into storm load, which occurs during rain events, and base load, which represents the groundwater contribution to the load. We will use a hydrograph separation method to divide the flow into stormflow and baseflow and to determine the relative contributions of stormflow and increased baseflow during storms to total flow during storms (**Figure 5-6**). In this method, we will manually inspect continuous flow data to determine storm events based on peaks in flow (Ward and Robinson, 2000). We will interpolate the baseflow during storm events between a point prior to the peak and after the peak to give a reasonable estimate for baseflow during storm conditions. Storm events increase shallow groundwater flow,

thus increasing baseflow. Sustained elevation of baseflow after-rain events was observed consistently throughout DCERP1. Because our sites are generally above the range of tidal influence, assessing the impacts of tidal elevation on the hydrograph is not routinely required. Analyzing base load and storm load separately will provide insight into the differences in loading that occur due to changes in land coverage that may influence flow patterns and runoff characteristics. We will use GIS to map calculated baseflow and stormflow loads and land use to link land management decisions to potential changes in material loading. We will determine functional measures of development, such as directly connected impervious area (Roy and Shuster, 2009), and evaluate these as drivers of change in loading patterns and magnitudes. These data will allow us to determine the load of carbon, nutrients, and suspended sediments from MCBCL to the NRE with specific details on the effects of MCBCL land use and management.

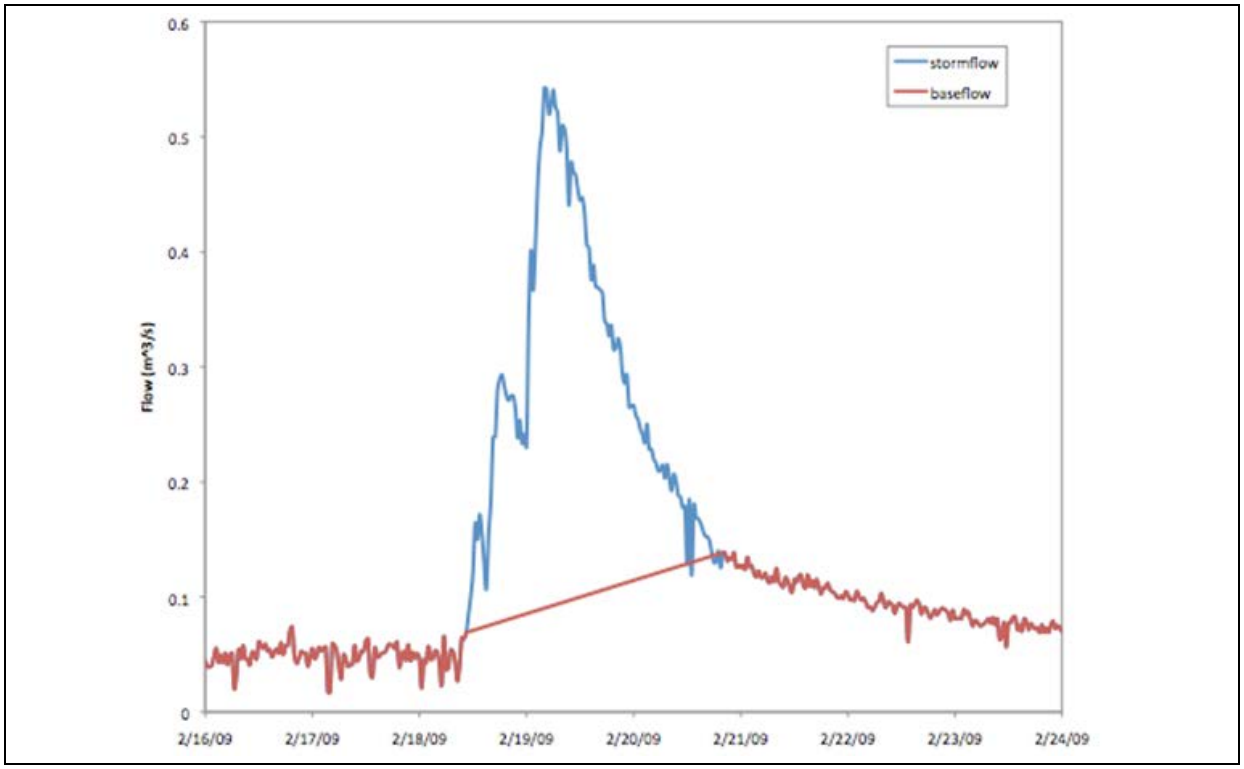

Figure 5-6. A hydrograph depicting the graphical separation technique used to isolate stormflow and baseflow components of flow.

For all portions of this study, we will conduct analyses to determine not only the quantity of carbon loaded, but also to determine the reactivity of the carbon. We will run bioassays with POC that will measure oxygen consumption to assess the reactivity of carbon (Richardson, 2008). We will also run DOC assays in conjunction with Research Project AE-6. We will incubate filtered water with an inoculum of native bacteria and will assess the disappearance of DOC from 2–28 days. These data will allow us to determine any differences in biological availability of the load of carbon from MCBCL watersheds to the NRE.

We will assess stream thermal loading through 2 years at five streams using previously collected flow data as previously described and continuous temperature measurements that will be made at

each station. We will separate base loading and storm loading as previously described. We will compare thermal loading patterns to watershed imperviousness, forested area, and other measures of development to determine the likely causes of differences in loading from the five streams. Our study streams flow directly into the NRE, potentially leading to increased estuarine temperatures in streams with increased thermal load. Due to the economic and ecological importance of estuaries, and the impacts that increased temperatures can have on their ecosystem services by affecting variables such as disease prevalence or species distributions (Najjar et al., 2000), it is valuable to understand the effects of land-use changes on coastal stream thermal loading. We will provide temperature and thermal loading data to Research Project AE-6 to inform the design of their temperature manipulation experiments.

During Years 3 and 4 of DCER2, in collaboration with Research Project T-3, we will make targeted deployments at forested streams in land areas subjected to midstory and understory thinning and burning for RCW habitat enhancement. In managed and reference watersheds, we will gauge streams as previously described and will record base loading and storm loading of carbon, nutrients, and sediments as previously detailed. We will also assess the condition of the stream beds, including riparian vegetation and coarse woody debris. Stream loading data will provide an export term for carbon, nutrients, and sediments under varied forest management regimes.

We will evaluate stormwater BMP function through targeted deployment of the flow and water sampling array previously described. We will determine the mass balance of materials (nutrients, sediments, and carbon) entering and leaving study structures. We intend to determine the range of stormwater BMPs present on Base and to sample a range of the most common types. We believe there will likely be variability in dissolved carbon, for example, related to BMP design. Open long-residence time devices that retain water may have the potential to be a source of new carbon, for example. We plan an extended deployment at a stormwater detention structure in one of our study watersheds. Analyses and calculations will be identical to those previously described. We will compare the loading from the subwatershed with the BMP to a less developed reference site. We will also collect grab samples at a range of BMPs in several watersheds during baseflow and stormflow conditions to provide a broader examination of the extent to which the engineering solution has reduced excessive loading of nutrients, suspended solids, and carbon to the concentrations observed in less developed watersheds. Understanding not only the function of coastal stormwater BMPs as engineering solutions, but also their role in the broader context of coastal landscape biogeochemistry are ongoing and important research focuses.

5.4.3 Assessment of Climate Change Impacts

Research Project AE-5 will measure tributary stream thermal loading, assessing the impacts of land uses (e.g., training ranges, managed forest lands, developed lands), and determining the ecological significance of variable thermal loads. Additionally, we will quantify freshwater discharge and loading of dissolved and particulate carbon, suspended solids, and dissolved nutrients during baseflow and stormflow conditions for various land uses. These data will permit predictions about the interactive effects of increased storminess and land-use change on freshwater supplies and material loading to the estuary. We will also continuously gather salinity data at each tributary creek site to allow for a detailed assessment of the salinity regime and the ability to detect the possible impacts from increases in storminess and sea level rise. Research

Project TSP-2 will also use stream loading data to help model future changes in the estuary, including potential climate change, using the ESM.

5.4.4 Milestones

1. Quantify material (carbon, nutrient, and sediment) loading from five target creeks 3/2013–1/2015
2. Map watershed land cover and carbon, nutrient, and suspended solids loading 2/2014–2/2015
3. Map watershed land use and carbon, nutrient, and suspended solids load 2/2014–2/2015
4. Quantify material loading from stormwater BMPs 2/2014–2/2016
5. Quantify material loading from targeted managed forests 2/2015–2/2017
6. Map management practices (forestry and stormwater) and measured loads (see 3 and 4 above) 2/2016–6/2017
7. Develop a report that translates loading information for a range of land uses to MCBCL managers 6/2017
8. Prepare and deliver final Research Report 9/2017

5.4.5 Deliverables

1. Deliver GIS maps linking land use and land cover to carbon, nutrient, and suspended solids loading 3/2015
2. Contribute to the development of a carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5) Draft 3/2015; final 3/2017
3. Deliver GIS maps linking forestry and stormwater management to carbon, nutrient, and suspended solids loading 6/2017
4. Deliver report that translates carbon, nutrient, and suspended solids loading information to a range of land uses to MCBCL managers 6/2017
5. Prepare and deliver final Research Report Draft 3/2017; final 9/2017

5.4.6 Planned Publications

Submit a journal article in fall 2014 on the role of coastal creeks in modulating estuarine water quality. This article will detail nutrient, TSS, and carbon loading from coastal streams in our study and discuss implications for water quality resulting from watershed-specific distinctions in the delivery of these materials.

5.5 Research Project AE-6: Climatic Drivers Regulating Benthic–Pelagic Carbon and Associated Nutrient Exchanges in the New River Estuary

Lead Investigator: Dr. Iris C. Anderson (VIMS)

Supporting Researchers: Drs. Mark Brush (VIMS), Craig Tobias (UCONN), Brent McKee (UNC-CH), Scott Ensign (AquaCo), Carolyn Currin (NOAA)

Technical Objectives/Goals:
This research will assess the role of climatic drivers and nutrients in regulating estuarine carbon metabolism, exchanges, and burial. Research Projects AE-6, AE-4, AE-5, CW-4, CW-5, and CB-5 will all contribute to the development of a net carbon budget for the estuarine and coastal regions of MCBCL. We will use data collected by Research Project AE-6 to validate the ESM as part of Research Project TSP-2, which is used to predict estuarine responses to current and future climate change and for developing management decision-support tools.

Research Questions:

1. At the estuarine-wide scale, what are the annual net benthic–pelagic exchanges of carbon, nitrogen, and phosphorus (this will build on data collected during DCERP1)?
2. Based on diel variations in DIC, DO, and ^{18}O signatures, what is the net metabolic status (autotrophy versus heterotrophy) of the shallow estuarine zone of the NRE?
3. How do air–water pCO2 exchanges in the shallow estuarine zone vary spatially (along the estuary) and temporally at diel, seasonal, and inter-annual scales?
4. How do the sources and fates of POC and DOC derived from the NRE watersheds vary temporally and spatially?
5. What are the metabolic and nutrient flux responses of the shallow zone to climatic drivers (e.g., fresh water delivery [salinity]) and temperature (based on controlled experimental manipulations)?

5.5.1 Background

The NRE is a shallow, microtidal, lagoonal system with a long average flushing time (64 days) and more than half of the estuary has water depths less than 2 m (msl). In such systems, light, nutrients (nitrogen and phosphorus), temperature, and salinity regulate net ecosystem metabolism (NEM), which determines to a large extent the partitioning of carbon between respiration, burial, and exchanges with the atmosphere, sediments, and coastal ocean (Caffrey, 2004; Gazeau et al., 2005; Kennish and Paerl, 2010; Paerl et al., 2010a; Raymond et al., 2000). Data collected during DCERP1 demonstrated that delivery of carbon, nitrogen, and phosphorus in dissolved and particulate forms from external sources (e.g., watersheds) to the estuary were strongly affected by freshwater delivery during episodic (e.g., storms) and chronic (e.g., drought) events and, in turn, regulated both benthic and pelagic gross primary production (GPP) (Peierls et al., 2012). The fate of carbon, nitrogen, and phosphorus derived from external sources depends on the sources and lability of the organic components and uptake of inorganic components by benthic and pelagic primary producers, provided that sufficient light is available (Kemp et al., 1997 and 2005). As planktonic biomass moves down-estuary and settles to the sediment surface, it is recycled by benthic microorganisms to organic and inorganic forms of carbon, nitrogen, and phosphorus, some of which may be sequestered in the benthos by benthic microorganisms and eventually buried, some released to support planktonic production, and some exchanged with the atmosphere and ocean (Anderson et al., 2010; Crosswell et al., 2012, in press; Hardison et al., 2011; Nixon, 1986; Zimmerman and Canuel, 2000). In the shallow NRE, the benthos plays an important role in mitigating the effects of nutrient enrichment. Data collected during DCERP1 demonstrated that the NRE is moderately eutrophic with the benthos contributing more than 40%

of the total production for the entire estuary. The effectiveness of the benthic filter for nutrient and carbon sequestration is determined primarily by light availability and a variety of physical variables such as wind, residence time, and temperature (Anderson et al., 2010; McGlathery et al., 2007; Sundbäck et al., 2004). A net autotrophic system will either sequester organic carbon as POC in sediments or export it as POC and DOC to the ocean, whereas a net heterotrophic system will be a source of CO_2 to the atmosphere and DIC to the coastal ocean (Cai, 2011; Hopkinson and Smith, 2005). Macrotidal and large estuaries have generally been thought to be net heterotrophic because of the processing of external dissolved organic matter (DOM) (Caffrey, 2004; Gazeau et al., 2005; Smith and Hollibaugh, 1997; Staehr et al., 2012). However, much less is known about NEM in microtidal, shallow, lagoonal systems such as the NRE, which may be representative of up to half of the estuarine surface area in the United States (NOAA, 2011). Shifts toward net heterotrophy due to natural or anthropogenic disturbances are likely to result in reductions in water and sediment quality with increased occurrences of hypoxia or anoxia and potential impacts on higher trophic levels.

One of the major goals of DCERP2 is to develop a net carbon budget for the estuarine and coastal regions of MCBCL in the context of climate change. Research Project AE-6 will contribute to this budget, along with Research Projects AE-4, AE-5, CW-4, CW-5, CB-5, and TSP-2 and monitoring activities AEM-1, AEM-2, and AEM-3. The measurements necessary to produce the carbon budget are shown in **Figure 3-3** (see Section 3.3.2) and include inputs of DOC, DIC, and POC from watersheds, tributaries, marshes, and shoreline erosion; estuarine and marsh metabolism, including primary production and respiration; exchanges of pCO_2 between the estuary, marshes, and the atmosphere; and exchanges of DOC, DIC, and POC between the estuary and coastal ocean. Researchers from Research Projects AE-4 and AE-6 will work closely to determine estuarine-wide net exchanges of CO_2 between the water column and atmosphere and metabolic responses (primary production and respiration) to changes in freshwater discharge, nutrient inputs, and temperature. Research Project AE-6 will focus on the shallow zone around the periphery of the estuary where light may reach the benthos supporting benthic autotrophy and nutrient uptake, whereas Research Project AE-4 will sample primarily in the deeper channel zone of the NRE. Research Project AE-6 will also work with Research Project AE-5 to test the lability of DOC and DON during their transport from the head of estuary at Jacksonville (in North Carolina) and from MCBCL impacted tributaries through the estuary. A major potential sink for carbon in the NRE is burial in sediment. Research Project AE-6 will work with Research Projects CW-4 and CB-5 to collect cores throughout the estuary, marshes, and barrier islands. The core sections will be dated using geochronological methods (McKee, UNC-IMS), analyzed for carbon sources using biomarkers and stable isotopes (Tobias, UCONN), and analyzed for bulk properties (Anderson, VIMS). As carbon data (sources, sinks, and transformations) are determined by the various modules (Aquatic/Estuarine, Coastal Wetlands, and Coastal Barrier), individual carbon budgets for the estuary, marshes, and barrier island will be developed. These individual module budgets will then be summed to create a final net estuarine/coastal carbon budget, which will be compared to the carbon budget modeled using the ESM (Research Project TSP-2).

A second major objective of DCERP2 is to identify estuarine responses to climate change. Climate warming is predicted to have many impacts on both physical factors (e.g., stratification, freshwater discharge, light availability, nutrient loads, solubility of gases in the water phase) and biological factors (e.g., the timing and composition of phytoplankton blooms, community

composition, microbial nutrient cycling rates, benthic and pelagic organic matter decomposition, and ecosystem metabolism; Canuel et al., 2012; Fulweiler and Nixon, 2009; Harley et al., 2006; Nixon et al., 2009; O'Connor et al, 2009; Weston and Joye, 2005). Although primary production is expected to increase as a function of temperature, the response will depend upon resource availability, which is expected to vary along with temperature change. However, we expect that rates of respiration will increase faster than production resulting in increased net system heterotrophy relative to autotrophy (O'Connor et al., 2009). In addition to warming, climate change is predicted to change estuarine salinity, either due to sea level rise or to increased storminess and accompanying freshwater discharge. Salinity has been observed to impact rates of organic matter decomposition, nutrient cycling, and increase fluxes of ammonium from sediments (Giblin et al., 2010; Neubauer and Craft, 2009; Weston et al., 2011). To obtain more detailed information on specific responses of the benthos to the variables most likely to change in the NRE in response to climate, a mesocosm study will be performed by Research Project AE-6 that will assess the impacts of various combinations of elevated temperature (2°C and 5°C above ambient) and salinity on benthic metabolism (e.g., benthic primary production and respiration) and nutrient fluxes. An additional experiment run in collaboration with Research Project AE-4 will determine responses of phytoplankton primary production and total ecosystem metabolism to changes in temperature at end member sites in the upper and lower estuary. Rate process data generated during these experiments will be used to verify predicted NRE responses to climate change (increased temperature and changes in freshwater inputs and therefore salinity) simulated with the ESM as part of Research Project TSP-2.

5.5.2 Methods

5.5.2.1 Estuarine–wide Effectiveness of the Benthic Filter

To scale benthic processes to system-wide estimates for the entire estuary, we will measure benthic metabolic and nutrient cycling process rates, which include nutrient fluxes, autotrophic nitrogen demand, gross nitrogen mineralization (MIN), nitrogen fixation (NFix), and denitrification (DNF) on sediment cores sampled at representative water depths across the entire estuary in the fall. As conducted in the summer and spring (July 2010 and April 2011, respectively) during DCERP1, sediment cores will be collected at sites in the upper, middle, and lower regions of the NRE at three different water depths (approximately 0.5 m, 1.5 m, and 3 m msl) (**Figure 5-7**). To determine benthic metabolism and nutrient fluxes, three sediment mesocosm cores (clear acrylic, 6.5-cm inner diameter × 30-cm tall, 10-cm sediment depth) will be collected at each of the nine sites (three depths per each of three regions [27 cores total]). After returning from the field and prior to starting the incubations, overlying water from the cores will be removed and replaced with filtered site-specific water to measure benthic processes only. Site water will be filtered through a series of 142-mm glass fiber filters, GF/D (2.7 µm), and GF/F (0.7 µm), followed by polyethersulfone (0.2 µm). The cores used for the benthic metabolism and nutrient fluxes will be incubated in fiberglass chambers filled with water taken from the specific sampling station at in situ temperature and light. Cores collected from the 1.5-m and 3-m water depths will be covered with shade cloth to attenuate light to levels as similar as possible to in situ conditions. Samples will be taken from the benthic flux cores at dawn, dusk, and the following dawn for determinations of DIC, dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP), and dissolved organic nitrogen (DON). At the end of the flux experiments, additional samples will be collected for benthic chl *a*. Water

samples will be processed and analyzed as listed in **Table 5-3**, and metabolic rates (GPP, respiration, and net community metabolism), nutrient fluxes, and autotrophic nitrogen demand will be calculated as described by Anderson et al. (2003). Nitrogen gross MIN will be measured in laboratory incubations using a $^{15}NH_4^+$ isotope-pool dilution technique (Anderson et al., 2003) with 10 sediment cores collected at each of the nine sites (5.7-cm ID × 20-cm tall, 10 cm of sediment; 90 cores total). Measurements of NFix will be made using the acetylene reduction method, assuming a ratio of 4 moles of acetylene reduced to 1 mole of N_2 fixed. The 0- to 1-cm subsection of five sediment cores per site (45 cores total) will be collected and incubated aerobically in the light and dark in 60-mL serum bottles amended with 15 mL of acetylene for 6 hours at ambient water temperature. Ethylene will be measured by flame ionization gas chromatography. For DNF, three sediment cores (17-cm sediment × 7.5 cm in diameter, approximately 400-mL water column) will be collected from the 0.5 m and 3.0 m depth contours of the upper, middle, and lower estuary (six sites; 18 cores total). In collaboration with Dr. Michael Piehler (UNC-IMS), DNF will be determined in flow-through cores held in the dark, with analysis of N_2/argon by membrane inlet mass spectrometry, as described by Piehler and Smyth (2011).

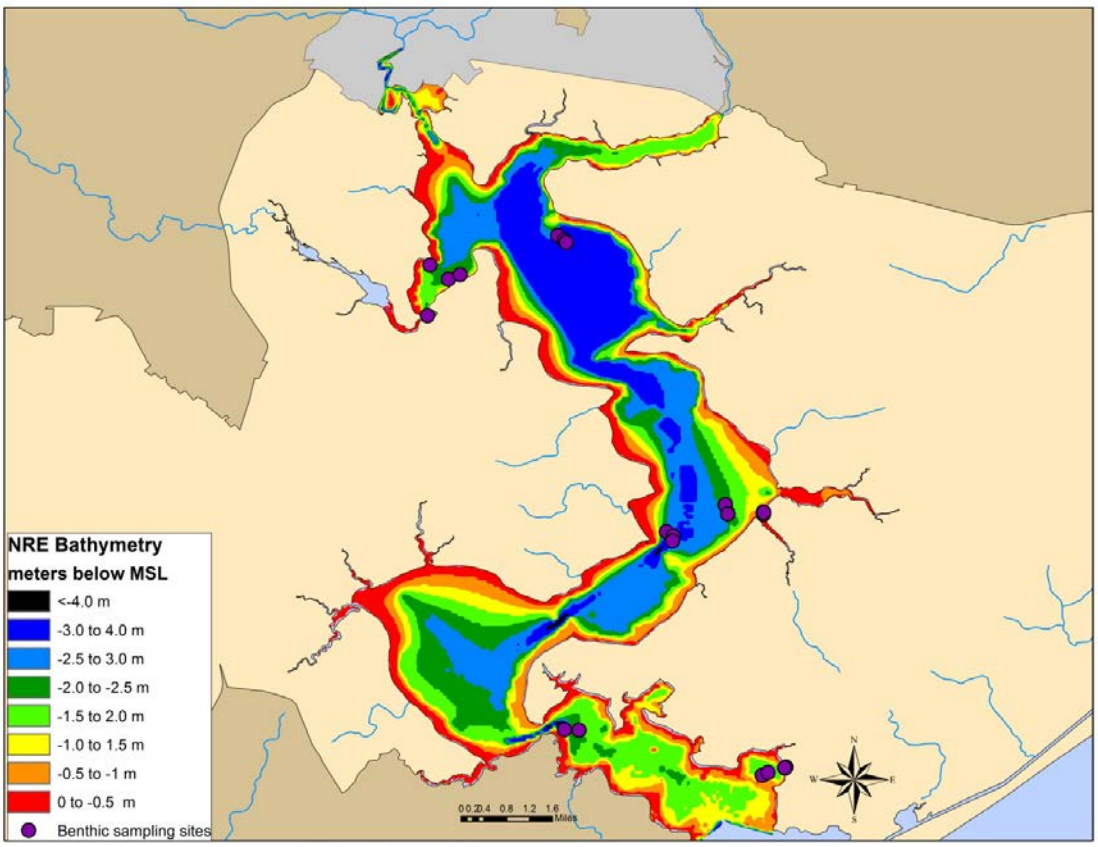

Figure 5-7. NRE bathymetry (North American Vertical Datum of 1988 [NAVD 88]) and depth experiment benthic sampling stations in the upper, middle, and lower regions of the estuary.

The NAVD 88 to msl offset is +0.01 m for the Wilmington, NC, Center for Operational Oceanographic Products and Services (CO-OPS) station #8658120 (National Tidal Datum Epoch of 1983–2001; NOAA, 2004).

Table 5-3. Summary of nutrient and carbon analytical methods

Analyses	Methods/Instrument	References
Nitrate, nitrite	Cadmium reduction/diazotization; Lachat[a]	Smith and Bogren, 2001
Ammonium	Phenol hypochlorite method; Lachat[a]	Liao, 2001
Dissolved inorganic phosphorus (phosphate)	Molybdate method; Lachat[a]	Knepel and Bogren, 2001
Total dissolved nitrogen (TDN)/ dissolved organic nitrogen (DON)	Alkaline persulfate digestion; Lachat[a]	Koroleff, 1983
Dissolved inorganic carbon (DIC)	Acidification to CO_2; LI-6252 CO_2 analyzer	Neubauer and Anderson, 2003
Dissolved organic carbon (DOC)	680°C catalytically aided combustion oxidation/non-dispersive infrared detection; Shimadzu TOC-V analyzer	

[a] The Lachat auto analyzer (QuikChem 8000 Automated Ion Analyzer, Lachat Instruments, Loveland, CO) is a continuous flow automated analytical system that complies with U.S. Environmental Protection Agency standards.

5.5.2.2 Estimation of Air–Water CO_2 Exchanges and Net Metabolic Status (Autotrophy Versus Heterotrophy) in the Shallow Estuarine Zone Based on Diel Variations in DIC, DO, and ^{18}O Signatures

Estuarine-wide net exchanges of CO_2

To determine estuarine-wide net exchanges of CO_2 between the water column and atmosphere and metabolic responses to changes in freshwater discharge, nutrient inputs, and temperature in the shallow water zone, we will continuously measure the pCO_2 in the surface water along the shallow shoreline bimonthly, using a pCO_2–Dataflow system, as described for Research Project AE-4. In summary, the Dataflow system is a small boat-based flow-through series of instruments that collect continuous measurements (approximately every 30 m or 2 seconds) of surface water pCO_2, DO, in vivo chlorophyll, turbidity, CDOM, salinity, and temperature. Dataflow uses a pCO_2 analyzer, as described by Crosswell et al. (2012); a YSI 6600 multiparameter datasonde, WET Labs's CDOM sensor, a Garmin global positioning system (GPS), and a LabVIEW data acquisition system. The shoreline transect will be conducted at dawn, dusk, and the following dawn in parallel with a main channel transect, performed by Research Project AE-4, to assess both diel and lateral variability of measured parameters. In addition, samples for analysis of POC, particulate nitrogen, DIC, and pH will be collected in triplicate at six stations along the Dataflow transects to constrain auxiliary carbon cycle parameters. This is critical information needed for producing an estuarine-wide carbon budget and scaling instantaneous measurements to daily and longer scales.

To be assured that estimates of diel variations in pCO_2 based on measurements made during dawn, dusk, and dawn Dataflow cruises along the shoreline of the NRE are representative of actual diel variation, team members from Research Projects AE-4 and AE-6 will perform intercomparisons between the Dataflow measurements and those using fixed systems, which log pCO_2 at 15-minute intervals throughout the day. The fixed systems will be deployed concurrently in the channel zone, attached to the upper estuarine AVP, and close by in the shallow zone. These systems will measure pCO_2 (Li-Cor, Model 840 infrared gas analyzer), as described in Crosswell et al. (2012), salinity, DO, temperature, pH, depth (YSI, Model 6600

datasonde) and PAR. Depending upon the variability observed both in the Dataflow data and fixed station data, additional deployments may be necessary at other locations within the estuary. All sampling efforts by Research Projects AE-4, AE-5 and AE-6 will be coordinated to minimize temporal and spatial uncertainty and thereby support the model projections of Research Project TSP-2 as a tool to guide management decisions. These measurements will be used to calculate physical and biogeochemical carbon fluxes to assess the environmental controls on the carbon cycle of the NRE. To facilitate the integration of data from Research Projects AE-4, AE-5, and AE-6 into a unified carbon budget, all three modules will use similar analytical and data analysis methodologies.

Determinations of daily net ecosystem metabolism, gross primary production, and respiration

Currently, there is a great deal of controversy concerning the most accurate way to measure net ecosystem metabolism, GPP, and respiration (Caffrey, 2003; Giordano et al., 2012; Hopkinson and Smith, 2005; Kemp et al., 1997; Kemp and Boynton, 1980; Maher and Eyre, 2012; Staehr et al., 2012). During DCERP1, measurements were made at the square-meter scale using the component method, in which metabolism is measured based on fluxes of DIC and DO in sediment plus water cores and in water cores alone. Alternatively, metabolism on a larger scale can be measured using the Open Water method, in which DO is monitored continuously in situ using a YSI model 6600 datasonde with corrections for air–water exchanges. In DCERP2, metabolism will be calculated based on DO data collected by monitoring activity AEM-3 using the Open Water method (Caffrey, 2003) and corrected for air–water gas exchange as described is Section 5.3 (Research Project AE-4) and using the parameterization for gas transfer velocity as described in Jiang et al. (2008), unless alternative estuarine gas transfer parameterizations are then available. YSI model 6600 datasondes with Li-Cor PAR sensors will be deployed bimonthly at three sites in the upper, middle, and lower NRE for week-long periods and after storm events (to be conducted by Dr. Ensign of AquaCo). Validation of the Open Water method for calculating metabolism will be conducted using additional data on diel changes in DIC concentrations measured bimonthly during dawn, dusk, and dawn Dataflow cruises and corrected for air–water exchange (see above; Maher and Eyre, 2012; Staehr et al, 2012), and on changes in ^{18}O natural abundance (to be conducted by Dr. Tobias, UCONN) measured in water samples collected seasonally over diel cycles, as described by Tobias et al. (2007).

5.5.2.3 Sources and Lability of POC and DOC

Sources of carbon to the NRE

Contributions of marine, terrestrial, and marsh particulate and DOC to the NRE will be determined based upon ^{13}C natural abundance (Peterson, 1999; Peterson et al., 1985). Water samples will be collected seasonally from the shallow water zone of the upper, middle, and lower regions of the NRE and from mouths of creeks included in Research Project AE-5. For POC isotopic analyses, water samples will be filtered onto pre-combusted (500°C for 5 hours) glass fiber filters (0.7–µm pore size) to concentrate particles and acidified to remove inorganic carbon. Filters will be analyzed in Dr. Tobias's (UCONN) laboratory using an isotope ratio mass spectrometer (IRMS) coupled to an elemental analyzer. For DOC isotopic analysis, water samples will be filtered (Gelman Supor, 0.45 µm), preserved with 85% phosphoric acid (H_3PO_4), and lyophilized prior to analysis by IRMS in Dr. Tobias's laboratory.

Lability of DOM

The lability of DOC and DON will be determined in month-long incubations of filtered water with added bacterial inoculum (McCallister et al., 2006; Wiegner et al., 2006). Water samples will be collected seasonally from the shallow water shoreline and creeks in the upper, middle, and lower NRE in conjunction with Research Project AE-5 and filter-sterilized through a 0.5-µm polypropylene canister filter in the field and 0.2-µm polyethersulfone filter in the laboratory to remove bacteria and nanoflagellates (less than 6 hours after field collection). An additional water sample from each station will be collected and filtered through a pre-combusted (500°C for 5 hours) glass fiber filter to serve as a bacterial inoculum. The inoculum will be added to the respective filter-sterilized water and incubated at in situ temperature in the dark in an environmental chamber. Water samples will be taken at timed intervals over the 4 weeks to determine changes in DON, DOC, and DIN concentrations. All nutrient analyses will be performed as listed in **Table 5-3.**

5.5.2.3 Responses to Climate Change in the NRE

Experimental manipulation to determine responses to temperature and salinity variations in the NRE

Responses in both the benthic and pelagic zones to shifts in salinity and temperature due to acute weather events in the NRE in experimental manipulations performed in mesocosms as described in **Table 5-4**. Coefficients derived from these short time–scale experimental manipulations will be used in the ESM to predict responses to longer term climate change. To measure effects on benthic processes, sediment cores sampled seasonally from the shallow water zone of the upper and lower estuary will be exposed to water with salinities adjusted to represent the maximum and minimum salinities to which that portion of the estuary is typically exposed. Temperatures will be varied (ambient, +2°C, +5°C), to represent conditions predicted by Najjar et al. (2010) for the mid-Atlantic area of the United States. Sediment cores will be collected in triplicate for each treatment block from each site (36 cores total). Prior to beginning the incubations, overlying water in the cores will be replaced with ambient water or mixtures of fresh river water with high nutrients plus CDOM and inlet water with low nutrients and CDOM. The salinities of the mixtures will be based on observed seasonal data collected during DCERP1 from 2008–2011, in which salinities varied from 1.5 ppt to 25.7 ppt in the upper estuary and 21.6 ppt to 39.1 ppt in the lower estuary. To focus on benthic processes, phytoplankton will be removed from site water by filtration through a series of 142-mm filters: GF/D (2.7 µm), GF/F (0.7 µm), and polyethersulfone (0.2 µm). Cores will be incubated at ambient temperature and ambient +2°C and +5°C to simulate climate warming in an environmental chamber at in situ light levels. Water samples taken from the sediment cores during incubation will be processed and analyzed for DO, DIC, DIP, DON, and DOC as described in **Table 5-4**. Metabolic and nutrient flux rates will be calculated as described by Anderson et al. (2003).

Table 5-4. Two-way factorial experimental design of temperature and salinity for experimental manipulation of sediment cores (n=3 per block per site)

Ambient Temperature/Ambient Salinity	Ambient Temperature/Different Salinity
Ambient + 2°C/ambient salinity	Ambient + 2°C/different salinity
Ambient + 5°C/ambient salinity	Ambient + 5°C/different salinity

To further determine the effects of climate warming on both pelagic and whole system (benthic+pelagic) processes, sediment cores and water will be collected from the shallow water zone of the upper and lower NRE and exposed to varied temperatures (ambient, +2ºC, +5ºC), in collaboration with Research Project AE-4. Sediment cores and water column only cores will be incubated in triplicate for each temperature level and site as previously described, except water will be unfiltered (18 sediment cores total; 18 water column cores). In addition, to the analyses previously described, water column samples will be taken for analyses of chl *a*.

Long-term sequestration of carbon by burial in sediments

In collaboration with Research Projects CW-4 and CB-5, annual to decadal burial of carbon and nitrogen, derived from phytoplankton, terrestrial, and marsh sources, in estuarine sediments will be determined by geochronological methods (conducted by Dr. McKee at UNC using ^{210}Pb and ^{137}Cs) in cores collected throughout the NRE. In addition, bulk properties (bulk density and porosity conducted by Dr. Anderson at VIMS), organic carbon and total nitrogen content, and bulk+compound specific ^{13}C analyses (conducted by Dr. Tobias at UCONN) (Bianchi et al., 2011) will be performed on subsections of each core. Geochronology will be established as described by Research Project CB-5 (Section 7.4), using the downcore distribution of excess ^{210}Pb activities and by assigning a date of 1964 to the ^{137}Cs impulse peak (DeMaster et al., 1985). Dr. Tobias (UCONN) will examine both the temporal and spatial distribution of terrestrial and marine biomarkers, as well as the bulk and compound-specific stable carbon isotopes. Lignin-phenol monomers and dimers, as well as cutin, will be measured via CuO oxidation of sediments and subsequent gas chromatography–isotope ratio mass spectrometry (GC-IRMS) analysis. Lipid classes will be measured via extraction and saponification of sediments and also by analysis with GC-IRMS. Bulk carbon isotopes will be quantified with an elemental analyzer– isotope ratio mass spectrometer (EA-IRMS; Barrett et al., 1995; Bianchi, 2007; Bianchi and Canuel, 2011; Bianchi et al., 2011; Bosak et al., 2008; Canuel et al., 1995; Ertel and Hedges, 1984; Goñi and Eglinton, 1996; Goñi and Hedges, 1990; Hedges and Ertel, 1982; Volkman, 2006).

5.5.3 Assessment of Climate Change Impacts

Responses of the NRE to drivers expected to vary with climate change will be evaluated at time scales varying from diel to annual to century-long. Short-term variability will be determined by experimental manipulations of the key parameters most likely to drive biological responses in the NRE (e.g., temperature, salinity). A mesocosm study will be performed to assess the impacts of various combinations of elevated temperature (2°C and 5°C above ambient) and salinity (observed extremes) on benthic metabolism (e.g., benthic primary production and respiration) and nutrient fluxes. In conjunction with Research Project AE-4, an additional mesocosm study will be performed to determine ecosystem and pelagic metabolic responses to temperature in the upper and lower estuary. In addition, Research Projects AE-4 and AE-6 will collaborate in measuring spatial and temporal variations of pCO_2 throughout the estuary, on both short time scales (diel) and longer time scales (annual), and in response to episodic storm events. The pCO_2 data collected in parallel with metabolic process rate data over daily to annual time scales will allow us to determine responses to nutrient loading, freshwater discharge, and seasonality, all of which are predicted to vary in response to climate change. Carbon sequestration at century-long time scales through analyses of geochronology, isotopic, and biomarker signatures in cores taken throughout the estuary in collaboration with Research Project CB-5. These data will allow us to

relate long-term changes in land use (e.g., establishment of MCBCL) and climate to carbon burial. Data generated by Research Projects AE-4, AE-5, and AE-6 together will allow us to calibrate and verify the carbon cycle as modeled by the ESM in Research Project TSP-2 based upon current conditions, and through scenario testing with the ESM, allow us to forecast estuarine responses to long-term changes in climate.

5.5.4 Milestones

1. Complete scaling of benthic processes to estuarine-wide scale 12/2014
2. Determine sources and fates of particulate organic matter and DOM 12/2016
3. Estimate air–water pCO_2 exchanges 12/2016
4. Determine NEM in near-shore environments 1/2017
5. Complete analysis of experimental manipulation studies 5/2017
6. Prepare and deliver Final Report 9/2017

5.5.5 Deliverables

1. Deliver Microsoft PowerPoint slides and present posters at the Coastal Estuarine Research Federation Conference 12/2013
2. Deliver Microsoft PowerPoint slides and present posters at the Coastal Estuarine Research Federation Conference 3/2014
3. Contribute to the development of a carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5) Draft 3/2015; final 3/2017
4. Deliver Microsoft PowerPoint slides and present posters at the Coastal Estuarine Research Federation Conference 12/2015
5. Deliver GIS maps of pCO_2 and water quality from Dataflow 12/2016
6. Deliver final report Draft 3/2017; final 9/2017

5.5.6 Planned Publications

Submit a journal article that discusses the scaling of benthic processes to estuarine-wide scale. The submission of this article is planned for December 2015.

5.6 Literature Cited

Alexander, R.B., P.J. Johnes, E.W. Boyer, and R.A. Smith. 2002. A comparison of models for estimating the riverine export of nitrogen from large watersheds. *Biogeochemistry 57/58*:295–339.

Alin, S.R., F. Maria de Fátima, C.I. Salimon, J.E. Richey, G.W. Holtgrieve, A.V. Krusche, and A. Snidvongs. 2011. Physical controls on carbon dioxide transfer velocity and flux in low-gradient river systems and implications for regional carbon budgets. *Journal of Geophysical Research 116*(G1):G01009.

Anderson, I.C., J.W. Stanhope, A.K. Hardison, and K.J. McGlathery. 2010. Sources and fates of nitrogen in Virginia coastal bays. Pp. 43–72 in *Coastal Lagoons: Critical Habitats of Environmental Change*. Edited by M. Kennish and H. Paerl. CRC Marine Science Series. Boca Raton, FL: CRC Press.

Anderson, I.C., K.J. McGlathery, and A.C. Tyler. 2003. Microbial mediation of "reactive" nitrogen in a temperate lagoon. *Marine Ecology Progress Series 246*:73–84.

APHA (American Public Health Association). 1998. *Standard Methods for the Examination of Water and Wastewater*. 20th edition. Edited by L.S. Clesceri, A.D. Eaton, A.E. Greenberb. American Public Health Association. 1,220 pages.

Band, L, and D. Salveston [Eds.]. 2009. *Climate Change Committee Report*. UNC-Chapel Hill Institute for the Environment. University of North Carolina at Chapel Hill, Chapel Hill, NC. 180 pages.

Barrett, S.M., J.K. Volkman, G.A. Dunstan, and J.M. Leroi. 1995. Sterols of 14 species of marine diatoms (*Bacillariophyta*). *Journal of Phycology 31*:360–369.

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, and I.M. Held. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science 327*(5964):454–458.

Bianchi, T.S. 2007. *Biogeochemistry of Estuaries.* New York: Oxford University Press, New York.

Bianchi, T.S., and E.A. Canuel. 2011. *Chemical Biomarkers in Aquatic Ecosystems.* Princeton and Oxford: Princeton University Press.

Bianchi, T.S., L.A. Wysochi, K.M. Schreiner, T.R. Filley, D.R. Corbett, and A.S. Kolker. 2011. Sources of terrestrial organic carbon in the Mississippi plume region: Evidence for the importance of coastal marsh inputs. *Aquatic Geochemistry 17*:431–456.

Birgand, F., T.W. Appelboom, G.M. Chescheir, R.W. Skaggs, and J.W. Gilliam. 2006. Evaluation of time proportional sampling strategies for estimating annual nutrient fluxes at the outlets of coastal plain watersheds. Pp.208–217 in *Proceedings of the American Society of Agricultural and Biological Engineers*, New Bern, NC.

Boesch, D.F., E. Burreson, W. Dennison, E. Houde, M. Kemp, V. Kennedy, R. Newell, K. Paynter, R. Orth, and W. Ulanowicz. 2001. Factors in the decline of coastal ecosystems. *Science 293*:629–638.

Bosak, T., R.M. Losick, and A. Pearson. 2008. A polycyclic terpenoid that alleviates oxidative stress. *Proceedings of the National Academy of Sciences of the USA 105*:6725–6729.

Brown, J.H., J.F. Gillooly, A.P. Allen, V.M. Savage, and G.B. West. 2004. Toward a metabolic theory of ecology. *Ecology 85*:1771–1789.

Caffrey, J.M. 2004. Factors controlling Net Ecosystem Metabolism in U.S. Estuaries. *Estuaries 27*:90–101.

Caffrey, J.M. 2003. Production, respiration, and net ecosystem metabolism in U.S. estuaries. *Environmental Monitoring and Assessment 81*:207–219.

Cai, W.J. 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? *Marine Science 3*:123–145.

Canuel, E.A., S.A. Cammer, H.A. McIntosh, and C.R. Pondell. 2012. Climate change impacts on the organic carbon cycle at the land-ocean interface. *Annual Review of Earth and Planetary Sciences 40*:685–711.

Canuel, E.A., J.E. Cloern, D.B. Ringelburg, J.B. Guckert, and G.H. Rau. 1995. Molecular and isotopic tracers used to examine sources of organic matter and its incorporation into the food webs of San Francisco Bay. *Limnology and Oceanography 41*:67–81.

Chen, C.T.A., and A.V. Borges. 2009. Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2. *Deep Sea Research Part II: Topical Studies in Oceanography 56*:578–90.

Christian, R.R., J.E. O'Neal, B. Peierls, L.M. Valdes, and H.W. Paerl. 2004. *Episodic Nutrient Loading Impacts on Eutrophication of The Southern Pamlico Sound: The Effects of the 1999 Hurricanes*. Report No. 349. University of North Carolina Water Resources Research Institute, Raleigh, NC.

Cloern, J. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series 210*:223–253.

Cloern, J.E., N. Knowles, L.R. Brown, D. Cayan, M.D. Dettinger, T.L. Morgan, D.H. Schoellhamer, M.T. Stacey, M. van der Wegen, R.W. Wagner, and A.D. Jassby. 2011. Projected evolution of California's San Francisco Bay-Delta-River system in a century of climate change. *PloS ONE 6*(9):e24465.

Crain, C.M., B.S. Halpern, M.W. Beck, and C.V. Kappel. 2009. Understanding and managing human threats to the coastal marine environment. *Annals of the New York Academy of Sciences 1162*:39–62

Crosswell, J.R, M.S. Wetz, B. Hales, and H.W. Paerl. 2012, in press. Air-water CO_2 fluxes and dissolved inorganic carbon dynamics in the microtidal, seasonally stratified Neuse River Estuary, North Carolina. *Journal of Geophysical Research*. In press.

Crosswell, J.R, M.S. Wetz, B. Hales, and H.W. Paerl. 2012, in review. Globally significant CO_2 emissions from shallow coastal waters during hurricane passage: Implications for the global carbon cycle in a stormier future? Submitted to *Nature*.

Day, J.W., and W.M. Kemp (Eds.). 1989. *Estuarine Ecology*. Wiley Interscience: New York.

Deaton, A.S., W.S. Chappell, K. Hart, J. O'Neal, and B. Boutin. 2010. *North Carolina Coastal Habitat Protection Plan*. North Carolina Department of Environment and Natural Resources, Division of Marine Fisheries, Morehead City, NC. 639 pages.

DeMaster, D.J., B.A. McKee, C.A. Nittrouer, D.C. Brewster, and P.E. Biscaye. 1985. Rates of sediment reworking at the HEBBLE site based on measurements of Th-234, Cs-137 and Pb-210. *Marine Geology 66*:133–148.

Diaz, R.J., and R. Rosenberg. 2008. Spreading dead zones and consequences or marine ecosystems. *Science 321*(5891):926–929.

Elsner, J.B., J.P. Kossin, and T.H. Jagger. 2008. The increasing intensity of the strongest tropical cyclones. *Nature 455*(7209):92–95.

Ertel, J.R., and J.I. Hedges. 1984. The component of humic substances: Distribution among soil and sedimentary humic, fulvic and base-insoluble fractions. *Geochimica et Cosmochimica Acta 48*:2065–2074.

Fulweiler, R.W., and S.W. Nixon. 2009. Responses of benthic-pelagic coupling to climate change in a temperate estuary. *Hydrobiologia 629*:147–156.

Gallegos, C.L., T.E. Jordan, A.H. Hines, and D.E. Weller. 2005. Temporal variability of optical parameters in a shallow, eutrophic estuary: Seasonal and inter-annual variability. *Estuarine, Coastal Shelf Science 64*:156–170.

Gazeau, F., A.V. Borges, C. Barron, C.M. Duarte, N. Iversen, J.J. Middelburg, B. Delille, M-D Pizay, M. Frankignoulee, and J-P Gattuso. 2005. Net ecosystem metabolism in a micro-tidal estuary (Randers Fjord, Denmark): evaluation of methods. *Marine Ecology Progress Series 301*:23–41

Giblin, A.E., N.B. Weston, G.T. Banta, J. Tucker, and C.S. Hopkinson. 2010. Losses from an oligohaline estuarine sediment. *Estuaries and Coasts 33*:1054–1068.

Giordano, J.C.P., M.J. Brush, and I.C. Anderson. 2012. Ecosystem metabolism in shallow coastal lagoons: patterns and partitioning of planktonic, benthic, and integrated community rates. *Marine Ecology Progress Series 458*:21–38.

Goñi, M.A., and T.I. Eglinton. 1996. Stable carbon isotopic analyses of lignin-derived CuO oxidation products by isotope ratio monitoring-gas chromatography-mass spectrometry (IRM-GC-MS). *Organic Geochemistry 24*:601–615.

Goñi, M.A., and J.I. Hedges. 1990. Cutin-derived CuO reaction products from purified cuticles and tree leaves. *Geochimica et Cosmochimica Acta 54*:3065–3072.

Hall, N.S., H.W. Paerl, B.L. Peierls, A.C. Whipple and K.L. Rossignol. 2012. Effects of climatic variability on phytoplankton biomass and community structure in the eutrophic, microtidal, New River Estuary, North Carolina, USA. *Estuarine and Coastal Shelf Science*. In press.

Hardison, A.K., I.C. Anderson, E.A. Canuel, C.R. Tobias and B. Veuger. 2011. Carbon and nitrogen dynamics in shallow photic systems: Interactions between macroalgae, microalgae, and bacteria. *Limnology and Oceanography 56*(4):1489–1503.

Harley, C.D.G., A. Randall Hughes, K.M. Hultgren, B.G. Miner, C.J.B. Sorte, C.S. Thornber, L.F. Rodriguez, L. Tomanek, and S.L. Williams. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters 9*:228–241.

Harris, L.A., C.M. Duarte, and S.W. Nixon. 2006. Allometric laws and prediction in estuarine and coastal ecology. *Estuaries and Coasts 29*:340–344.

Hatt, B.E., T.D. Fletcher, C.J. Walsh, and S.L. Taylor. 2004. the influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management 34*:112–124.

Hedges, J.I., and J.R. Ertel. 1982. Characterization of lignin by gas capillary chromatography of cupric oxide oxidation-products. *Analytical Chemistry 54*:174–178.

Hobbie, J.E. (Ed.). 2000. *Estuarine Sciences—A Synthetic Approach to Research and Practice*. Island Press: Washington, DC.

Holland, G.J., and P.J. Webster. 2007. Heightened tropical cyclone activity in the North Atlantic: Natural variability of climate trend? *Philosophical Transactions of the Royal Society A 365*(1860):2695–2716.

Hopkinson, C.S., and E.M. Smith. 2005. Estuarine respiration: an overview of benthic, pelagic and whole system respiration. Pp. 122–146 in *Respiration in Aquatic Ecosystems.* Edited by P.A. del Giorgio. New York: Oxford University Press.

IPCC (Intergovernmental Panel on Climate Change). 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Edited by C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley). Cambridge University Press: Cambridge, UK, and New York, NY. 582 pages.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007*. Working Group III Report. United Nations Environmental Programme, New York.

Jiang, L.Q., W.J. Cai, and Y. Wang. 2008. A comparative study of carbon dioxide degassing in river-and marine-dominated estuaries. *Limnology and Oceanography 53*:2603–2615.

Kaushal, S., G. Likens, N. Jaworski, M. Pace, A. Sides, D. Seekell, K. Belt, D. Secor, and R. Wingate. 2010. Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment 8*:461–466.

Kaushal, S.S., P.M. Groffman, L.E. Band, C.A. Shields, R.P. Morgan, M.A. Palmer, K.T. Belt, C.M. Swan, S.E.G. Findlay, and G.T. Fisher. 2008. Interaction between urbanization and climate variability amplifies watershed nitrate export in Maryland. *Environmental Science and Technology 42*:5872–5878.

Kemp, W.M., W.R. Boynton, J.E. Adolf, D.F. Boesch, W.C. Boicourt, G. Brush, J.C. Cornwell, T.R. Fisher, P.M. Glibert, J.D. Hagy, L.W. Harding, E.D. Houde, D.G. Kimmel, W.D. Miller, R.I.E. Newell, M.R. Roman, E.M. Smith, and J.C. Stevenson. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Marine Ecology Progress Series 303*:1–29.

Kemp, W.M., E.M. Smith, M. Marvin-DiPasquale, and W.R. Boynton. 1997. Organic carbon balance and net ecosystem metabolism in Chesapeake Bay. *Marine Ecology Progress Series 150*:229–248.

Kemp, W.M., and W.R. Boynton. 1980. Influence of biological and physical processes on dissolved-oxygen dynamics in an estuarine system: implications for measurement of community metabolism. *Estuarine and Coastal Marine Science 11*:407–431.

Kennish, M.J, and H.W. Paerl. 2010. Coastal lagoons: Critical habitats of environmental change. Chapter 1, Pp. 1–16 in *Coastal Lagoons: Critical Habitats of Environmental Change*. Edited by M. Kennish, and H. Paerl. CRC Marine Science Series, CRC Press: Boca Raton, FL.

Knepel, K., and K. Bogren. 2001. Revised 2002. *Determination of orthophosphate by flow injection analysis. QuikChem Method 31-115-01-1-H*. Lachat Instruments, Milwaukee, WI.

Koroleff, F. 1983. Total and organic nitrogen. Pp. 162–169 in *Methods of Seawater Analysis*. Edited by K. Grasshoff, M. Ehrhardt, and K. Kremling. Weinheim, Germany: Verlag-Chemie.

Large, W.G., and S. Pond. 1981. Open ocean momentum flux measurements in moderate to strong winds. *Journal of Physical Oceanography 11.3*:324–336.

Laruelle, G.G., H.H. Dürr, C.P. Slomp, and A.V. Borges. 2010. Evaluation of sinks and sources of CO_2 in the global coastal ocean using a spatially explicit typology of estuaries and continental shelves. *Geophysical Research Letters 37*:L15607.

Liao, N. 2001. Revised 2002. *Determination of ammonia in brackish or seawater by flow injection analysis. QuikChem Method 31-107-06-1-B.* Lachat Instruments, Milwaukee, WI.

Luettich, R.A., Jr., J.E. McNinch, H.W. Paerl, C.H. Peterson, J.T. Wells, M. Alperin, C.S. Martens, and J.L. Pinckney. 2000. *Neuse River Estuary Modeling and Monitoring Project Stage 1: Hydrography and Circulation, Water Column Nutrients and Productivity, Sedimentary Processes and Benthic Pelagic Coupling*. Report UNC-WRRI-2000-325B. Water Resources Research Institute of the University of North Carolina at Chapel Hill, Raleigh, NC.

Madden, C., and J. Day. 1992. An instrument system for high-speed mapping of chlorophyll *a* and physico-chemical variables in surface waters. *Estuaries 15*(3):421–427.

Maher, D.T., and B.D. Eyre. 2012. Carbon budgets for three autotrophic Australian estuaries: Implications for global estimates of the coastal air-water CO_2 flux. *Global Biogeochemical Cycles 26*:GB1032.

McCallister S.L., J.E. Bauer, and E.A. Canuel. 2006. Bioreactivity of estuarine dissolved organic matter: A combined geochemical and microbiological approach. *Limnology and Oceanography 51*:94–100.

McGlathery, K.J., K. Sundbäck, and I.C. Anderson. 2007. Eutrophication in shallow coastal bays and lagoons: the role of plants in the coastal filter. *Marine Ecology Progress Series 348*:1–18.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology 83*(10):2869–2877.

Mulholland, P.J., and E.J. Kuenzler. 1979. Organic carbon export from upland and forested wetland watersheds. *Limnology and Oceanography 24*:960–966.

Najjar, R., H. Walker, P. Anderson, E. Barron, R. Bord, J. Gibson, V. Kennedy, C. Knight, J. Megonigal, R. O'Connor, C. Polsky, N. Psuty, B. Richards, L. Sorenson, E. Steele, and R. Swanson. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research 14*:219–233.

Najjar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. *Estuarine, Coastal and Shelf Science 86*:1–20.

Neubauer, S.C., and C.B. Craft. 2009. Global change and tidal freshwater wetlands: Scenarios and impacts. Pp. 253–266 in *Tidal Freshwater Wetlands*. Edited by A. Barendregt, D.F. Whigham, and A.H. Baldwin. Leiden, The Netherlands: Backhuys Publishers.

Neubauer, S.C., and I.C. Anderson. 2003. Transport of dissolved inorganic carbon from a tidal freshwater marsh to the York River estuary. *Limnology and Oceanography 48*:299–307.

Niemi, G., D. Wardrop, R. Brooks, S. Anderson, V. Brady, H. Paerl, C. Rakocinski, M. Brouwer, B. Levinson, and M. McDonald. 2004. Rationale for a new generation of indicators for coastal waters. *Environmental Health Perspectives 112*:979–986.

Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. *Ophelia 41*:199–219.

Nixon, S.W. 1986. Nutrient dynamics and the productivity of marine coastal waters. Pp. 97–115 in *Proceedings of the First Arabian Gulf Conference on Environment and Pollution*, Kuwait, 1982. Edited by R. Halwagy. Oxford, England: The Alden Press, Ltd.

Nixon S.W., R.W. Fulweiler, B.A. Buckley, S.L. Granger, B.L. Nowicki, and K.M. Henry. 2009. The impact of changing climate on phenology, productivity, and benthic-pelagic coupling in Narragansett Bay. *Estuarine and Coastal Marine Science 82*:1–18.

NOAA (National Oceanic and Atmospheric Administration). 2011. *NOAA Coastal Geospatial 653 Data Project*. Available at http://coastalgeospatial.noaa.gov/data_gis.html.

NOAA. 2004. *North Carolina Bathymetry/Topography Sea Level Rise Project: Determination of Sea Level Trends*. NOAA Technical Report NOS CO-OPS 041. Silver Spring, MD. May.

NRC (National Research Council). 2000. *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*. National Academy Press: Washington, DC.

O'Connor, M., M. Piehler, D. Leech, A. Anton, and J. Bruno. 2009. Warming and resource availability shift food web structure and metabolism. *PLoS Biology 7*:e1000178.

Paerl, H.W. 2002. Primary productivity and producers. Pp. 329–341 in *Manual of Environmental Microbiology* (2nd Edition). Edited by C.J. Hurst. ASM Press: Washington, DC.

Paerl, H.W., and J. Huisman. 2009. Climate change: A catalyst for global expansion of harmful cyanobacterial blooms. *Environmental Microbiology Reports 1*(1):27–37.

Paerl, H.W., and J. Huisman. 2008. Blooms like it hot. *Science 320*:57–58.

Paerl, H.W., N.S. Hall, B.L. Peierls, K. Rossignol and A.R. Joyner. 2012. Hydrologic controls of phytoplankton community structure and function in two shallow, lagoonal estuaries: Drowning out the anthropogenic nutrient signal? *Estuaries and Coasts* (Special Issue on Shallow Water Photic Ecosystems). Submitted.

Paerl, H.W., N.S. Hall, K.S. Rossignol, B.L. Peierls, A.R. Joyner, I.C. Anderson, M.J. Brush, and J. Stanhope. 2011. The role of hydrologic variability in determining microalgal biomass, community structure and water quality in the New River Estuary, Marine Corps

Base Camp Lejeune, NC. Poster presented at SERDP/ESTCP's Partners in Environmental Technology Technical Symposium and Workshop, Washington, DC.

Paerl, H.W., K.L. Rossignol, N.S. Hall, B.L. Peierls, and M.S. Wetz. 2010a. Phytoplankton community indicators of short- and long-term ecological change in the anthropogenically and climatically impacted Neuse River Estuary, North Carolina, USA. *Estuaries and Coasts 33*:485–497.

Paerl, H.W., R.R. Christian, J.D. Bales, B.L. Peierls, N.S. Hall, A.R. Joyner, and S.R. Riggs. 2010b. Assessing the response of the Pamlico Sound, North Carolina, USA to human and climatic disturbances: Management implications. Pp.17-42 in *Coastal Lagoons: Critical Habitats of Environmental Change*. Edited by M. Kennish and H. Paerl. CRC Marine Science Series. Boca Raton, FL: CRC Press.

Paerl, H.W., L.M. Valdes, A.R. Joyner, and V. Winkelmann. 2007. Phytoplankton indicators of ecological change in the nutrient and climatically impacted Neuse River-Pamlico Sound System, North Carolina. *Ecological Applications 17*(5):88–101.

Paerl, H.W., L.M. Valdes, J.L. Pinckney, M.F. Piehler, J. Dyble, and P.H. Moisander. 2003. Phytoplankton photopigments as indicators of estuarine and coastal eutrophication. *BioScience 53*:953–964.

Paerl, H.W., M.A. Mallin, C.A. Donahue, M. Go, and B.L. Peierls. 1995. *Nitrogen Loading Sources and Eutrophication of the Neuse River Estuary, NC: Direct and Indirect Roles of Atmospheric Deposition*. UNC Water Resources Research Institute Report No. 291. 119 pages.

Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics 32*:333–365.

Peierls, B.L., N.S. Hall and H.W. Paerl. 2012. Non-monotonic responses of phytoplankton biomass accumulation to hydrologic variability: a comparison of two coastal plain North Carolina estuaries. *Estuaries and Coasts 35*(6):1376–1392.

Peierls, B., R. Christian, and H. Paerl. 2003.Water quality and phytoplankton as indicators of hurricane impacts on a large estuarine ecosystem. *Estuaries 26*:1329–1343.

Peierls, B.L., R.R. Christian, and H.W. Paerl. 2003. Water Quality and phytoplankton as indicators of hurricane impacts on a large estuarine ecosystem. *Estuaries 26*:1329–1343.

Peterson B.J. 1999. Stable isotopes as tracers of organic matter input and transfer in benthic food webs: A review. *Acta Oecologica 20*:479−487.

Peterson B.J., R.W. Howarth, and R. H. Garritt. 1985. Multiple stable isotopes used to trace the flow of organic matter in estuarine food. *Science 227*:1361–1363.

Piehler, M.F., and A.R. Smyth. 2011. Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services. *Ecosphere 2*:1–16.

Pinckney, J.L., T.L. Richardson, D.F. Millie, and H.W. Paerl. 2001. Application of photopigment biomarkers for quantifying microalgal community composition and in situ growth rates. *Organic Geochemistry 32*:585–595.

Ramus, J., L.A. Eby, C.M. McClellan and L.B. Crowder. 2003. *Phytoplankton forcing by a record freshwater discharge event into a large lagoonal estuary. Estuaries 26*:1344–1352.

Raymond, P.A., J.E. Bauer, and J.J. Cole. 2000. Atmospheric CO_2 evasion, dissolved inorganic carbon production, and net heterotrophy in the York River estuary *Limnology and Oceanography 45*(8):1707–1717.

Richardson, D.C. 2008. *Transport, Sources, and Quality of Seston in a Piedmont Headwater Stream*. Ph.D. Dissertation, University of Maryland, College Park, MD.

Roy, A.H., and W.D. Shuster. 2009. Assessing impervious surface connectivity and applications for watershed management. *Journal of the American Water Resources Association (JAWRA) 45*(1):198–209.

Seitzinger, S.P., J.A. Harrison, E. Dumont, A.H.W. Beusen, and A.F. Bouwman. 2005. Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application. *Global Biogeochemical Cycles 19*:GB4S01.

Smith, M.J., D.T. Ho, C.S. Law, J. McGregor, S. Popinet, and P. Schlosser. 2011. Uncertainties in gas exchange parameterization during the SAGE dual-tracer experiment. *Deep Sea Research Part II: Topical Studies in Oceanography 58*(6):869–881.

Smith, P., and K. Bogren. 2001. *Determination of nitrate and/or nitrite in brackish or seawater by flow injection analysis colorimetry. QuikChem Method 31-107-04-1-E*. Lachat Instruments, Milwaukee, WI.

Smith, S.V., and J.T. Hollibaugh. 1997. Annual cycle and inter-annual variability of ecosystem metabolism in a temperate climate embayment. *Ecological Monographs 67*:509–533.

Sobota, D.J., J.A. Harrison, and R.A. Dahlgren. 2009. Influences of climate, hydrology, and land use on input and export of nitrogen in California watersheds. *Biogeochemistry 94*:43–62.

Staehr, P.A., J.M. Testa, W.M. Kemp, J.J. Cole, K. Sand-Jensen, and S.V. Smith. 2012. The metabolism of aquatic ecosystems: History, applications, and future challenges. *Aquatic Science 74*:15–29.

Stevens, H.H., J.F. Ficke, and G.F. Smoot. 1975. Water temperature, influential factors, field measurement, and data presentation. Book 1, Chapter D1 in *U.S. Geological Survey Techniques of Water Resources Investigations*.

Sundbäck, K., F. Linares, F. Larson, A. Wulff, and A. Engelsen. 2004. Benthic nitrogen fluxes along a depth gradient in a microtidal fjord: The role of denitrification and microphytobenthos. *Limnology and Oceanography 49*:1095–1107.

Sundbäck, K., A. Miles, S. Hulth, L. Pihl, P. Engstrom, E. Selander, and A. Avenson. 2003. Importance of benthic nutrient regeneration during initiation of macroalgal blooms in shallow bays. *Marine Ecology Progress Series 246*:115–126.

Tobias C., J.K. Böhlke, and J.W. Harvey. 2007. The oxygen-18 isotope approach for measuring aquatic metabolism in high productivity waters. *Limnology and Oceanography* 52:1439–1453.

Tomas, C.R., J. Peterson, and A.O. Tatters. 2007. *Harmful Algal Species from Wilson Bay, New River, North Carolina: Composition, Nutrient Bioassay, and HPLC Pigment Analyses*. Report number 369. Water Resources Research Institute of the University of North Carolina, Raleigh, NC.

Valiela, I., G. Collins, J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawley, and C.H. Sham. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: New method and application. *Ecological Applications 7*(2):358–380.

Vogel, S. 1994. *Life in Moving Fluids: The Physical Biology of Flow*. Princeton University Press.

Volkman, J.K. (Ed.). 2006. Lipid markers for marine organic matter. Pp. 27–70 in *Marine Organic Matter: Biomarkers, Isotopes and DNA.* Edited by J.K. Volkman. Springer: Heidelberg.

Volkman, J.K., S.M. Barrett, S.I. Blackburn, M.P. Mansour, E.L. Sikes, and F. Gelin. 1998. Microalgal biomarkers: A review of recent research developments. *Organic Geochemistry 29*:1163–1179.

Wanninkhof, R. 1992. Relationship between wind speed and gas exchange. *Journal of Geophysical Research 97*:7373–7382.

Ward, R.C., and M. Robinson. 2000. *Principles of Hydrology* (4th edition). McGraw-Hill: London, UK.

Webster, P.J., G.J. Holland, J.A. Curry, and H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science 309*:1844–1846.

Weiss, R. 1974. Carbon dioxide in water and seawater: The solubility of a non-ideal gas. *Marine Chemistry 2*:203–215.

Weston N.B., M.A. Vile, S.C. Neubauer, and D.J. Velinksy. 2011. Accelerated microbial organic matter mineralization following salt-water intrusion into tidal freshwater marsh soils. *Biogeochemistry 102*:135–151.

Weston, N.B., and S.B. Joye. 2005. Temperature driven accumulation of labile dissolved organic carbon in marine sediments. *Proceedings of the National Academy of Sciences (US) 102*:17036–17040.

Wetz, M.S., E.A. Hutchinson, R.S. Lunetta, H.W. Paerl, and J.C. Taylor. 2011. Severe droughts reduce estuarine primary productivity with cascading effects on higher trophic levels. *Limnology and Oceanography 56*:627–638.

Wiegner, T.N., S.P. Seitzinger, P.M. Glibert, and D.A. Bronk. 2006. Bioavailability of dissolved organic nitrogen and carbon from nine rivers in the eastern United States. *Aquatic Microbial Ecology 43*:277–287.

Zimmerman, A.R., and E.A. Canuel. 2000. A geochemical record of eutrophication and anoxia in Chesapeake Bay sediments: anthropogenic influence on organic matter composition. *Marine Chemistry* 69:117–137.

6.0 Coastal Wetlands Module

6.1 Introduction

Coastal marshes are a vital component of the estuarine landscape (**Figure 6-1**) and link terrestrial and freshwater habitats with the sea (Levin et al., 2001). These interactions include the exchange of solutes, including carbon and nutrients (Cai, 2011; Jordan et al., 1983); fauna; and sediment between marsh, estuary, and adjacent landforms. In the intertidal zone, marshes help to stabilize sediments and minimize erosion (Gedan et al., 2011; Knutson et al., 1982; Möller et al., 1999). Wetlands improve water quality by acting as nutrient transformers and by trapping sediment (Harrison and Bloom, 1977; Morris, 1991; Valiela and Teal, 1979). Generally speaking, marshes consume (denitrify) nitrate dissolved in flood water and, thus, have a beneficial effect on estuarine water quality. In addition, coastal wetlands provide critical habitat area for a diverse group of estuarine organisms, serve as nursery habitat for commercially important fishery species (Kneib, 1997), and provide recreational opportunities for people.

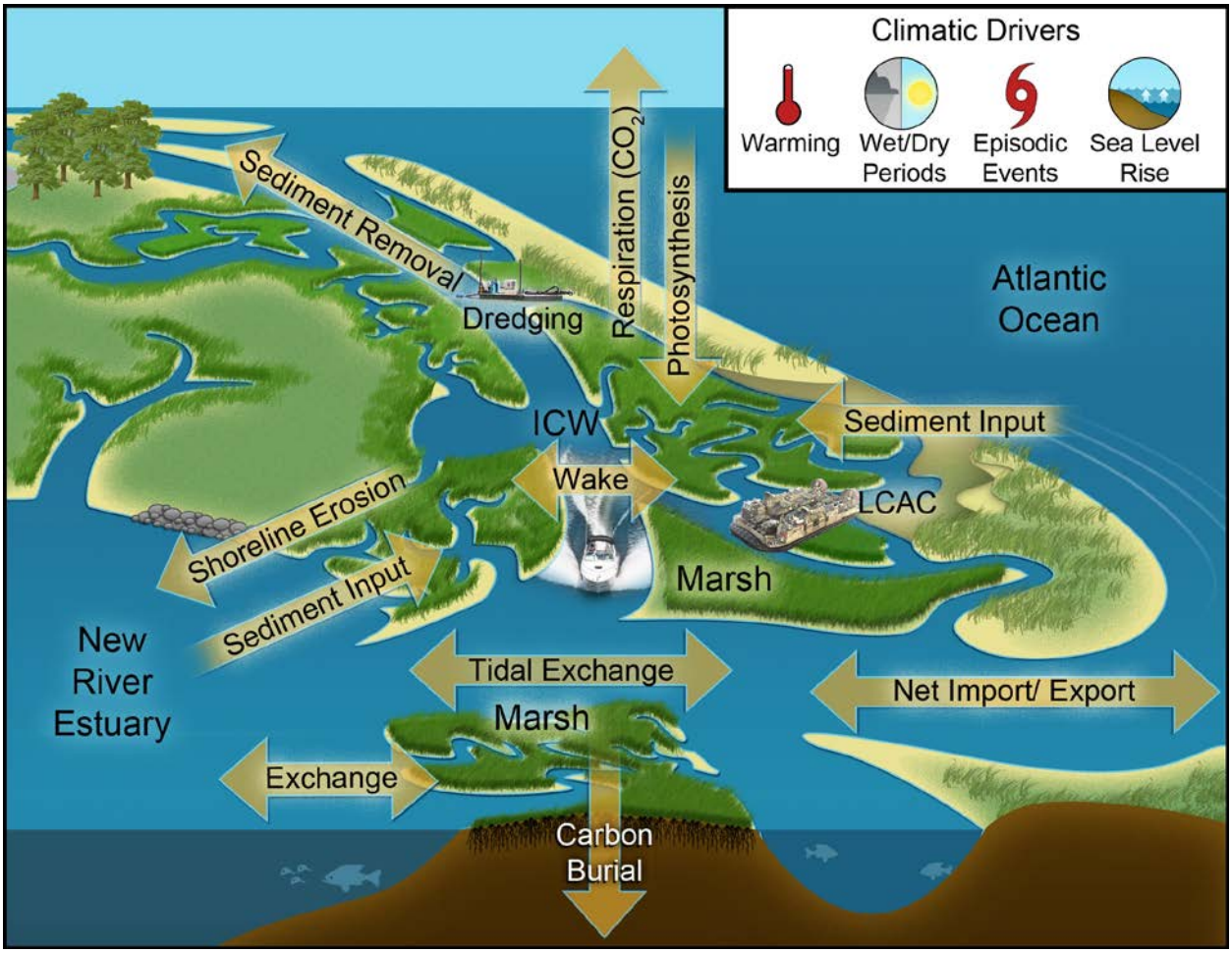

Figure 6-1. Conceptual model for the Coastal Wetlands Module.

Salt marshes also play an important role in the global carbon cycle. Recent estimates suggest that some coastal habitats store more carbon per area and take up more carbon annually than terrestrial habitats (Nellemann et al., 2009). As a result, these coastal habitats, even though they account for a small percent of land cover, are approximately an equivalent carbon sink as other major terrestrial habitats, including temperate, tropical, and boreal forests (Mcleod et al., 2011; Nelleman et al., 2009). However, across the United States, coastal salt marshes have declined in area over the past 200 years, which prior to the 1972 Clean Water Act was primarily due to human activities. However, in the most recent assessment of U.S. coastal wetland status and trends, 99% of wetland loss was attributed to effects from "coastal storms, land subsidence, sea level rise and other ocean processes" (Dahl, 2011), which resulted in the conversion of salt marsh to open water. This is consistent with recent literature which has documented the loss of salt marsh a as result of sea level rise, storm events, erosion, and changes in land-use practices (Cahoon et al., 2006; Kirwan and Blum, 2011; Mattheus et al., 2010; Morris et al., 2002). Projected acceleration in sea level rise (Bindoff et al., 2007; Vermeer and Rhamstorf, 2009) will exacerbate these processes and will require both improved modeling efforts and adaptive management approaches to minimize the adverse impact of marsh loss on coastal ecosystems.

The coastal wetlands of this module are defined as the vegetated intertidal habitat in salt and brackish waters and include the salt marshes along the lower NRE shoreline and ICW to the brackish marshes along the upper NRE shoreline and tributaries of the NRE. These areas within the MCBCL region are typically dominated by smooth cordgrass *(Spartina alterniflora*) and black needle rush (*Juncus roemerianus)*.

Figure 6-1 presents the conceptual model for the Coastal Wetlands Module, illustrating the complementary nature of critical estuarine physical, chemical, and biotic processes and interactions. Integration of the marsh–barrier island is crucial because marshes provide a platform over which the barrier dune system can migrate, and the dunes protect the marshes from erosive wave energy that would otherwise degrade them. Along the estuarine shoreline, marshes protect uplands from flooding and storm surge. The marshes will also migrate over the terrestrial landscape in response to rising sea level where the topography allows. Exchanges of sediment and inorganic and organic carbon with estuarine waters occur (via diffusion and settling) when the marsh is submerged. Exchange of carbon with the atmosphere and estuarine waters (via diffusive flux to the atmosphere and advective exchange of marsh porewater) can occur during emergent periods. Marsh primary production that is not decomposed and lost to the atmosphere or estuary can be buried through sediment accretion and net surface elevation increase, and this represents a net carbon sink to the ecosystem.

The following two research projects (**Table 6-1**) address challenges that are associated with stresses imposed as a consequence of MCBCL and other direct anthropogenic activities and of global climate change, particularly sea level rise.

Table 6-1. Coastal Wetlands Module research projects, senior researchers, outcomes and benefits to MCBCL, and duration of the projects

Project	Research Project Title	Senior Researchers and Duration
CW-4	*Improving Model Predictions for Marsh Response to Sea Level Rise and Implications for Natural Resource Management*	**Senior Researcher:** Carolyn Currin
	Outcomes and benefits: Develop landscape-scale predictive models to guide adaptive management strategies for sustaining coastal wetlands.	**Duration:** 3/2013–6/2017
CW-5	*Marsh—Atmosphere and Marsh—Creek Exchanges of Carbon*	**Senior Research:** Iris Anderson
	Outcomes and benefits: In conjunction with Research Project CW-4, develop a marsh carbon budget, which will be combined with the measured estuarine and barrier carbon budgets into the total final estuarine and coastal carbon budget that will be compared to predictions made by the ESM (Research Project TSP-2). Carbon sequestration in the estuary and adjacent marshes and barrier island may be used as offset for fossil fuel emissions of CO_2 on MCBCL.	**Duration:** 2/2015–10/2016

6.2 Knowledge Gaps in Conceptual Model and Research Needs

The ability of marshes to keep up with current and projected rates of sea level rise depends upon sediment availability, the rate of sea level rise, the density of marsh vegetation, the intensity and frequency of storms, and variables such as nutrient enrichment and salinity that affect the density and species distribution of marsh vegetation (Kirwan and Murray, 2007; Morris et al., 2002; Mudd et al., 2009). The vulnerability of coastal wetlands to sea level rise is a function of the local tidal amplitude and marsh surface elevation relative to local mean and high water (Morris et al., 2002). As the rate of sea level rise increases, the equilibrium elevation of the marsh will decrease. As this elevation approaches the lower limit of a wetland's range of tolerance, the marsh will convert to open water upon any further increase in the rate of sea level rise.

There remain crucial uncertainties that limit our ability to translate current model predictions to MCBCL. These uncertainties include a lack of data on temporal and spatial variability in suspended sediment concentrations (SSC); an incomplete understanding of how changes in tidal amplitude, which exist between Browns and New River Inlets, alter the distribution of plant biomass within the tidal frame; and regarding the relative roles of mineral sediments versus below-ground primary production in contributing to marsh surface elevation change across salinity and elevation gradients (Cahoon et al., 2004; Nyman et al., 2006). Geochronology of marsh cores will provide data on the impact of major anthropogenic (ICW creation in 1938, MCBCL establishment in 1940s) and storm events on marsh sediment accretion rates (Kolker et al., 2009), as well as a check of the accuracy of model hindcasts of marsh sediment accretion rates at different locations within MCBCL. In conjunction with measures of below-ground biomass production and decomposition, these data will provide estimates of the present and future carbon sequestration potential of MCBCL marshes. The conceptual models for the Coastal Wetlands Module and the respective research projects will be revised as existing data gaps are filled. Revisions will be made to include the new information and understanding of ecosystem processes gained and to make the information more useful to a wider audience of users.

Sources of carbon to marshes include DOC and (POC derived from terrestrial and estuarine sources and photosynthetic fixation of atmospheric CO_2 by marsh macrophytes and BMA (**Figure 6-2**). The fate of carbon fixed in the marsh includes losses of CO_2 to the atmosphere due to macrophyte and microbial respiration; erosion of POC to the estuary; diffusive losses of DIC and DOC to overlying water; advective losses of DIC, DOC, and POC to the adjacent creek; and burial in sediment (**Figure 6-2**; Hopkinson et al., 2012). Exchanges of carbon and nutrients between salt marshes and the atmosphere, overlying water, and adjacent creeks are expected to vary with marsh elevation, tidal range, and habitat conditions. To date, few studies have attempted to document net ecosystem exchanges of CO_2 and methane between marsh and atmosphere along with exchanges of DIC, DOC, DIN, DON, and DIP between the marsh, overlying water, and adjacent creeks (Tobias and Neubauer, 2009).

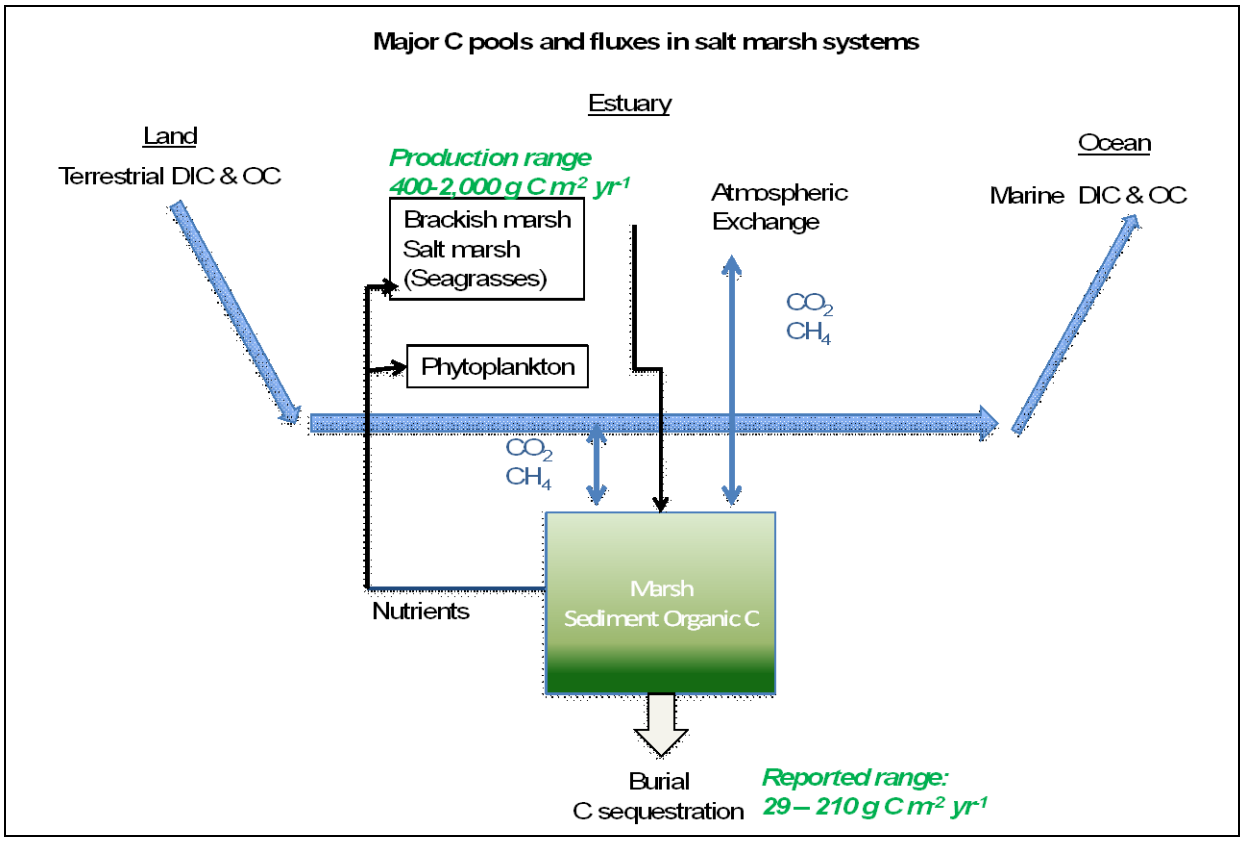

Figure 6-2. Conceptual model of carbon sources and sinks in estuarine systems, highlighting the role of salt marshes.

(Adapted from Hopkinson et al., 2012)
Note: C = carbon; OC = organic carbon.

Key objectives of research projects for the coastal wetlands of MCBCL include the following: (1) measuring processes (delivery of suspended sediments, production of above- and below-ground marsh biomass) that control marsh ability to keep pace with sea level rise; (2) improving model predictions on vulnerability of marshes to sea level rise across the MCBCL landscape; (3) assessing the factors affecting flux of carbon from marshes to the estuary and to the atmosphere; (4) determining the role of surface elevation and tidal dynamics on marsh carbon burial rate; and (5) developing strategies for adaptive management of coastal wetlands.

6.3 Research Project CW-4: Improving Model Predictions for Marsh Response to Sea Level Rise and Implications for Natural Resource Management

Lead Investigator: Dr. Carolyn A. Currin (NOAA)

Supporting Researchers: Drs. Craig Tobias (UCONN), Matt Kirwan (VIMS), Brent McKee (UNC-CH), Scott Ensign (AquaCo), two graduate students, and one post-doctorate appointment

Technical Objectives/Goals: The major objectives for Research Project CW-4 are to improve our understanding of the factors controlling salt marsh responses to sea level rise, provide predictive models for managers incorporating climate forcing factors, and develop and assess adaptive management strategies for sustaining coastal wetlands on MCBCL.

Specific objectives of this effort include the following:

1. Improve and expand model predictions of *Spartina* marsh sustainability across the MCBCL landscape
2. Obtain detailed information on temporal and spatial variability of SSC and develop a model of SSC delivery to marsh surface to improve marsh elevation predictions
3. Use surface elevation table (SET) and vegetation monitoring data and experimental results to develop a marsh elevation:biomass ratio for *Juncus*
4. Identify MCBCL marsh locations that are particularly susceptible to loss via drowning and erosion
5. Determine long-term (100-year) marsh accretion rates to compare with model hindcasts and predict carbon sequestration potential of marshes along the ICW and NRE (in conjunction with the Coastal Barrier and Aquatic/Estuarine Modules)
6. Contribute to the development of overall estuarine carbon budget with information on factors controlling below-ground marsh production, decomposition, and long-term carbon burial rates (with Research Projects CW-5, CB-5, and TSP-2)
7. Design and assess the effectiveness of adaptive management strategies, including thin-layer sediment disposal and living shoreline installations.

Research Questions:

1. What is the relationship between Spartina and Juncus above-ground and below-ground biomass, and how does it change with marsh surface elevation and the MCBCL salinity gradient?
2. How fast does marsh organic matter exposed via shoreline erosion decompose?
3. How do tidal harmonics and amplitude influence SSC and sediment deposition in salt marsh creeks?
4. What is the fate of sediment eroded from fringing marshes, and does it vary with wave exposure?
5. How does marsh vulnerability to sea level rise vary across the MCBCL landscape, and what factors are most important in vulnerable areas?
6. How will marsh transgression into upland elevations affect carbon sequestration rates?
7. How will sea level rise affect carbon storage in MCBCL marshes over the next century?

6.3.1 Background

Salt marshes occupy approximately 1,100 ha on MCBCL, ranging from *Spartina*-dominated marshes along the ICW to *Juncus*-dominated fringing marshes on embayments and tributaries of the NRE (**Figure 6-3**). These marshes provide important ecosystem services, including protection from storm-related wave energy (Gedan et al., 2011) and are also important sinks for carbon (Brigham et al., 2006; Mcleod et al. 2011). Projected rates of relative sea level rise along the North Carolina coast, in conjunction with forecast changes in storm frequency, pose significant threats to coastal wetlands (Cahoon et al., 2006; Kirwan and Murray, 2007; Morris et al., 2002). Man-made alterations to sediment supply and shoreline stabilization efforts can have

more immediate impacts on coastal wetlands (Kirwan and Blum, 2011; Mattheus et al., 2010). One- and two-dimensional models have been developed to predict the response of *Spartina*-dominated marshes to sea level rise via feedbacks between vegetation and sedimentation (e.g., Kirwan and Murray, 2007; Morris et al., 2002; Mudd et al., 2009). A recent review of this approach emphasized the important role of SSC and tidal range in predicting marsh sustainability to sea level rise (Kirwan et al., 2010).

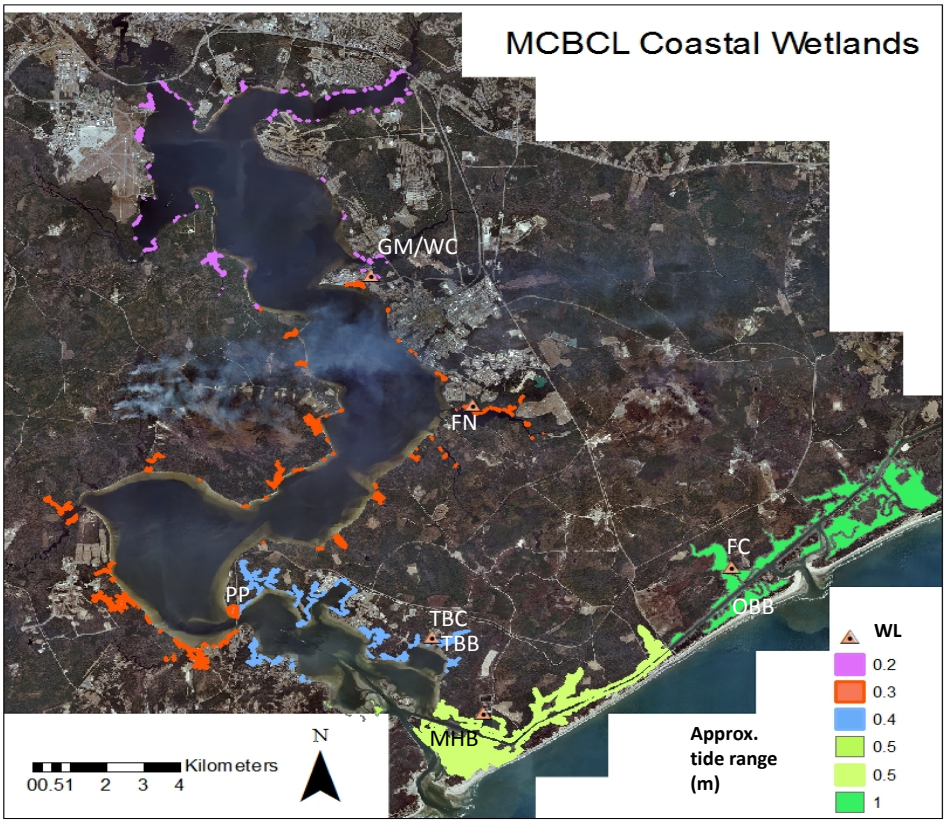

Figure 6-3. Distribution salt and brackish marsh on MCBCL across the estuarine tidal gradient.

DCERP marsh research sites and tide gauge stations are identified with site codes in white**.** *Spartina*-dominated sites include Freeman Creek (FC), Onslow Back Barrier (OBB), and Mile Hammock Bay (MHB). Mixed species marsh sites include Traps Bay Creek (TBC) and Traps Bay Bridge (TBB) and Pollocks Point (PP). French Creek (FN) is a *Juncus*-dominated site. Water level (WL) stations were used to estimated tide range, and include tide gauge stations at MHB and Gottshalk Marina/Wallace Creek (GM/WC), and pressure sensor loggers at FC, TBC, and FN. Each marsh research site has at least two SETs and permanent vegetation monitoring plots.

Results from DCERP1 demonstrate that although there is a statistically significant ($p<0.05$) linkage between inundation and net surface elevation change as measured by SETs at ICW marshes, and between inundation and sediment accretion as measured by marker horizons at all sites, the correlation is relatively weak ($r^2<0.20$; **Table 6-2**). The lack of a strong correlation between short-term (months) accretion and inundation is in contrast to that found in long-term (decades) studies based on geochronology, and the factors driving short-term variation are less well understood (Kolker et al., 2009). However, we also note that neither the SET or marker horizon measures would be impacted by subsidence, such as crustal movement, that occurs below the base of the SET benchmark, which is typically 6–8 m below the marsh surface.

DCERP1 results also demonstrate that the accretion of mineral sediments on the marsh surface exceeds the net surface elevation change by 1.5 to 3 times, in both *Spartina* and *Juncus* dominated marshes **(Figure 6-4)**. Part of this discrepancy could be due to local subsidence, which has been estimated at 0.8 to 1.0 mm y^{-1} (Engelhart et al., 2009; Kemp et al., 2011), and so could contribute up to 25% of the observed difference in sediment accretion rates. These results suggest that SSC variability may be an important control of net surface elevation change in MCBCL marshes.

Table 6-2. Regression analysis of DCERP1 measures of site inundation time in hours (Inund), net SET elevation change in mm (SET Elev), and surface accretion as measured by marker horizons in mm (MH accretion).

Regions include sites adjacent to the ICW (i.e., Freeman Creek, Onslow Back Barrier, Mile Hammock Bay) and to the NRE (i.e., Traps Bay, Traps Creek, Pollocks Point, and French Creek). We ran regressions on data representing 3- to 4-month intervals. The length of analysis differed by site and was determined by the availability of water level data.

Region	Regression	P	R^2
ICW	SET Elev versus Inund	0.0006	0.1661
NRE	SET Elev versus Inund	0.2832	0.0155
ICW	MH accretion versus Inund	0.0241	0.1583
NRE	MH accretion versus Inund	0.0061	0.1736
Combined	SET Elev versus Inundation	0.0090	0.047

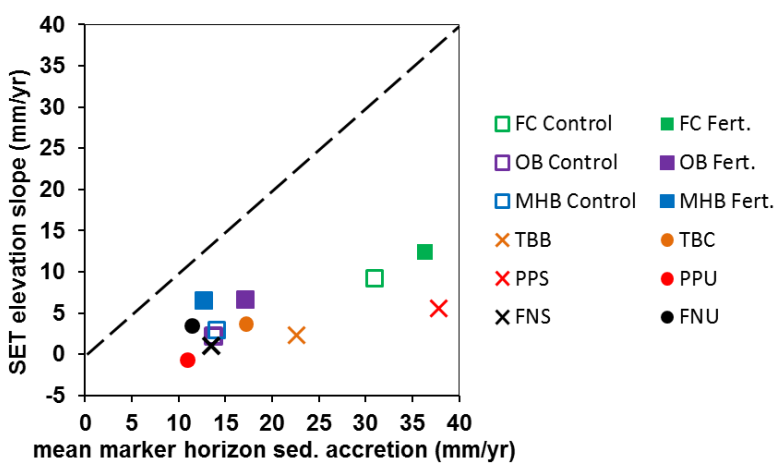

Figure 6-4. Relationship between net surface elevation change, as measured by SETs, and surface accretion, as measured by marker horizons, in MCBCL marshes.

Note: The dashed line represents the 1:1 ratio if sediment accretion depth matched net surface elevation change. Site key and locations are in **Figure 6-3**. Control = no fertilization; FC = Freeman Creek; Fert = fertilized site; FNS = French Creek Shore; FNU = French Creek Upper; MHB = Mile Hammock Bay; OB = Onslow Beach; PPS = Pollocks Point Shore; PPU = Pollocks Point Upper; TBB=Traps Bay Bridge; TBC = Traps Bay Creek.

Tidal amplitude is an important driver affecting marsh biomass distribution and advective exchanges between the marsh and estuary, and thus will control both marsh response to sea level rise and net carbon flux. The relationship of sea level rise on tidal amplitude is not well understood; it is likely to vary with site-specific geomorphology and hydrodynamics. In addition

to sea level rise, tidal amplitude can be affected by inlet dynamics, including dredging to maintain navigation. In North Carolina, dredging is suggested to have contributed to observable increases in the tide range at three stations (Zervas, 2004). DCERP1 results demonstrated significant differences in tidal amplitude between a marsh site near Browns Inlet (Freeman Creek [FC]), and a site near the New River Inlet (Mile Hammock Bay [MHB]), as well as attenuation of the tidal signal up-estuary (**Figure 6-5**). The tide range at Freeman Creek was approximately 1 m, which is twice the tide range at Mile Hammock Bay, in both spring and fall (**Figure 6-5)**. Both sites exhibit the typical seasonal pattern of lower sea level in the winter–spring and higher stand in the fall, which, in North Carolina, can result in an annual range in mean monthly water level of 15–20 cm (Zervas, 2004). The importance of tide range on distribution of *Spartina* biomass is illustrated in **Figure 6-6**. The lower tide range at Mile Hammock Bay results in a narrower range of plant distribution (−0.15 to 0.35 m NAVD88) compared to Freeman Creek (−0.45 to 0.45 m NAVD88). On MCBCL, significant alteration to New River Inlet hydrodynamics may result from dredging operations and other efforts to stabilize North Topsail Island. Although Browns Inlet is not maintained, the adjacent ICW is frequently dredged for navigation purposes. Forecasting the future of MCBCL marshes and assessing their future potential to sequester carbon, requires a knowledge of the relationship between tidal amplitude, seasonal water level, and marsh primary production and advective exchanges with the estuary.

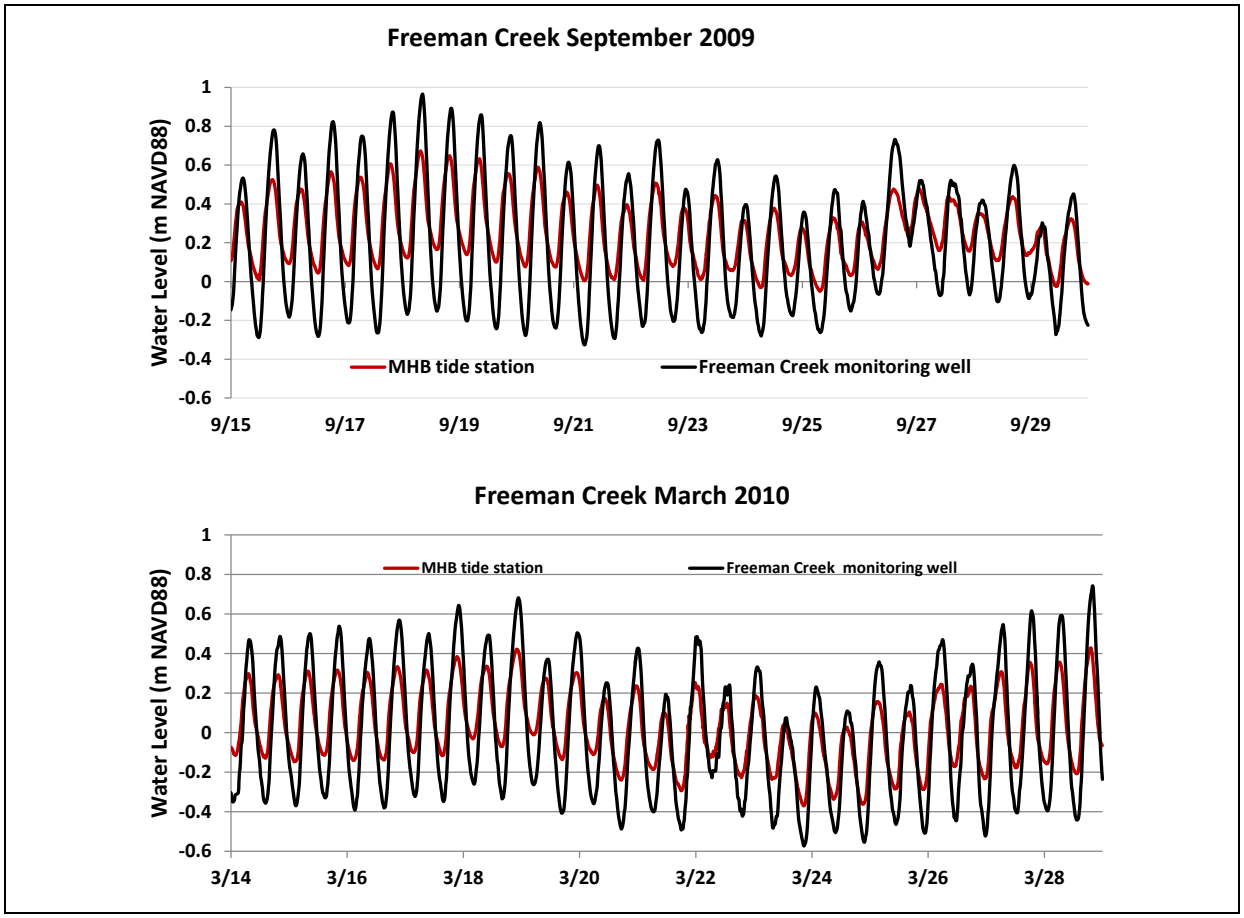

Figure 6-5. Water level data from Freeman Creek, near Browns Inlet, and Mile Hammock Bay (MHB), near the New River Inlet, showing differences in tidal amplitude in September 2009 (top) and March 2010 (bottom).

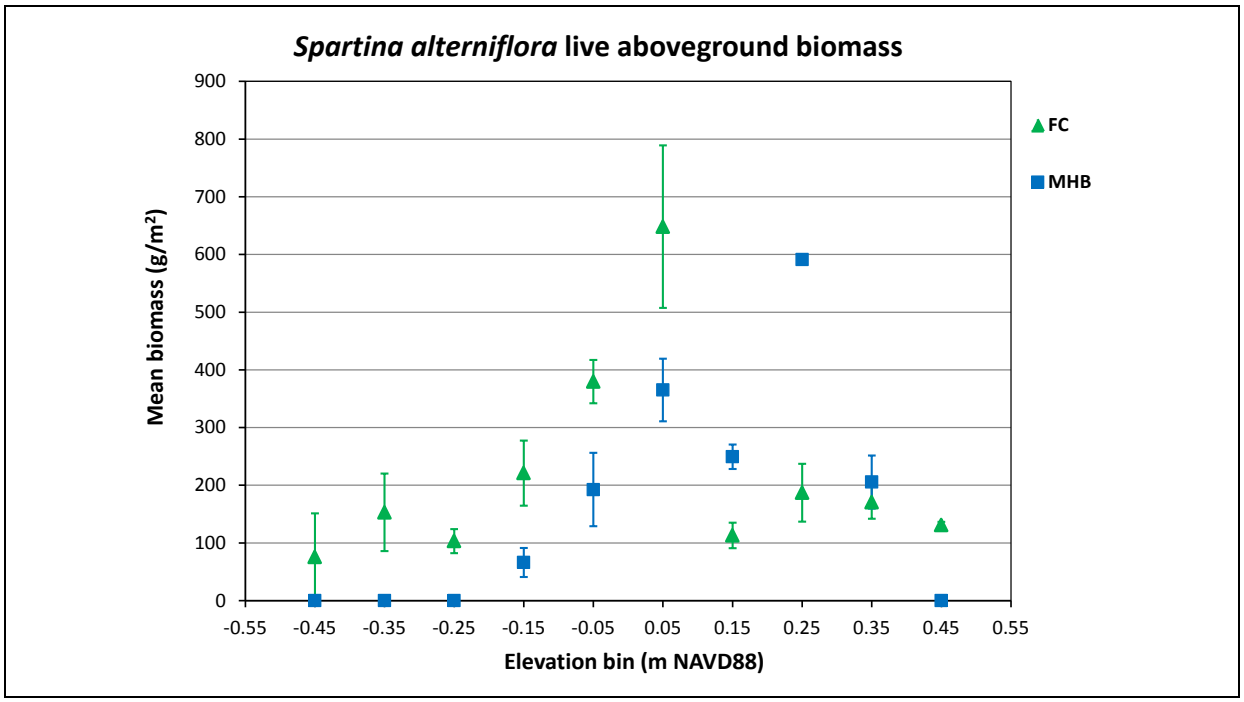

Figure 6-6. Relationship between *Spartina* above-ground biomass and surface elevation at two ICW sites, Freeman Creek (FC) and Mile Hammock Bay (MHB), with differing tidal amplitude.

Data are from field harvests of marsh plants.

Although the general response of the marsh platform to sea level rise has been modeled successfully with the Marsh Equilibrium Model (MEM) at individual points at MCBCL, the spatial variability of the response is unknown and is critical to predicting which marshes within MCBCL are most vulnerable to climate change. Towards this goal, we will develop a new, spatially explicit model of marsh accretion that incorporates competition between plant species and their effects on organic accumulation and mineral sediment deposition.

The relative influence of sea level rise, storms, and sediment supply on marsh elevation has been shown to vary with the physical exposure and tide range of the marsh (Kolker et al., 2009), consistent with our observations on MCBCL during DCERP1. Factors driving the response of the marsh shoreline are less well-understood than those determining sediment accretions, and are less often incorporated into predictive models of marsh response to sea level rise (Chauhan, 2009; Kirwan and Murray, 2007). A landscape-scale assessment of the vulnerability of MCBCL marshes will include an assessment of marsh edge erosion based on wave exposure, sediment supply, and geomorphology. Rates of marsh edge erosion will be compared to rates of marsh expansion into inland forest determined from the modeling previously described. We will examine the fate of marsh organic matter liberated via shoreline erosion via decomposition experiments and biomarker analysis, and we will test the assumptions made by Pendleton et al. (2012) on the contribution of marsh loss to coastal carbon budgets.

6.3.2 Methods

Experiments (in conjunction with the Coastal Wetlands monitoring program) will take place at six marsh sites (three *Spartina*-dominated, two mixed spp., and one *Juncus*-dominated), which will offer a gradient in tidal amplitude, wave energy, salinity, and sediment supply **(Figure 6-3)**. Monitoring data are available from 2008 for marsh surface elevation, above-ground biomass, stem density, and species percent cover. Water-level stations will be maintained in the upper and lower portions of the NRE, at Gottshalk Marina (GM/WC) and Mile Hammock Bay, respectively. Precise (2-cm vertical) measure of marsh surface elevation at all research sites is available with the recent completion of a Height Modernization campaign in conjunction with the North Carolina Geodetic Survey, and includes all SET stations.

Specific experiments and data collections to support the goals of Research Project CW-4 include the following:

1. **Factors affecting marsh biomass production and decomposition.** We will examine the effect of site factors on plant below-ground biomass (Blum and Christian, 2004) and above-ground biomass to surface elevation relationships (Morris et al., 2002) along transects from the marsh channel edge to uplands at six sites. We will deploy mesh bags filled with a peat and sand mix in holes from which 10 cm in diameter sediment cores will be removed to estimate below-ground production by marsh plants across the marsh elevation gradient. We will obtain cores in late summer at the time of peak biomass, to a depth of 30 cm. We will sort below-ground material into live and dead root/rhizome fractions and will dry, weigh, and analyze them for carbon:nitrogen content (Blum, 1993; Christian et al., 1990).

   Manipulative experiments include measuring the decomposition rate of marsh core organic matter, using both a litterbag technique and respiration measures (see Research Project CW-5). We will collect replicate cores from eroding shoreline sites at two locations, section them by depth, and place the contents in litterbags to measure weight and carbon loss. We will deploy litterbags in the nearshore environment to imitate the transfer of marsh organic matter to the estuarine system. We will coordinate core collection sites with the collection of cores for geochronology and carbon flux.

2. **SSC dynamics.** The dynamics influencing SSC in tidal creeks are essential to parameterizing models of sediment dynamics of coastal wetlands. We will implement a sampling scheme for SSC to characterize the following: (1) the factors influencing SSC within the tidal creeks, which deliver sediment to coastal wetlands; and (2) the factors affecting SSC in flood water as it travels across the wetland surface. During 2013, we will conduct intensive sampling of SSC at two points distributed longitudinally (near the mouth of the creek and upstream near the head-of-tide, approximately 200 m apart) along Freeman Creek. We will sample SSC (collected in accordance with methods prescribed by the USGS for isokinetic sampling; USGS, 2005) at 0.33-hour intervals during the period between mean water level to high tide (n=9 SSC measurements × two sites) within the tidal creek channel at the surface of the water column. During the period when the marsh is inundated, we will conduct SSC sampling of water overlying the marsh along a transect perpendicular to the creek channel at five locations in quick succession (less than 5 minutes). We will repeat this over-marsh sampling twice during each site visit. We will

conduct sampling from boardwalks at the upstream and downstream location in Freeman Creek (Figure 6-7 in Section 6.4); the length of this over-marsh SSC transect will depend upon the location in which the boardwalk is installed. We will conduct site visits 12 times during the year, with visits targeting a range of seasonal tidal datums, rainfall events, and wind events. Concurrent with this over-marsh SSC sampling, we will measure sediment deposition at the two locations using approximately five filter traps (Leonard et al., 1995, Wood and Hine, 2007) deployed from the boardwalk for the duration of that tidal cycle's inundation. We will examine the spatial (along-creek axis and across-marsh axis) and temporal (tidal cycle-scale and seasonal scale) variations in SSC and short-term sediment deposition using a mixed-effects regression model to develop an empirical model of SSC based on tidal amplitude, seasonal tidal datum, tide stage, and atmospheric events (runoff and wind) on Freeman Creek.

The empirical models of in-channel and over-marsh SSC and short-term accretion developed in Freeman Creek will be tested in Traps Creek (2013–2014) and French Creek (2014–2015). We will implement an identical sampling strategy in each creek as previously described. We will evaluate the applicability of the models to these difference hydrogeomorphic environments (i.e., Traps Creek is a fringing, mesohaline marsh with limited drainage area, and French Creek is a mesohaline marsh with a relative large drainage area), and use this to test whether a different set of predictor variables needs to be included in the empirical model to account for hydrogeomorphic environment. Tidal harmonics may be added as a predictor variable as described in the paragraph below. Ultimately, the validated SSC models (in-channel and over-marsh) will allow for the development of a frequency-magnitude analysis, in which a single, representative SSC value can be used for input to the morphological response model to be developed by Dr. Kirwan. The magnitude-frequency model will allow prediction of the dominant SSC concentration affecting marsh morphology, given the dynamic range in tidal inundation. We will use Digital Elevation Models (DEMs) and ArcGIS Spatial Analyst tools to calculate the shoreline erosion rates and volume of sediment lost or gained (Cowart et al., 2010; Mattheus et al., 2010).

3. **Tidal harmonics:** We will use time series of water level measures (tide gauges at Mile Hammock Bay; pressure loggers at Freeman Creek, Traps Bay Creek, and French Creek) to evaluate tidal harmonics contributing to spatio-temporal patterns in sediment flux to marsh surfaces. We will use the software program T-Tide (Pawlowicz et al., 2002) to determine tidal harmonics. We will use these data to parameterize the magnitude-frequency model of SSC previously described.

4. **Marsh Evolution Simulations:** We will use a spatially explicit numerical model of marsh accretion (Kirwan and Murray, 2007) to make simulations of salt marsh evolution and carbon sequestration at three or four marshes across the estuarine gradient. These simulations will begin with high-resolution topographic maps and will proceed under a range of sea level rise scenarios adjusted for local subsidence using procedures recommended by SERDP. In the model, mineral sediment deposition will be a function of inundation duration, settling velocity, and SSC (Kirwan and Mudd, 2012; Mudd et al., 2009). Organic sediment accumulation will be a function of above-ground plant biomass, a root-to-shoot ratio, and the fraction of biomass that remains in the soil after long-term

decay (approximately the lignin content of newly produced roots). Thus, modeled accretion rates will vary in both time (sea level rises influences inundation duration and vegetation) and space (faster accretion near channels and marsh edge where sediment concentrations are higher). The model will incorporate measurements of SSC across the estuary and marsh interior and the linkages between vegetation biomass and elevation to predict how carbon sequestration and marsh vulnerability change across the marsh landscape and throughout the next century in response to sea level rise. The modeling effort will also incorporate results from ongoing research by other investigators on the response of organic matter and production and decomposition to increases in atmospheric CO_2 and/or elevated temperature (e.g., Kirwan and Blum, 2011; Langley et al., 2009). However, preliminary work suggests that enhanced decomposition approximately offsets enhanced productivity, so that the net effect may be dwarfed by the impacts of accelerated sea level rise (Kirwan and Mudd, 2012).

5. **Sedimentation Rates:** At each of the six marsh locations, we will collect cores (four) across an elevation transect and process as described in Research Project CB-5, except there will not be radiocarbon dating, ^{137}Cs will be determined when possible, and bulk plus compound-specific carbon analysis will be conducted (see also the Research Project AE-6 description). A constant initial concentration model (non-steady state) will be used to determine sedimentation rates from a down-core distribution of excess ^{210}Pb activities (Appleby and Oldfield, 1992). A geochronology will be established utilizing the down-core distribution of excess ^{210}Pb activities and by assigning a date of 1964 to the ^{137}Cs impulse peak (DeMaster et al., 1985). Using this approach, we can employ changes in the slope of the excess ^{210}Pb profile down core (in conjunction with ^{137}Cs profiles) to document changes in sedimentation rates during the past 100+ years that result from changes in sediment supply, such as due to land-use changes (McKee et al., 2005; Ruiz-Fernandez et al., 2009).

6. **Adaptive Management Pilots Studies:** We will design pilot studies of two adaptive management approaches (thin-layer disposal and shoreline stabilization utilizing "living shorelines") to improving marsh sustainability on MCBCL (Croft et al., 2006; Currin et al., 2010; Stagg and Mendelssohn, 2010). These small studies will consist of adding 10–20 cm of dredge spoil to small (approximately 1 m^2) plots at two elevations and planting *Spartina alterniflora* along two 30-m stretches of shoreline currently experiencing erosion. We will complete the design of large-scale approaches in collaboration with MCBCL EMD personnel, and in discussions with USACE and the North Carolina Division of Coastal Management staff. Implementation of projects would require additional funding, which may be provided by USACE and the North Carolina Department of Coastal Management. These discussions were initiated during DCERP1, and results from DCERP2 research on SSC and marsh biomass:elevation relationships will further inform site selection and project design. To complete this work, permits and funding must be obtained by January 2015.

7. **Research at Eglin AFB.** We will obtain data to determine the *Juncus* biomass to elevation relationship from marshes at Eglin AFB in 2016. This will include obtaining cores for below-ground material and harvesting above-ground biomass across a marsh elevation gradient. Data will be collected during two different field trips. This should

provide us with sufficient data to provide MEM results for the *Juncus* marshes at Eglin AFB. We will use existing Light Detection and Ranging (LiDAR), tide, and/or water quality data to prepare predictions of marsh response to sea level rise at Eglin AFB in Florida and make recommendations on adaptive management approaches. In addition to LiDAR, we will ground-truth our sample plot elevations with real-time kinematic global positioning system (RTK-GPS) to minimize elevation error from the LiDAR data. We will use this project as an opportunity to meet with Eglin natural resource managers, describe our research results and predictions for coastal wetlands, and demonstrate our models and adaptive management approaches. In addition, we will coordinate activities and potential marsh core analysis with a SERDP Research Project RC-1702, examining barrier island response to sea level rise and storm activity.

6.3.3 Assessment of Climate Change Impacts

Research Project CW-4 will assess the impacts of sea level rise on marsh sustainability with a point-based model that incorporates sediment transport processes influenced by vegetation. We will also assess past marsh response to sea level rise using core geochronology and will conduct experiments on the effects of surface elevation and tidal dynamics on marsh carbon flux. Using scenario testing, we will test marsh response to sea level rise under both a constant and accelerated rates. We will work with SERDP to develop these assumptions. Research Project CW-4 and the Aquatic/Estuarine Monitoring Program will measure the impact of storm (wind) events and tidal inundation on sediment delivery to salt marshes.

6.3.4 Intended Study Areas

MCBCL is the primary location for field work. In 2016, we will conduct field studies at Eglin AFB in Florida. Refined models will be adaptable for use in other estuarine locations with *Spartina alterniflora* or *Juncus roemerianus*–dominated marshes.

6.3.5 Milestones

1.	Complete marsh carbon decomposition experiments	10/2015
2.	Determine the relationship between surface elevation, tidal range and tidal datums (MHHW, MHW, and MSL), and below-ground *Spartina* production	12/2015
3.	Provide estimates of SSC and delivery to marsh surface at three sites (Freeman Creek, Mile Hammock Bay, and Traps Creek)	6/2016
4.	Assess long-term sediment accretion rates and predictions of carbon sequestration	12/2016
5.	Determine the relationship between *Juncus* above-ground and below-ground production across salinity and elevation gradients	12/2016
6.	Finalize the geospatial, morphological model (and user's guide) of factors driving marsh sustainability to sea level rise; provide predictions of *Spartina* and *Juncus* marsh site sustainability on MCBCL	12/2016

7. Report on the initial survey of *Juncus* marshes on Eglin AFB and provide management recommendations 6/2017
8. Prepare and deliver final Research Report 6/2017

6.3.6 Deliverables

1. Contribute to the development of carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5) Draft 3/2015; final 3/2017
2. Convene a special session at international conference (e.g., Society of Wetlands Scientists, American Geophysical Union, Coastal Education and Research Foundation) on marsh carbon sequestration and fate of eroded marsh sediment 12/2016
3. Finalize the geospatial, morphological model (and user's guide) of factors driving marsh sustainability to sea level rise 12/2016
4. Provide GIS layers and maps showing the predicted fate of MCBCL marshes under different sea level rise scenarios 9/2017
5. Report on the initial survey of *Juncus* marshes on Eglin AFB and provide management recommendations 9/2017
6. Report on adaptive management options for maintaining marsh habitats on MCBCL, with recommendations for large-scale implementation 12/2016
7. Make a presentation on marsh carbon fluxes at the Coastal Estuarine Research Federation Conference 11/2017
8. Prepare and deliver final Research Report Draft 3/2017; final 6/2017

6.3.7 Planned Publications

Submit an article with the preliminary title of "The Effect of Tidal Harmonics on Suspended Sediment in Salt Marsh Creeks, with Application to Parameterization of Salt Marsh Accretion Models." In this publication, we will synthesize our data on what controls in-channel SSC in tidal creeks and empirical relationships between marsh flooding and SSC. The expected submission date is June 2016.

Submit an article with the preliminary title of "Variability in Belowground Marsh Carbon Across an Estuarine Landscape." This will be a summary of our assessment of above-ground and below-ground biomass in *Spartina* and *Juncus* marshes with different tidal dynamics and across an elevation gradient. The expected submission date is December 2017.

Submit an article with the preliminary title of "A Mass Balance Carbon Budget for a Southeastern *Spartina alterniflora* Marsh." This article will summarize results of the marsh carbon flux studies. The expected submission date is December 2017.

6.4 Research Project CW-5: Marsh–Atmosphere and Marsh–Creek Exchanges of Carbon

Lead Investigator: Dr. Iris C. Anderson (VIMS)

Supporting Researchers: Drs. Carolyn Currin (NOAA), Craig Tobias (UCONN), and Scott Ensign (AquaCo)

Technical Objectives/Goals: The goals of Research Project CW-5 are to determine (1) seasonal exchanges of CO_2 and methane between marshes and the atmosphere in marshes of different elevations, vegetated with *Spartina alterniflora*, and located both along Freeman Creek in the ICW and Mile Hammock Bay within the NRE; and (2) seasonal diffusive and advective exchanges of DIC, DOC, and nutrients between marshes, overlying water, and tidal creeks.

Research Questions:

1. In *Spartina alterniflora*–dominated salt marsh at similar elevations, how does tide range affect GPP?
2. How will the ratio of production to respiration (P/R) vary with sediment accretion rate and elevation?
3. On an annual time scale, will NRE salt marshes demonstrate a net uptake of CO_2?
4. Is methane an important fate of fixed carbon in the salt marshes of the NRE?
5. What are the contributions of DIC, pCO_2, and DOC to diffusive and advective losses of carbon from salt marshes to the overlying water and adjacent tidal creeks?
6. On an annual time scale, will NRE salt marshes demonstrate a net uptake of DIN and phosphorus from overlying water?

6.4.1 Background

Salt marshes are bioreactors for carbon and nutrients and are sites of high primary production, organic matter decomposition, and respiration and nitrogen processing (Anderson et al., 1997; Miller et al., 2001; Neubauer et al., 2000 and 2005; Tobias et al., 2001; Tobias and Neubauer, 2009). The ability of marshes to keep up with sea level rise depends upon ecogeomorphic feedbacks resulting from marsh accretion due either to net accumulation of below-ground organic matter or sedimentation of particulate mineral matter, as described in Research Project CW-4 (Craft et al., 2009; Friedrichs and Perry, 2001; Kirwan et al., 2010 and 2012; Morris, 2007; Morris et al., 2002; Neubauer et al., 2002). Sources of carbon to marshes include photosynthetic fixation of atmospheric CO_2 by both macrophytes and BMA and deposition of POC delivered by tidal waters and associated with sediments. Potential fates of fixed carbon include losses as DIC and pCO_2 due to root/rhizome and microbial respiration, loss to the overlying water as DOC and POC, trophic transfer through the food web, and burial in sediment (Anderson et al., 1997; Childers et al., 2000; Miller et al., 2001; Neubauer et al., 2000). Research Project CW-5 will focus on determining the allocation of carbon fixed by marsh autotrophs to net ecosystem exchange (NEE) of CO_2 and methane with the atmosphere, export to overlying water and adjacent creeks as DIC or DOC, and burial as POC in sediments (Neubauer and Anderson, 2003; Neubauer et al., 2000 and 2002). Marshes are cited as important and, in some cases, dominant sources of DIC and pCO_2 to estuaries (Cai, 2011; Cai and Wang, 1998; Jiang et al., 2008; Neubauer and Anderson, 2003; Neubauer et al., 2000; Wang and Cai, 2004). In addition, degassing of estuarine pCO_2 derived from marshes may also be a significant source of CO_2 to the atmosphere (Cai, 2011; Raymond et al., 2000) and may exceed burial of carbon in sediments (Cai, 2011). Methane is another potentially important gaseous product of organic matter respiration in marshes because of its high global warming potential; however, we expect that in salt marshes, the NEE of methane will be minor, relative to CO_2 because of the

availability of sulfate in seawater, supporting anaerobic organic matter decomposition by sulfate reduction, an energetically more favorable reaction than CO_2 reduction to methane (Megonigal et al., 2004; Tobias and Neubauer, 2009; Weston et al., 2006 and 2011). DOC export from marshes to overlying water and tidal creeks has also been shown to be important in some marshes (Tobias and Neubauer, 2009).

Factors likely to determine the fate of the carbon fixed in marsh biomass include marsh elevation, vegetation type, inputs of nutrients, the duration of tidal marsh flooding (hydroperiod), tidal range, stresses due to sulfide and hypersalinity, light availability, and temperature (Friedrichs and Perry, 2001; Morris and Bradley, 1999; Morris et al., 2002; Tobias and Neubauer, 2009). Data from DCERP1 demonstrated large differences in tidal amplitude that influenced peak live above-ground biomass at two high salinity *Spartina alterniflora* sites, Freeman Creek (located off of the ICW) and Mile Hammock Bay (close to the inlet of the NRE; **Figure 6-7**). Mile Hammock Bay, which exhibits a higher tidal platform than Freeman Creek and was exposed to a smaller tidal range (**Figure 6-7**), demonstrated lower levels of peak above-ground biomass (**Figure 6-7**). One might expect that higher above-ground biomass would correlate with higher GPP, measured as daytime uptake of atmospheric CO_2 even though below-ground biomass usually represents a higher percentage of total marsh grass biomass (Schubauer and Hopkinson, 1984).

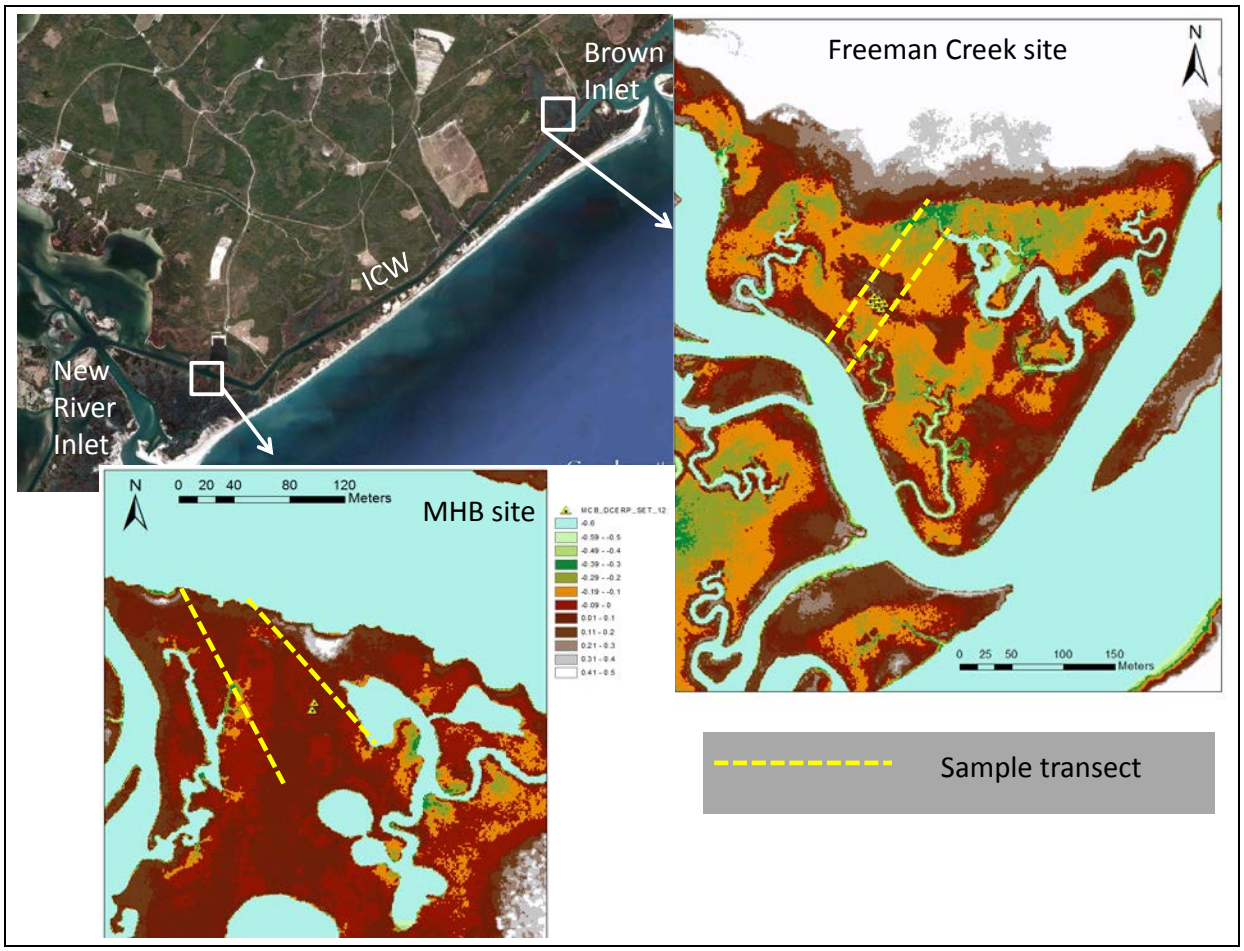

Figure 6-7. Location of proposed Mile Hammock Bay (MHB) and Freeman Creek (FC) sample sites along the ICW.

LiDAR imagery (2007) is used for site closeups. Existing SETs are illustrated with yellow triangles, and proposed sampling transects for CW-5 flux studies are shown with dotted yellow lines. The overall higher elevation of the MHB marsh is evident from the dark orange color of the marsh surface versus light orange to green color surface of the FC site. Both sites have depressions or ponded areas in the interior marsh.

To relate NEE of CO_2 and methane to elevation and tidal range, we propose to establish two transects each in the Freeman Creek and Mile Hammock Bay marshes. The transects will encompass elevational gradients, which include areas that appear to be accreting, eroding, and are ponded. We expect to observe a gradient in the ratio of P/R, varying with habitat condition, such that ponded areas will exhibit the lowest P/R. To scale short-term measures (minutes) of CO_2 and methane exchanges with the atmosphere to longer time scales (diel, seasonal, annual), we will make measurements at all sites seasonally and at multiple light levels to produce a series of production versus irradiance (P versus I) relationships, as described by Neubauer et al. (2000). The P versus I curves will allow us to integrate NEE through annual cycles and provide data required to determine a net carbon budget for *Spartina* marsh in the lower NRE system. In addition to measuring gas exchanges, we will also collect samples using fluctuating water chambers to assess exchanges of DIC, DOC, DON, DIN, and DIP between the marsh and overlying water. We will also collect samples along the marsh edge and will analyze them for

DIN, DON, DIC, DOC, and DIP to calculate advective losses of these constituents to the adjacent tidal creek.

6.4.2 Methods

6.4.2.1 Determination of Net Ecosystem Exchanges of CO_2 and Methane

Measurement of carbon fluxes

We will embed aluminum collars 10 cm into the sediment at three stations along two transects in both FC and MHB marshes (six chambers per marsh). The collars will remain in place for the duration of the study. The collars allow gas-tight attachment of a flux chamber, as shown in **Figure 6-8**. We will plug holes at the sediment surface, which allow drainage of water from the collar, prior to collecting flux measurements. We will collect these measurements between 10:00 a.m. and 3:00 p.m. and will cover the chambers with various layers of shade cloth to achieve full light, in the dark, and at intermediate light levels. We use three fans to stir air within the chamber and will use a heat exchanger, as described by Neubauer et al. (2000), to maintain temperature. We will continuously recirculate air within the chamber and will use a Li-Cor infrared gas analyzer to determine CO_2 concentrations. We will calibrate the instrument as described by Neubauer et al. (2000). We will record CO_2 concentrations at 1-minute intervals by datalogger for a total of between five and 15 measurements depending on the season. We will deploy two flux chambers at once: one for measuring CO_2 and the other for methane. Both measures will be made in the light and dark. We will collect samples for methane analyses by using a gas-tight syringe at 5- to 10-minute intervals for 30–60 minutes, depending on season, and will store them in gas-tight over pressurized Hungate tubes. We will return the methane samples to the laboratory for analysis by flame ionization detector gas chromatography. We will continuously monitor light and temperature using a Li-Cor photosynthetically active radiation sensor, while collecting gas flux measurements.

Measurements of benthic microalgal production and microbial respiration and calculation of marsh metabolic rates

As previously described, we will measure benthic microalgal production and microbial respiration, as described by Miller et al. (2001), using a small Plexiglas chamber, which can be placed between marsh plants. We will collect respiration measurements (e.g., microbial, root, faunal) in the dark. We will calculate marsh net community production, GPP, and respiration based on measured marsh exchanges of CO_2 and methane and microbial respiration as described by Anderson et al. (1997); Neubauer et al. (2000 and 2005); and Miller et al. (2001).

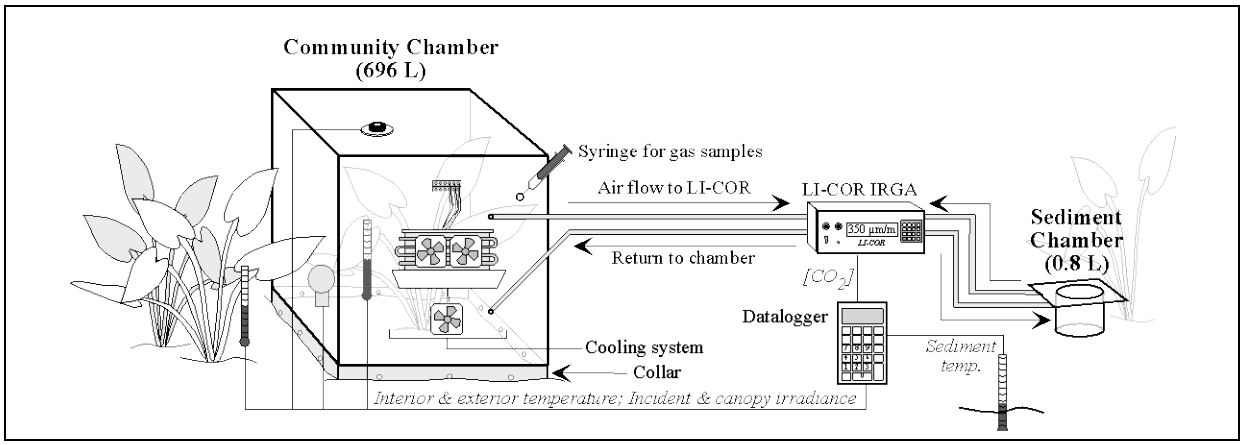

Figure 6-8. Temperature controlled chamber for determinations of marsh–atmosphere CO_2 and methane fluxes.

6.4.2.2 Diffusive and Advective Fluxes of Carbon and Nutrients Between Marshes, Overlying Water, and Adjacent Tidal Creeks

Measurements of diffusive carbon and nutrient fluxes

We will deploy fluctuating water level chambers, as shown in **Figure 6-9** and as described by Chambers (1992) and Chambers et al. (1992), seasonally along each transect and will use the instruments to collect water samples as tidal water floods the marsh surface. We will filter the samples collected in these chambers (0.2 µm) and will store them frozen until we are ready to analyze them for DIN, DON, DIC, DOC, and DIP, as shown in **Table 6-3**.

Figure 6-9. Fluctuating water chambers for measurements of diffusive fluxes of carbon and nutrients between the marsh and overlying water.

(Photo from Caitlin White)

Table 6-3. Summary of analytical methods

Analyses	Methods/Instrument	References
Nitrate, nitrite	Cadmium reduction/diazotization; Lachat[a]	Smith and Bogren, 2001
Ammonium	Phenol hypochlorite method; Lachat[a]	Liao, 2001
Dissolved inorganic phosphorus (DIP; phosphate)	Molybdate method; Lachat[a]	Knepel and Bogren, 2001
Total dissolved nitrogen (TDN)/dissolved organic nitrogen (DON)	Alkaline persulfate digestion; Lachat[a]	Koroleff, 1983
Dissolved inorganic carbon (DIC)	Acidification to CO_2; LI-6252 CO_2 analyzer or Shimadzu TOC-V analyzer	Neubauer and Anderson, 2003
Dissolved organic carbon (DOC)	680°C catalytically aided combustion oxidation/non-dispersive infrared detection; Shimadzu TOC-V analyzer	

[a] The Lachat auto analyzer (QuikChem 8000 automated ion analyzer, Lachat Instruments, Loveland, CO) is a continuous flow automated analytical system that complies with U.S. Environmental Protection Agency standards.

Measurements of pore water advection from marshes to adjacent creeks

We will install pore water sippers, as described by Neubauer and Anderson (2003), 1 m from the marsh edge at FC and MHB. We will collect water samples seasonally and will analyze them for DIC, DOC, DIN, DON, and DIP concentrations. We will calculate advection of these constituents using concentrations and an empirically derived linkage between the area of marsh edge and the marsh elevation over the tidal creeks (Lettrich, 2011).

6.4.2.3 Burial of Organic Carbon in Marsh Sediments

Long-term burial of carbon and nitrogen from phytoplankton, terrestrial, and marsh sources in marsh sediments will be determined, as described by Research Projects CW-4 and CB-5 based on down-core ^{210}Pb and ^{137}Cs geochronology (McKee, UNC), analyses of bulk density (Currin, NOAA; Anderson, VIMS), organic carbon, total nitrogen content, and bulk + compound-specific ^{13}C analyses (Tobias, UCONN).

6.4.3 Assessment of Climate Change Impacts

Research Project CW-5 will measure exchanges of carbon (as methane and CO_2) between the intertidal marsh surface, the atmosphere, overlying water, and the adjacent creek. We will take measurements in light and dark conditions and at various light levels and temperatures, including the current range in seasonal temperature variation. These data will be used for calibration and/or validation of the ESM run under different scenarios of climate change. Assessing the effects of climate change on the role of marshes in the estuarine/coastal carbon budget within the ESM (Research Project TSP-2) will involve simulations with increased temperatures (derived from Research Project CC-1), sea level (scenarios approved by SERDP), and atmospheric CO_2 levels. This will also involve changes in the supply of nutrients and sediments, which will be based upon estimated changes in freshwater supply due to changes in precipitation (derived from Research Project CC-1).

6.4.4 Milestones

1. Determine marsh metabolic parameters 7/2016
2. Determine marsh–atmosphere CO_2 and methane exchanges 10/2016
3. Determine marsh–water diffusive carbon and nutrient exchanges 7/2016
4. Determine marsh–creek advective carbon and nutrient exchanges 10/2016
5. Develop marsh carbon budget 6/2016
6. Prepare and deliver final Research Report 10/2016

6.4.5 Deliverables

1. Contribute to the development of carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5) Draft 3/2015; final 3/2017
2. Make a presentation at the Coastal Estuarine Research Federation Conference 12/2016
3. Prepare and deliver final Research Report 10/2016

6.5.6 Planned Publications

Submit a journal article discussing the seasonal exchanges of CO_2, methane, carbon, and nutrients between marshes, overlying water, and tidal creeks. The submission of this article is planned for December 2016.

6.5 Literature Cited

Anderson, I.C., C.R. Tobias, B.B. Neikirk, and R.L. Wetzel. 1997. Development of a process-based mass balance model for a Virginia *Spartina alterniflora* salt marsh: Implications for net DIN flux. *Marine Ecology Progress Series 159*:13–27.

Appleby, P.G., and F. Oldfield. 1992. Application of lead-210 to sedimentation studies. In *Uranium-Series Disequilibrium: Applications to Earth, Marine and Environmental Sciences*. Edited by M. Ivanovich, and R. Harmon. Clarendon Press: Oxford.

Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan. 2007. *Observations: Oceanic Climate Change and Sea Level. Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge.

Blum, L. 1993. *Spartina alterniflora* root dynamics in a Virginia marsh. *Marine Ecology Progress Series 102*:69–178.

Blum, L.K., and R.R. Christian. 2004. Belowground production and decomposition along a tidal gradient in a Virginia salt marsh. Pp. 47–74 in *The Ecogeomorphology of Tidal Marshes*. Edited by S. Fagherazzi, M. Marani, and L.K. Blum. American Geophysical Union, Washington, DC.

Brigham, S.D., J.P. Megonigal, J.K. Keller, N.P. Bliss, and C. Trettin. 2006. The carbon balance of North American wetlands. *Wetlands 26*:889–916.

Cahoon, D.R., M.A. Ford, and P.G. Hensel. 2004. Ecogeomorphology of *Spartina patens*-dominated tidal marshes-soil organic matter accumulation, marsh elevation dynamics, and disturbance. *Coastal and Estuarine Studies 59*:247–266.

Cahoon, D.R., P.F. Hensel, T. Spencer, D.J. Reed, K.L. McKee, and N. Saintilan. 2006. Coastal wetland vulnerability to relative sea- level rise: wetland elevation trends and process controls. *Wetlands and Natural Resource Management: Ecological Studies 190*:271–292.

Cai, W.J. 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? *Annual Review of Marine Science 3*:123–145.

Cai, W.J., and Y. Wang 1998. The chemistry, fluxes, and sources of carbon dioxide in the estuarine waters of the Satilla and Altamaha Rivers, Georgia. *Limnology and Oceanography 43*:657–668.

Chambers, R.M. 1992. A fluctuating water level chamber for biogeochemical experiments in tidal marshes. *Estuaries 15*:53–58.

Chambers, R.M., J.W. Harvey, and W.E. Odum. 1992. Ammonium and phosphate dynamics in a Virginia salt marsh. *Estuaries 15*:349–359.

Chauhan, P.P.S. 2009. Autocyclic erosion in tidal marshes. *Geomorphology 110*:45–57.

Childers, D.L., J.W. Day Jr., and H.N. McKellar Jr. 2000. Twenty more years of marsh and estuarine flux studies: Revisiting Nixon (1980). Pp. 391–423 in *Concepts and Controversies in Tidal Marsh Ecology*. Edited by M. Weinstein, and D.A. Kreeger. Kluwer Academic Publishing: Dordrecht, The Netherlands.

Christian, R.C., W.L. Bryant, and M.M. Brinson. 1990. Juncus roemerianus production and decomposition along gradients of salinity and hydoperiod. *Marine Ecology Progress Series 68*:137–145.

Cowart, L., J.P. Walsh, and D.R. Corbett. 2010. Analyzing estuarine shoreline change: A case study of Cedar Island, NC. *Journal of Coastal Research 26*(5):817–830.

Craft, C., J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H. Guo, and M. Machmuller. 2009. Forecasting the effects of accelerated sea level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment 7*:73–78.

Croft, A.L., L.A. Leonard, T.D. Alphin, L.B. Cahoon, and M.H. Posy. 2006. The effects of thin layer sand renourishment on tidal marsh processes: Masonboro Island, North Carolina. *Estuaries and Coasts 29*:737–750.

Currin, C.A., W.S. Chappell, and A. Deaton. 2010. Developing alternative shoreline armoring strategies: The living shoreline approach in North Carolina. Pp. 91–102 in *2010, Puget Sound Shorelines and the Impacts of Armoring-Proceedings: USGS Scientific Investigations Report 2010-5254*. Edited by H. Shipman, M. Dethier, G. Gelfanbaum, K.L. Fresh, and R.S. Dinicola.

Dahl, T.E. 2011. *Status and Trends of Wetlands in the Conterminous United States 2004–2009*. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC. 108 pages.

DeMaster, D.J., B.A. McKee, C. Nittrouer, Q. Jiangchu, and C. Guodong. 1985. Rates of sediment accumulation and particle reworking based on radiochemical measurement from continental shelf deposits in the East China Sea. *Continental Shelf Research 4*:143–158.

Engelhart, S.E., B.P. Horton, B.C. Douglas, W.R. Peltier, and T.E. Tornqvist. 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic Coast of the United States. *Geology 37*:1115–1118.

Friedrichs, C.T., and J.E. Perry. 2001. Tidal salt marsh morphodynamics: A synthesis. *Journal of Coastal Research 27*:7–37.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. *Climatic Change 106*:7–29.

Harrison, A.F. and K.L. Bloom. 1977. Estimation of soil bulk density from loss-on-ignition values. *Journal of Applied Ecology 8*:919–927.

Hopkinson, C., W.J. Cai, and X. Hu. 2012. Carbon sequestration in wetland dominated coastal systems—A global sink of rapidly diminishing magnitude. *Current Opinions on Environmental Sustainability 4*:186–194.

Jiang L.Q., W.J. Cai, and Y. Wang. 2008. A comparative study of carbon dioxide degassing in river- and marine-dominated estuaries. *Limnology and Oceanography 53*(6):2603–2615.

Jordan, T.E., D.L. Correll, and D.F. Whigham. 1983. Nutrient flux in the Hode River: Tidal exchange of nutrients by brackish marshes. *Estuarine Coastal and Shelf Science 17*:651–667.

Kemp, A.C., B.P. Horton, J.D. Donnelly, M.E. Mann, M. Vermeer, and S. Rahmstorf. 2011. Reply to Grinsted et al.: estimating land subsidence in North Carolina. In *Proceedings of the National Academy of Sciences 108*:E783.

Kirwan, M.L., and A.B. Murray. 2007. A coupled geomorphic and ecological model of tidal marsh evolution. *PNAS 104*:6118–6122.

Kirwan, M.L., and L.K. Blum. 2011. Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences 8*:987–993.

Kirwan, M.L., R.R. Christian, L.K. Blum, and M.M. Brinson. 2012. On the relationship between sea level and *Spartina alterniflora* production. *Ecosystems 15*(1):140–147.

Kirwan M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters 37*:L23401. 5 pages.

Kirwan, M.L., and S.M. Mudd. 2012. Response of salt-marsh carbon accumulation to climate change. *Nature* 489:550–553.

Kneib, R.T. 1997. The role of tidal marshes in the ecology of estuarine nekton. Pp. 163–220 in *Oceanography and Marine Biology: Annual Review*. Edited by A.D. Ansell, R.N. Gibson, and M. Barnes. Kluwer Academic Publishers.

Knepel, K., and K. Bogren. 2001. Determination of Orthophosphate by Flow Injection Analysis. QuikChem Method 31-115-01-1-H. Lachat Instruments, Milwaukee, WI.

Knutson, P.L., R.A. Brochu, W.N. Seelig, and M. Inskeep. 1982. Wave damping in *Spartina alterniflora* marshes. *Wetlands* 2:87–104.

Kolker, A.S., S.L. Goodbred, S. Hameed, and J.K. Cochran. 2009. High-resolution records of the response of coastal wetland systems to long-term and short-term sea level variability. *Estuarine, Coastal and Shelf Science. 84*:493–508.

Koroleff, F. 1983. Total and organic nitrogen. Pp. 162–169 in *Methods of Seawater Analysis*. Edited by K. Grasshoff, M. Ehrhardt, and K. Kremling. Verlag-Chemie: Weinheim, Germany.

Langley, J.A., K.L. McKee, D.R. Cahoon, J.A. Cherry, and J.P. Megonigal. 2009. Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea level rise. In *Proceedings of the National Academy of Sciences 106*:6182–6186.

Leonard, L.A., A.C. Hine, M.E. Luther, and E.E. Weight. 1995. Sediment transport processes in a west-central Florida open marine marsh tidal creek—The role of tides and extra-tropical storms. *Estuarine Coastal and Shelf Science* 41:225–248.

Lettrich, M. 2011. *Balancing Nitrogen Advection and Losses in Southeastern North Carolina Salt Marshes*. Master's Thesis. University of North Carolina at Wilmington, Wilmington, NC.

Levin, L.A., D.F. Boesch, A. Covich, C. Dahm, C. Erséus, K.C. Ewel, R.T. Kneib, A. Moldenke, M.A. Palmer, P. Snelgrove, D. Strayer, and J.M. Weslawski. 2001. The function of marine critical transition zones and the importance of sediment biodiversity. *Ecosystems 4*:430–451.

Liao, N. 2001. Determination of Ammonia in Brackish or Seawater by Flow Injection Analysis. QuikChem Method 31-107-06-1-B. Lachat Instruments, Milwaukee, WI.

Mattheus, C.R., A. Rodriguez, B. Mckee, and C.A. Currin. 2010. Impact of land-use change and hard structures on the evolution of fringing marsh shorelines. *Estuarine, Coastal and Shelf Science 88*: 365–376.

McKee, B., A.S. Cohen, D.L. Dettman, M.R. Palacios-Fest, S.R. Alin, and G. Ntungumburanye. 2005. Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: II. Geochronologies and mass sedimentation rates based on C-14 and Pb-210 data. *Journal of Paleolimnology 34*:19–29.

Mcleod, E., G.L. R. Salman, M. Bjork, S. Bouillon, C. Duarte, C. Lovelock, and B.R. Silliman. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment 9*(10):552–560.

Megonigal, J.P., M.E. Hines, and P.T. Visscher. 2004. Anaerobic metabolism: Linkages to trace gases and aerobic processes. Pages 317–424 in *Biogeochemistry*. Edited by W.H. Schlesinger. Elsevier-Pergamon: Oxford, UK.

Miller, W.D., S.C. Neubauer, and I.C. Anderson. 2001. Effects of sea level induced disturbances on high salt marsh metabolism. *Estuaries 24*(3):357–367.

Möller, I., T. Spencer, J.R. French, D. Legget, and M. Dixon. 1999. Wave transformation over salt marshes: A field and numerical modeling study from North Norfolk, England. *Estuarine Coastal and Shelf Science 49*:411–426.

Morris, J.T. 1991. Effects of nitrogen loading on wetland ecosystems with particular reference to atmospheric deposition. *Annual Review of Ecology and Systematics 22*:257–279.

Morris, J.T. 2007. Ecological engineering in intertidal salt marshes. *Hydrobiologia* 577:161–168.

Morris, J.T., and P.M. Bradley. 1999. Effects of nutrient loading on the preservation of organic carbon in wetland sediments. *Limnology and Oceanography 44*:699–702.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology 83*:2869–77.

Mudd, S.M., S.M. Howell, and J.T. Morris. 2009. Impact of dynamic feedbacks between sedimentation, sea level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. *Estuarine, Coastal and Shelf Science 82*:377–389.

Nellemann, C., E. Corcoran, C.M. Duarte, L. Valdes, C. DeYoung, L. Fonseca, and G. Grimsditch (Eds.). 2009. *Blue Carbon. A Rapid Response Assessment*. United Nations Environment Programme, GRID-Arendal. GRID number ISBN: 978-82-7701-060-1.

Neubauer, S.C., and I.C. Anderson. 2003. Transport of dissolved inorganic carbon from a tidal freshwater marsh to the York River Estuary. *Limnology and Oceanography 48*:299–307.

Neubauer, S.C., I.C. Anderson, and B.B. Neikirk. 2005. Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh. *Estuaries 28*:909–922.

Neubauer, S.C., I.C. Anderson, J.A. Constantine, and S.A. Kuehl. 2002. Sediment deposition and accretion in a mid-Atlantic (USA) tidal freshwater marsh. *Estuarine Coastal and Shelf Science 54*:713–727.

Neubauer, S.C., W.D. Miller, and I.C. Anderson. 2000. Carbon cycling in a tidal freshwater marsh ecosystem: A gas flux study. *Marine Ecology Progress Series* 199:13–30.

Nyman, J.A., R.J. Walters, R.D. Delaune, and W.J. Patrick. 2006. Marsh vertical accretion via vegetative growth. *Estuarine Coastal Shelf Science 69*:370–380.

Pawlowicz, R., B. Beardsley, and S. Lentz. 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Computers & Geosciences 28*:929–937.

Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, C. Craft, J.W. Fourqurean, J.B. Kauffman, N. Marbà, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, and A. Baldera. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS One 7*:e43542.

Raymond, P.A., J.E. Bauer, and J.J. Cole. 2000. Atmospheric CO_2 evasion, dissolved inorganic carbon production, and net heterotrophy in the York River Estuary *Limnology and Oceanography 45*(8):1707–1717

Ruiz-Fernandez, A., C. Hillaire-Marcel, A. de Vernal, M.L. Machain-Castillo, L. Vasquez, B. Ghaleb, J. Aspiazu-Fabian, and F. Paez-Osuna. 2009. Changes of coastal sedimentation in the Gulf of Tehuantepec, South Pacific Mexico, over the last 100 years from short-lived radionuclide measurements. *Estuarine, Coastal and Shelf Science 82*(3):525–536.

Schubauer, J.P., and C.S. Hopkinson. 1984. Above-and below-ground emergent macrophyte production and turnover in a coastal marsh ecosystem, Georgia. *Limnology and Oceanography 29*:1052–1065.

Smith, P., and K. Bogren. 2001. Determination of Nitrate and/or Nitrite in Brackish or Seawater by Flow Injection Analysis Colorimetry. QuikChem Method 31-107-04-1-E. Lachat Instruments, Milwaukee, WI.

Stagg, C.L., and I.A. Mendelssohn. 2010. Restoring ecological function to a submerged salt marsh. *Restoration Ecology 18*:10–17.

Tobias, C.R., and S.C. Neubauer. 2009. Salt marsh biogeochemistry—an overview. P. 445 in *Coastal Wetlands: An Integrated Ecosystem Approach*. Edited by G.M.E. Perillo, E. Wolanski, D.R. Cahoon, and M.M. Brinson. Elsevier Science. ISBN: 978-0-444-53103-2.

Tobias, C.R., I.C. Anderson, E.A. Canuel, and S.A. Macko. 2001. Nitrogen cycling through a fringing marsh–aquifer ecotone. *Marine Ecology Progress Series* 210:25–39.

Tobias, C.R., and S.C. Neubauer. 2009. Salt marsh biogeochemistry: An overview. Pp. 445–492 in *Coastal Wetlands: An Integrated Ecosystem Approach*. Edited by G. Perillo, E. Wolanski, D. Cahoon, and M. Brinson. Elsevier.

USGS (U.S. Geological Survey). 2005. *National Field Manual for the Collection of Water-Quality Data (TWR1 Book 9)*. Available at http://water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html.

Valiela, I., and J.M. Teal. 1979. The nitrogen budget of a salt marsh ecosystem. *Nature 280*:652–656.

Vermeer, M., and S. Rahmstorf. 2009. Global sea level linked to global temperature. In *Proceedings of the National Academy of Sciences 106*:21527–21532.

Wang, Z.A., and W.-J Cai. 2004. Carbon dioxide degassing and inorganic carbon export from a marsh dominated estuary (the Duplin River): A marsh CO_2 pump. *Limnology and Oceanography 49*:341–354.

Weston, N.B., M.A. Vile, S.C. Neubauer, and D.J. Velinksy. 2011. Accelerated microbial organic matter mineralization following salt-water intrusion into tidal freshwater marsh soils. *Biogeochemistry 102*:135–151.

Weston, N.B., W.P. Porubsky, V.A. Samarkin, M. Erickson, S.E. Macavoy, and S.B. Joye. 2006. Porewater stoichiometry of terminal metabolic products, sulfate, and dissolved organic carbon and nitrogen in estuarine intertidal creek-bank sediments. *Biogeochemistry 77*:375–408.

Wood, N., and A.C. Hine. 2007. Spatial trends in marsh sediment deposition within a microtidal creek system, Waccasassa Bay, Florida. *Journal of Coastal Research 23*(4):823–833.

Zervas, C. 2004. *North Carolina Bathymetry/Topography Sea Level Rise Project: Determination of Sea Level Trends*. NOAA Technical Report number NOS CO-OPS 041. Available at http://tidesandcurrents.noaa.gov/publications/techrpt41.pdf.

7.0 Coastal Barrier Module

7.1 Introduction

The coastal barrier ecosystem at MCBCL extends from the shoreface toe at −10-m water depth to the estuarine or ICW shoreline. This ecosystem encompasses the shoreface, tidal inlet, backshore beach, aeolian dune, shrub zone, maritime forest, and washover sand flat habitats. These habitats are defined by intrinsic ecological processes, but are linked together by sediment transport, nutrient exchange, and biological uses, each of which undergoes substantial change over multiple time scales.

The entire ecology of coastal barriers is organized directly and indirectly by the physical dynamics of meteorologically driven ocean forcing and the resulting sediment transport and morphologic changes (Godfrey and Godfrey, 1976; Wells and Peterson, 1986) (**Figure 7-1**). Variations in the underlying geology and bathymetry of coastal areas influence how shorelines will respond (i.e., accrete, erode, change in sediment type) to different physical forcings (McNinch, 2004; Rodriguez et al., 2004). Low-lying coastal barriers, such as those of MCBCL, experience frequent overwash during storms. This process reinitiates the succession of dune and shrub-zone plant communities, provides new habitat for bird nesting and foraging, and extends and revitalizes salt marshes when overwash progresses across the island to the sound shoreline. After storms form new washover fans, sediment transport across the island via aeolian processes is more efficient due to the reduction in vegetation density.

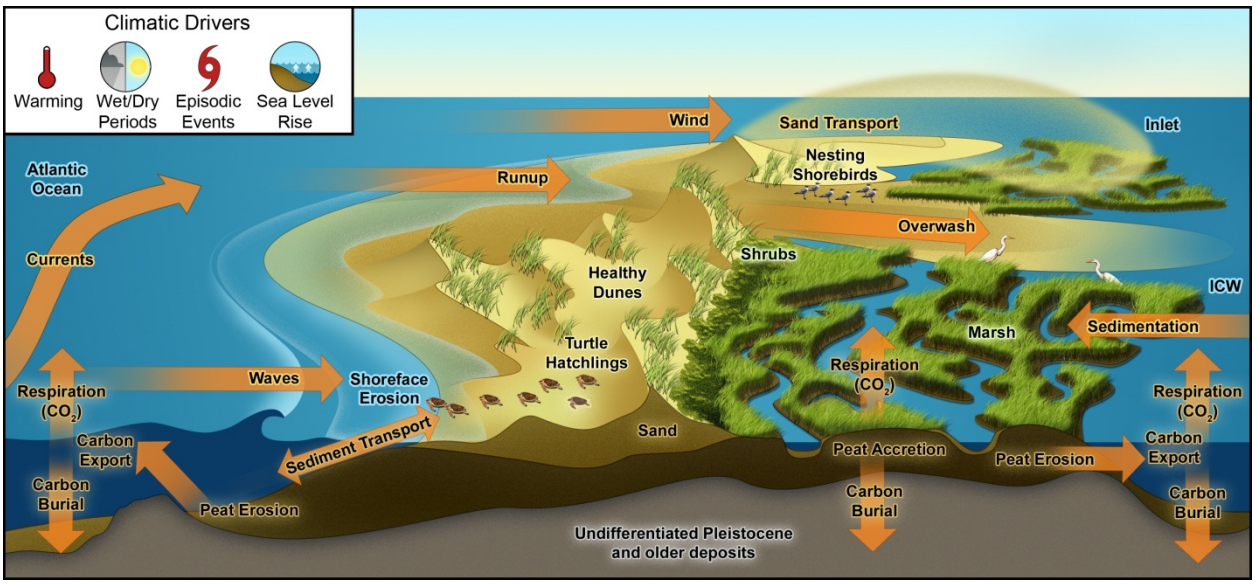

Figure 7-1. A conceptual model for the Coastal Barrier Module.

The intertidal portion of the shoreface enjoys a high production of characteristic invertebrates, such as coquina clams (*Donax variabilis*) and mole crabs (*Emerita talpoida*), and this qualifies the area as a key habitat, one that supplies food for abundant and valuable surf fishes, crabs, and shorebirds (Brown and McLachlan, 1990; Fraser et al., 2005), which were the focus of DCERP1. This area is also the most morphologically dynamic portion of the barrier, and it is constantly

changing shape with changing tides, sea state, and sea level. The proposed research projects of the Coastal Barrier Module (**Table 7-1**) build upon the monitoring and research data from DCERP1.

Table 7-1. Coastal Barrier Module research projects, senior researchers, outcomes and benefits to MCBCL, and the duration of the projects

Project	Research Project Title	Senior Researcher and Duration
CB-4	*Predicting Sustainability of Coastal Military Training Environments: Developing and Evaluating a Simplified, Numerical Morphology Model*	**Senior Researcher:** Jesse McNinch
	Outcomes and benefits: 1. Predict coastal conditions (e.g., waves, shoreline, beach width, surge) during storm events 2. Develop a calibrated beach morphology model that has constrained uncertainties needed for predicting longer, climate-relevant time periods 3. Predict shoreline position, beach width, and overwash over long time periods (assessed from observations over the past decade; forecast periods defined by SERDP–requested time scenarios) and graphically display results for the multiple scenarios of storminess and sea level rise for use by MCBCL. 4. Develop a Management Plan to help MCBCL determine the appropriate management strategies to follow for Onslow Beach to enhance sustainability of military training area under varying climate scenarios.	**Duration:** 5/2013–10/2017
CB-5	*Linking Barrier Island Transgression Induced by Storms and Sea Level Rise to the Carbon Cycle, Changes in Ecosystem Function, and Management Decisions*	**Senior Researcher:** Tony Rodriguez
	Outcomes and benefits: We will produce a barrier-island carbon budget, direct measures of island morphologic change, and maps to aid with decision support, including better predictions of areas subject to nest inundation, areas where dune restoration will be most beneficial, and management guidelines for deciding when island infrastructure (buildings, egresses, and access roads) should be moved landward. We will integrate Research Projects CB-4 (C15-CSHORE model), RC-1702, and TSP-2 and predictions of marsh accretion from Research Project CW-4 to determine the likely effects of projected increased rates of sea level rise and storminess on our measurements.	**Duration:** 3/2013–3/2017

Onslow Beach is a northeast-southwest trending barrier island located at MCBCL in southeastern North Carolina (**Figure 7-2**). Onslow Beach is a wave-dominated barrier with a mean significant wave height of 0.71 m and tidal range of 1.2 m based on 3 years of wave data (DCERP1 acoustic wave and current [AWAC] recorder) collected 750 m offshore of the island in 8 m of water (34.544000°, −77.296500°) and NOAA's tide gauge at Wrightsville Beach, NC (Station ID 8658163, located 60 km southwest of Onslow Beach), respectively. This 12 km–long barrier fronts salt marsh and is bounded by the New River Inlet to the southwest and Browns Inlet to the northeast. The ICW extends through the backbarrier marsh. The shoreline of Onslow Beach is sinusoidal, with a central headland separating two shallow, cuspate embayments. The morphology of the island also varies along its length. The northern arcuate section has a wide

beach (approximately 80-m wide) with multiple well-developed dune ridges (7–9 m in height). Landward of the dune ridges, a narrow (less than 100-m wide) maritime forest abuts the backbarrier salt marsh. This northern section of the barrier has low net decadal rates of accretion of approximately 0.25 m/y (Benton et al., 2004; Rodriguez et al., 2012). The central headland area has a narrow beach (approximately 20-m wide) with a single discontinuous dune ridge less than 4 m in height. Numerous washover fans extend less than 100 m across the dunes, and the vegetation is dominated by shrub thickets, but dead trees (standing and fallen) are frequently observed. The beach widens significantly along the southern embayment from 20 m in the northeast to 80 m in the southwest. The discontinuous dunes are less than 2 m in height, and washover fans can be extensive (250-m wide) and extend across backbarrier marshes. This southern portion of Onslow Beach has a net erosion rate of approximately 2 m/y, and erosion rates decrease toward the headland where shoreline position is highly variable through time (Benton et al., 2004; Rodriguez et al., 2012).

The variable morphology of Onslow Beach reflects its central location within Onslow Bay because it defines the border between the high-elevation regressive islands, with multiple beach ridges to the north and the low-elevation, narrow transgressive islands to the south (Cleary et al., 1996). The central headland is produced by a submarine rock ridge that intersects Onslow Beach (Riggs et al., 1995). The rock ridge is composed of the Oligocene Silverdale Formation, a sandy, molluscan-mold limestone unit (Harris et al., 2000). The Quaternary sediment layer is thin and patchy offshore of southern and central Onslow Beach, where more than 50% of the inner shelf is exposed limestone (Johnston, 1998); Riggs et al. (1995) labeled Onslow Beach as being "sediment starved." The washover fans in the central and southern portions of Onslow Beach indicate that storms are an important driver of geomorphologic change on the island. Historical records show that 35 hurricanes passed within 120 km of Onslow Beach from 1857 Anno Domini (A.D.) to 2011. Six out of the 35 hurricanes were Category 3 or higher (wind speeds ≤178 km/h; for more information, see NOAA's Web site at http://csc.noaa.gov/hurricanes). Hurricane Fran (Category 3) made landfall in September 1996 and transported 199,000 ±88,000 m^3 of sand across the backbarrier environments forming an extensive washover fan at the southern end of Onslow Beach (Foxgrover, 2009). Hurricane Bertha (Category 3) made landfall 2 months prior and likely contributed to significant overwash of the island during Hurricane Fran by eroding and degrading the dunes. After Hurricane Fran, Hurricane Irene (Category 1, wind speeds ≤119 km/h) was the next large storm to cause significant overwash at Onslow Beach. Hurricane Irene made landfall in August 2011 at Cape Lookout, NC, 70 km northeast of the study area, and formed washover terraces and fans along the southern and central parts of Onslow Beach. Low-lying coastal barriers, such as those of MCBCL, experience frequent overwash during storms. This process reinitiates the succession of dune and shrub-zone plant communities, provides a new habitat for bird nesting and foraging, and extends and revitalizes salt marshes when overwash progresses across the island to the sound-side shoreline. After storms form new washover fans, sediment transport across the island via aeolian processes is more efficient due to the reduction in vegetation density and the provision of smaller sized sand grains by overwash.

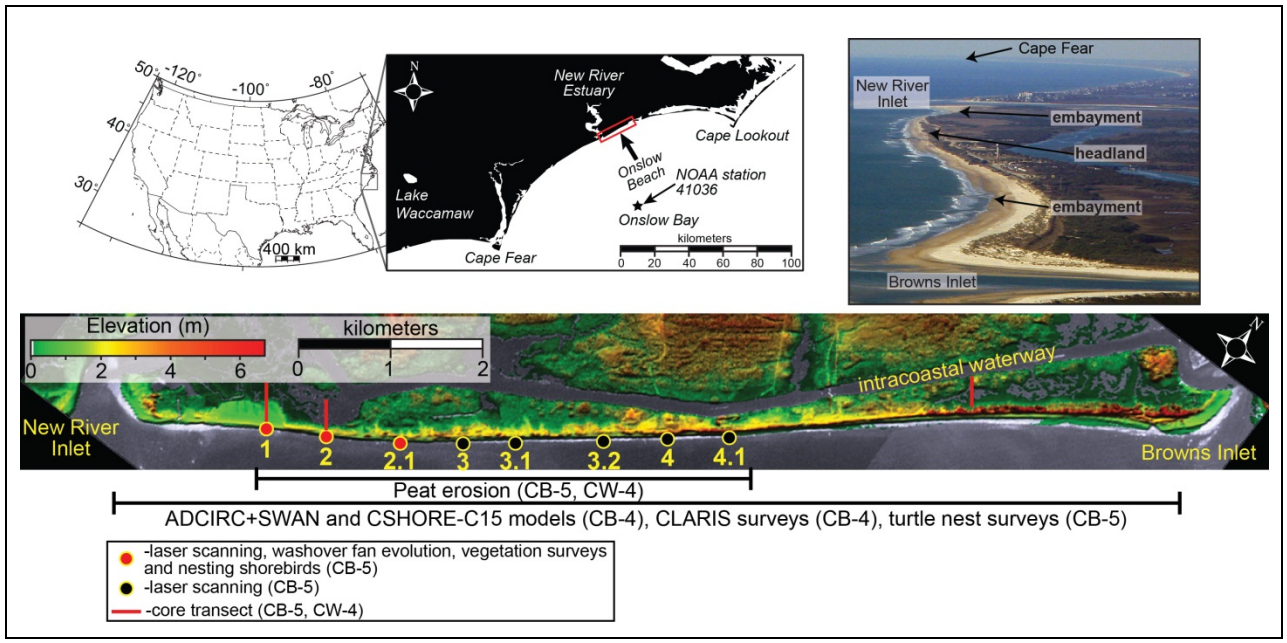

Figure 7-2. A study area map showing the proposed areas where data will be collected.

Note: ADCIRC = Advanced Circulation; CLARIS = Coastal LiDAR (Light Detection and Ranging) and Radar Imaging System; SWAN = Simulating Waves Nearshore; and NOAA station 41036 is an offshore buoy.

MCBCL created four, spatially explicit use zones along Onslow Beach. The southwestern portion of the island is used primarily by off-road recreational vehicles. People drive to this end of the island mainly to access fishing spots near the New River Inlet. The central part of the island is used for military training, and the main disturbance is large vehicles and equipment creating ruts in the beach. An access road (unpaved) behind the dune is also maintained. Egress points connect the road to the beach and are situated at natural breaks in the dune line that were formed by storms. Northeast of the training zone is the recreational portion of the beach, and the main impact there is from foot traffic. The northeastern end of the island serves as a buffer zone between Onslow Beach and adjacent Browns Island, which is an impact area that is used in ordnance testing. The northeastern end of the island is restricted from foot and vehicular traffic. Results from DCERP1 show that these different use zones, in their current state and intensities of activity, are not impacting the morphologic evolution of the island. Rather, storms and variations in the underlying sediment composition are the main drivers of morphologic change, and consequently ecological processes, at yearly time scales.

7.2 Knowledge Gaps in Conceptual Model and Research Needs

An improved understanding of the morphological response of the coastal barrier ecosystem to changes in sea level rise and storminess is critical for better shoreline management at MCBCL and at other coastal DoD installations (Pilkey et al., 1993). The activities of Research Project CB-4 will be carried out along the entire barrier island, whereas the activities of Research Project CB-5 will be localized (**Figure 7-2**). During DCERP2, we will address the following three fundamental research questions: (1) how will the morphology of Onslow Beach change in the future under different sea level rise and storminess conditions (Research Project CB-4), (2) how will this future morphology impact nesting shorebirds and sea turtles (Research Projects CB-4 and CB-5), and (3) how does the barrier function as a carbon sink and source (Research Project

CB-5)? The role of variations in the underlying geology and principal sediment-transport pathways in modulating shoreline-erosion rates, decadal-yearly shoreline changes along the island, and an overwash-prediction model for the island were produced as part of DCERP1. Extensive sub-bottom mapping and coring across the nearshore of Onslow Beach during DCERP1 also yielded a rarely matched constraint of the sediment budget. These data will be used in DCERP2 to help address fundamental research questions. However, modeling is required to determine how future rates of sea level rise and changes in storminess (e.g., frequency and magnitude of storms) will impact island morphology and vulnerability to storm overwash. It is important to note that Research Projects CB-4 and CB-5 will be using the same assumptions and information regarding overwash.

There is mounting interest in the role of “blue carbon” habitats in mitigating anthropogenic climate change by inducing long-term (i.e., millennial) burial of biological carbon, but it is unknown if the backbarrier marsh functions as a relevant carbon sink at a transgressive barrier setting such as Onslow Beach. Backbarrier salt marshes provide important ecosystem services, which include carbon sequestration from the atmosphere and below-ground storage in the form of peat and organic-rich sediment. As the barrier moves landward and over backbarrier marshes, this carbon is buried for some unknown period of time before it becomes exposed to the ocean’s hydrodynamic processes and is eroded on the beach. We do not know the time scale over which carbon is buried in the backbarrier marsh and subsequently eroded on the beach. In addition, we do not know the composition of the peat. These knowledge gaps need to be constrained before we can develop a barrier island carbon budget. Finally, to manage better nesting shorebirds and sea turtles, information will be needed to assess short-term impacts of washover and dune degradation and to document rates of recovery by the critical floral communities that transform the dynamics of the geologic formations (e.g., washover fans and dunes) and are directly used by threatened and endangered species. As these data gaps are filled, researchers will revise the conceptual models to reflect the new understanding of the ecosystem processes gained and to make the information more understandable for reaching the widest audience of users.

7.3 Research Project CB-4: Predicting Sustainability of Coastal Military Training Environments: Developing and Evaluating a Simplified, Numerical Morphology Model

Lead Investigator: Dr. Jesse McNinch (USACE CHL-ERDC)

Supporting Researchers: Drs. Richard Luettich (UNC-IMS), Janelle Fleming (Seahorse Coastal Consulting), Jason Fleming (Seahorse Coastal Consulting)

Technical Objectives/Goals: The objective of Research Project CB-4 is to predict oceanographic and beach morphology under varying climate change scenarios using a simplified, numerical morphology model.

We plan to use a coupled coastal hydrodynamics (Advanced Circulation [ADCIRC] model + Simulating Waves Nearshore [SWAN]) and morphology modeling (CSHORE-C15) system for predicting the response of the shoreline to variations in frequency of storms and intervening quiescent periods at MCBCL. Long term, sustainability practices could be enhanced at MCBCL and other coastal installations if surf and beach conditions (e.g., wave height, shoreline position, beach width, overwash) can be accurately predicted during storms and up-scaled to longer time periods. Coastal inundation from storm-driven processes (e.g., surge, tides, wave runup) often dwarf even the most extreme sea level rise predictions over 50 to 100 years, and it is critical that we have a beach morphology model that has been fully assessed and demonstrates skill during storm conditions and under more common, daily conditions. Existing models that fully couple morphology and coastal hydrodynamics (e.g., Delft3D, XBeach) are computationally expensive and difficult to run on time and spatial scales that are needed for SERDP–relevant climate change questions. We will evaluate CSHORE-C15 using data observed over the past 5 years of DCERP1 and the next 5 years of DCERP2. Model forecasts over longer time periods (10^0–10^2) will use sea-level and storminess scenarios defined by SERDP to aid in the management of coastal ecosystems and shape strategies for sustainability of training areas.

Hypotheses:

H1: Shoreline and beach morphology will be more sensitive to storm groupiness, defined by short time periods between storms, than the magnitude of the larger, individual storms.

H2: Beach width will decrease in the northeastern portion of Onslow Beach where the dune field is high and extensive; conversely, beach width will increase in the southwestern portion of Onslow Beach where the dunes are extensively overwashed.

7.3.1 Background

Sea level rise and associated shoreline transgression are important to coastal installations such as MCBCL at time scales spanning storm events to decades because the geology underlying the migrating beach dictates: (1) morphology and bathymetry of the surf zone, and (2) the volume of sand that may be recycled and contributed to the modern sediment budget. For example, regions of the barrier island that migrate into rock behave differently from regions that migrate into largely muddy sediments. Interestingly, it is not just a simple matter of one region being more erosion resistant than others or one region providing more sand than another. The characteristics of the geology exposed in the surf zone influence the bathymetry which, in turn, influences the wave energy and sediment transport at very small spatial scales (0–1,000 m; e.g., McNinch, 2004; McNinch et al., 2012). Recognizing this complex feedback between underlying geology and hydrodynamic processes at short time scales (storms-annual), and its implications to shoreline management, represents a significant advancement in the coastal processes community (developed, in part, from DCERP1 findings). These findings also demonstrate the error of simply projecting a new shoreline position based solely on raising water level to a matching topographic elevation (i.e., bathtub flooding approach) or extrapolating shoreline change using past shoreline

behavior. Much of the literature over the past couple of decades (e.g., Browder and McNinch, 2006; Houser et al., 2008; McNinch, 2004; Riggs et al., 1999; Schupp et al., 2006) correctly argued that geology played an important role in shoreline processes, but it was a very simplistic understanding based largely on spatial association and did not transition to physics-based equations that could be used in forecast models.

Currently, there are three general categories of shoreline change models: box models, equilibrium models, and deterministic physical models. Geology box models operate over large time and spatial scales and essentially undertake an accounting exercise that tracks the volume of sand encompassed within the island as it migrates under different scenarios of relative sea level change (e.g., the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations [GEOMBEST]). Although the geology box models can incorporate varying stratigraphy and the influence of shifts in relative sea level rise, they are not designed to provide predictions of shoreline position on a storm-by-storm basis.

Equilibrium models, used by researchers such as Yates et al. (2009) and Plant et al. (1999), can demonstrate skill for morphology change predictions, but the method is completely dependent upon an extensive set of training data, which are exceptionally uncommon. Furthermore, the level of uncertainty in the predictions is large for any previously unobserved conditions, such as transgression into different geology.

Deterministic physical models for nearshore change (e.g., Mike21, Delf3D, XBeach) are based on the solution of a two-dimensional (2-D) or 3-D horizontal hydrodynamic balance and sediment transport equations. These more resolved and computationally intensive methods have reached some level of maturity in the prediction of waves and currents (Dietrich et al., 2010). However, without a focus on the importance of breaking waves and without a representation of the swash zone, the predictions of nearshore transport and morphology have not approached a similar level of accuracy. Indeed, the practical ability to predict coastal morphology over storms and the intervening quiescent periods remain a challenge to the coastal community, but is ultimately necessary to correctly predict shoreline change over seasonal–decadal time periods to be relevant for installation management.

7.3.2 Methods

7.3.2.1 Field Data Collection

We will leverage other funded research projects near MCBCL to deploy a continuous, real-time wave buoy (Coastal Data Information Program [CDIP] Waverider) in shallow water to provide critical model validation for waves. This will provide an important indication of the hydrodynamic model performance and will be a critical component for establishing confidence in the morphological change model. Boundary conditions for the initiation of the morphology model will be garnered from the extensive bathymetry and topography data already collected along Onslow Beach during DCERP1. We will also oversee periodic measurements of the beach and nearshore morphology for 2 years during DCERP2 to both assess model skill and update boundary conditions.

High-resolution topography of the upper beach, primary dune face, and dune crest are critical boundary conditions for modeling wave runup, overwash, and the resulting beach topography. Traditional topographic data sources, such as USGS topographic maps and airborne LiDAR, are typically dated (rarely more frequent than annual), and the resolution of the dune crest and shape of the dune face are reduced by data density and vegetation. CLARIS is a fully mobile mapping system that integrates two state-of-the-art remote sensing technologies, a terrestrial laser scanner (Riegl LMS-z390i; vz1000) and an X-Band radar (4kW, X-band 9.4 GHz), with precise motion (Applanix's Positron and Orientation System for Land Vehicles [POS-LV]) and location (RTK-GPS) information (**Figure 7-3**). CLARIS will be run annually, to establish a baseline, and around (pre and post, if possible) storm events to capture accurate boundary conditions from which to run and evaluate the models.

Figure 7-3. CLARIS measures beach and dune topography and surf zone bathymetry during storms.

CLARIS, developed at the USACE Field Research Facility (Brodie and McNinch, 2011; McNinch et al, 2012), is a robust system capable of rapidly (10 km/hr) and quantitatively measuring beach and dune topography (accuracy of 10 cm) with terrestrial LiDAR, and nearshore bathymetry from radar-derived wave celerity measurements (to within 10% of the actual depth). Vehicle motion is removed from both radar and laser data using the POS-LV observations in real-time and post-processed using Applanix's PosPAC software for increased accuracy. The heading angle of each radar pulse is recorded using an Applanix's POS-LV motion system with a less than 0.05-degree accuracy, and the location of the center of each radar collection is recorded using RTK-GPS to 10- to 15-cm accuracy. The radar range is 1.2 km and at 10 km/hr, every location across the surf zone has at least a 10-minute time series of radar observations. Range resolution is 3 m, a function of analog to digital sampling using a 50 MHz card, and temporal resolution is 1.2 seconds. Radar observations are rectified through a polar transformation from azimuth-range space using heading and position information, to Cartesian coordinates (e.g., NC State Plane Easting and Northing, Horizontal Datum: North American Datum of 1983 [NAD 1983]). The laser scanner simultaneously scans the topography starboard of the vehicle during transit along the beach. Terrestrial laser scanner survey precision is on the order of 1.3 cm, and accuracy is ±5–10 cm. Point-cloud density averages 1,500 points per square meter, with higher density in the near-range. Mobile, ground-based LiDAR provides complete spatial coverage and high data density, enabling 3-D features such as the beach cusps, primary dunes, and the berm (shown in **Figure 7-4**) to be robustly mapped without the data-aliasing errors common in traditional survey methods (Plant et al., 2002). Once the LiDAR data are edited, they are typically gridded at 0.25- to 0.5-m spacing, and pertinent elevations such as dune crest are contoured.

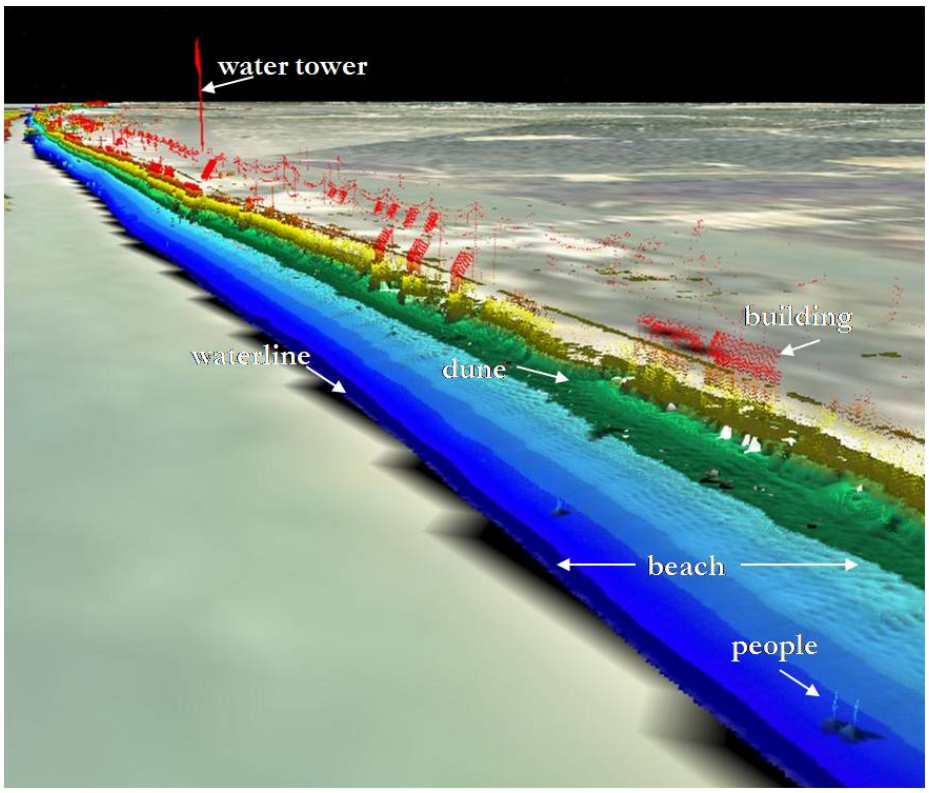

Figure 7-4. Beach and dune topography.

CLARIS–measured beach and dune topography at Onslow Beach showing the high resolution of geomorphic features that are critical to improving model skill (perspective view looking south).

CLARIS also provides a quasi-instantaneous measure of waves in the surf zone, providing a powerful tool for inferring bathymetry and showing the complexity of breaking wave parameters in the shallow surf zone. These data are useful for establishing boundary conditions and assessing the skill of wave model results, but a continuous modeled time series of wave conditions near the beach throughout storm events are needed to force the wave runup and overwash model.

7.3.2.2 Modeling Efforts

To address the hypotheses, we will use a numerical physical modeling approach. We will use the ADCIRC model (Luettich et al., 1992) to simulate tides, currents, and water surface elevation and will simulate wind driven waves with the SWAN model (Booij et al., 1999). The two-way interactions between the wave field and the water current and surface elevation will be handled by running ADCIRC and SWAN in a "coupled" mode (**Figure 7-5**; Dietrich et al., 2011 and 2012), in which the two models run simultaneously, passing data back and forth as needed to capture the physical interaction between waves, currents, and water surface elevation.

Once an ADCIRC+SWAN–coupled model run is complete, we will use the CSHORE-C15 model to compute the sediment transport rates and cross-shore morphology change, using the wave field, water current, and water surface elevations as computed by ADCIRC+SWAN. Although CSHORE-C15 is limited to cross-shore morphological changes, we believe the

computational tradeoff (in lieu of a fully 3-D morphology model that is difficult to run over longer climate-relevant time periods) is reasonable at the Onslow Beach setting because of the limited net longshore transport rate. Our wave model results from DCERP1 (STWave), which were forced by nearby observed wave data, indicated weak along-shore stress gradients and a gross long-shore transport that is quite bi-modal. Furthermore, our extensive mapping of the ebb tidal delta at New River Inlet revealed a morphology that is typical of a more tidal-dominated coast and certainly not a setting with dominant wave-driven, longshore transport. Although we do not believe that longshore transport is the primary long-term source of sediment to Onslow Beach (a large portion may derive from ravinement of underlying substrates during transgression); the CSHORE-C15 model does calculate longshore stress gradients (S_{xx} and S_{xy}). The initial modeling exercise (i.e., hindcast runs using the past 7 years and 40 years of shoreline data) will reveal mass balance problems at our side boundaries should longshore transport prove to be a large player and can be address through tuning of boundary conditions. Inlet dynamics likely play an important role in barrier island evolution; however, it is beyond the scope of this effort to determine these complex processes of adjacent inlets. Instead, we will include a shoreline accretion factor to account for the long-term southwest migration of the New River Inlet. Dr. Jesse McNinch will incorporate knowledge gained for two independently funded projects one from the Office of Naval Research and another DoD study) that are investigating the morphodynamics of the inlet into tuning model runs for DCERP2.

Seahorse Coastal Consulting will set up and operate the coupled ADCIRC+SWAN simulations, including conversion of output data into a form that is usable by CSHORE-C15. Seahorse Coastal Consulting was involved in ADCIRC modeling at Onslow Beach during DCERP1. The company will take advantage of its existing bathymetric grid and previously validated results. Dr. McNinch at USACE will receive the ADCIRC+SWAN output data from Seahorse Coastal Consulting and will run the CSHORE-C15 model to compute morphology changes.

The CSHORE-C15 morphology model uses the output from ADCIRC+SWAN as forcing for a complete hydrodynamic and sediment transport solution within the breaking wave region. The numerical model CSHORE-C15 has been under development for the past several years, approaching a practical and accurate code that predicts beach profile evolution over the nearshore region. The majority of the effort has been in the new and physically defensible sediment transport algorithms for a nearshore breaking wave environment. The model accounts for wave and current interaction, bedload and suspended loads, and wave-related sediment transport within the surf and swash zones. With a simple and robust formulation and computational efficiency, the coupled model system is able to successfully predict coastal morphology change over longer time-scales than the previously introduced modeling tools.

During DCERP1, we applied the coupled ADCIRC+SWAN model to North Carolina coastal waters with particular focus on the Onslow Beach area (Reynolds-Fleming et al., 2012). We have used the model to simulate water velocities, water levels, and wave information for several storm periods that occurred during DCERP1. We validated these simulations with acquired wave and velocity information from an in situ AWAC recorder and offshore NOAA wave buoys.

For DCERP2, Dr. McNinch, in collaboration with Seahorse Coastal Consulting, will develop and specify a limited set of representative storms or storm scenarios. Assembling input data, retrieving corresponding measured data (when and where available), and making other necessary

arrangements for implementing the specified storms or scenarios will be performed by Seahorse Coastal Consulting for ADCIRC+SWAN and by Dr. McNinch's team at USACE for CSHORE-C15.

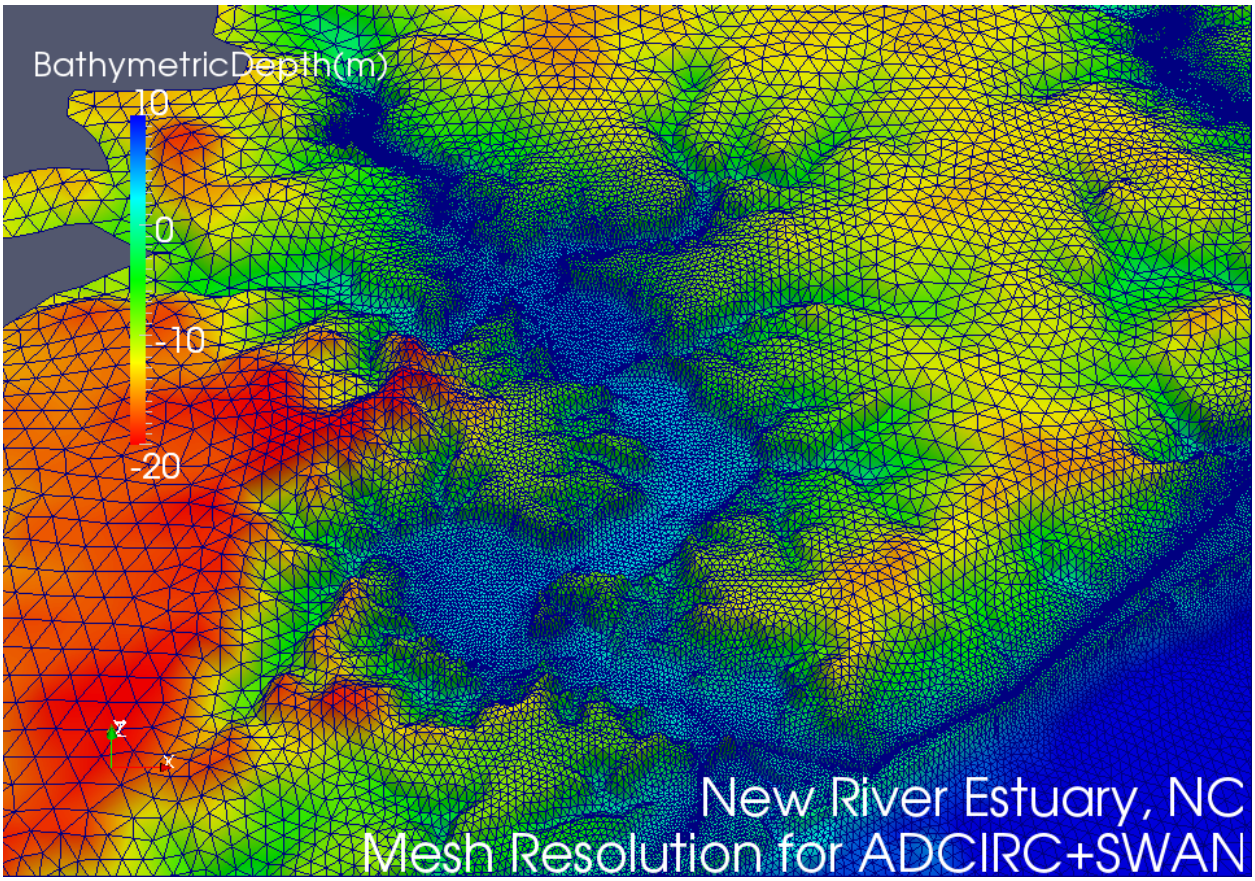

Figure 7-5. The study area showing spatial resolution for ADCIRC+SWAN.

DCERP2 model runs will be driven by input for tides, winds, and freshwater discharge. We will obtain tidal boundary conditions for ADCIRC from the Topex/Poseidon tidal database (Egbert et al., 1994) and will include time-varying nodal factors to account for the 18.6-year period of tidal modulation. ADCIRC itself continuously applies time varying body forces throughout the model domain during a simulation to obtain the contribution of time varying internally generated tides to the water surface elevation. Seahorse Coastal Consulting will download wind fields to drive the ADCIRC+SWAN model for the period(s) of interest from the National Centers for Environmental Prediction's Web site and are primarily from the North American Mesoscale (NAM) wind model. A time series of wind direction, wind speed, and atmospheric pressure over the entire ADCIRC grid domain are derived from the four daily NAM results and are used as input into the ADCIRC model. The wind speeds and direction derived from the NAM wind model compare favorably with those recorded at National Data Buoy Center's Buoys 41035 and 41036 (**Figure 7-6**) as demonstrated during DCERP1.

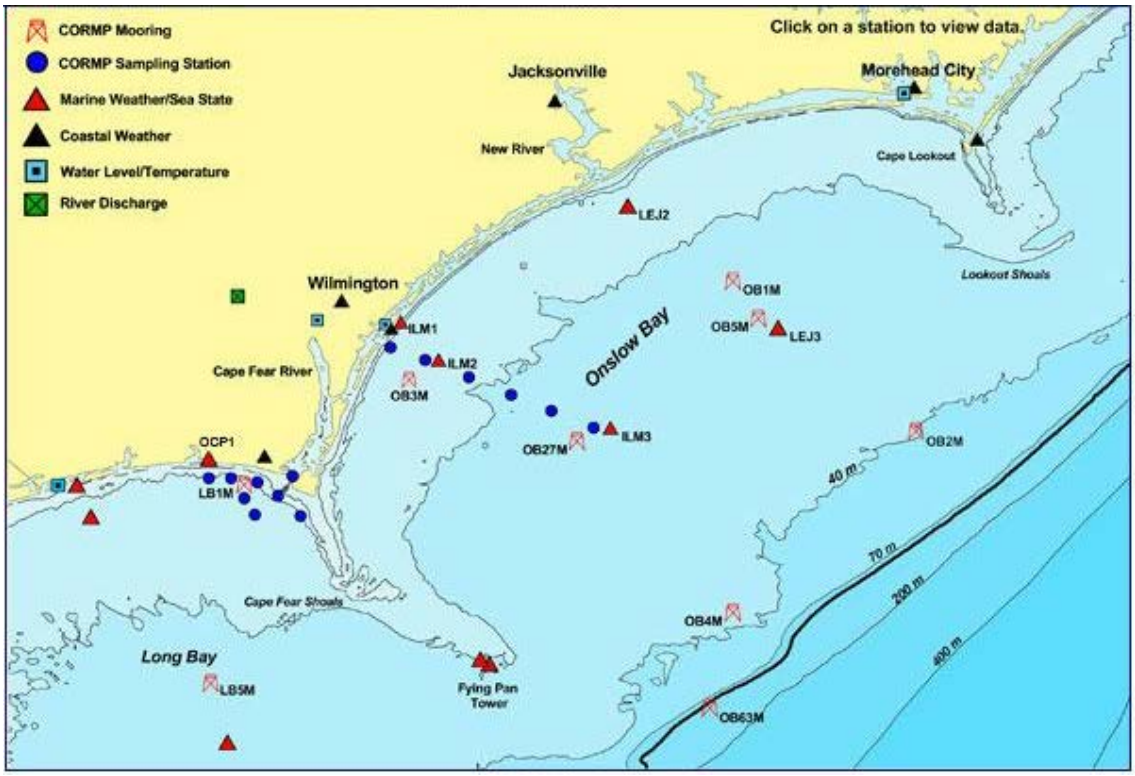

Figure 7-6. Inventory of archived measurement sites, including wave, tide, and meteorological data.

Seahorse Coastal Consulting will download daily freshwater discharge data from the USGS for the Gum Branch Road gage for the time periods of interest. Sample data from this gage are shown in **Figure 7-7**.

As part of this effort, Seahorse Coastal Consulting will implement the USACE's skill assessment and visualization software (i.e., the Interactive Model Evaluation and Diagnostics System [IMEDS] or the Automated Model Evaluation and Diagnostics System [AutoMEDS], to evaluate model results at available coastal observational stations (e.g., NOAA water level gauges, offshore buoys). A map depicting the existing inventory of measured data sources relevant to the study site is shown **Figure 7-6**. These data sources vary in their temporal coverage and frequency, and the coverage and resolution of the available measured data will be taken into account when designing the model scenarios.

We will conduct an overall evaluation each model component (e.g., Seahorse Coastal Consulting will evaluate tides and waves components; Dr. McNinch will evaluate shoreline position and beach width components). The morphology model will simulate changes to the coastal training ground under varying scenarios of storm frequency and sea level rise. We will determine long-term shoreline evolution using historical shoreline data dating as far back as 1872. We will then incorporate these data in the boundary conditions of the morphology model. We will perform shorter-term, storm response initialization of the model using the 7 years of DCERP1 data and some additional DCERP2 data. We will develop sea level rise scenarios in consultation with SERDP and will use Research Project RC-1702 as the source for current storm information; however, we will also develop future storminess scenarios in consultation with SERDP.

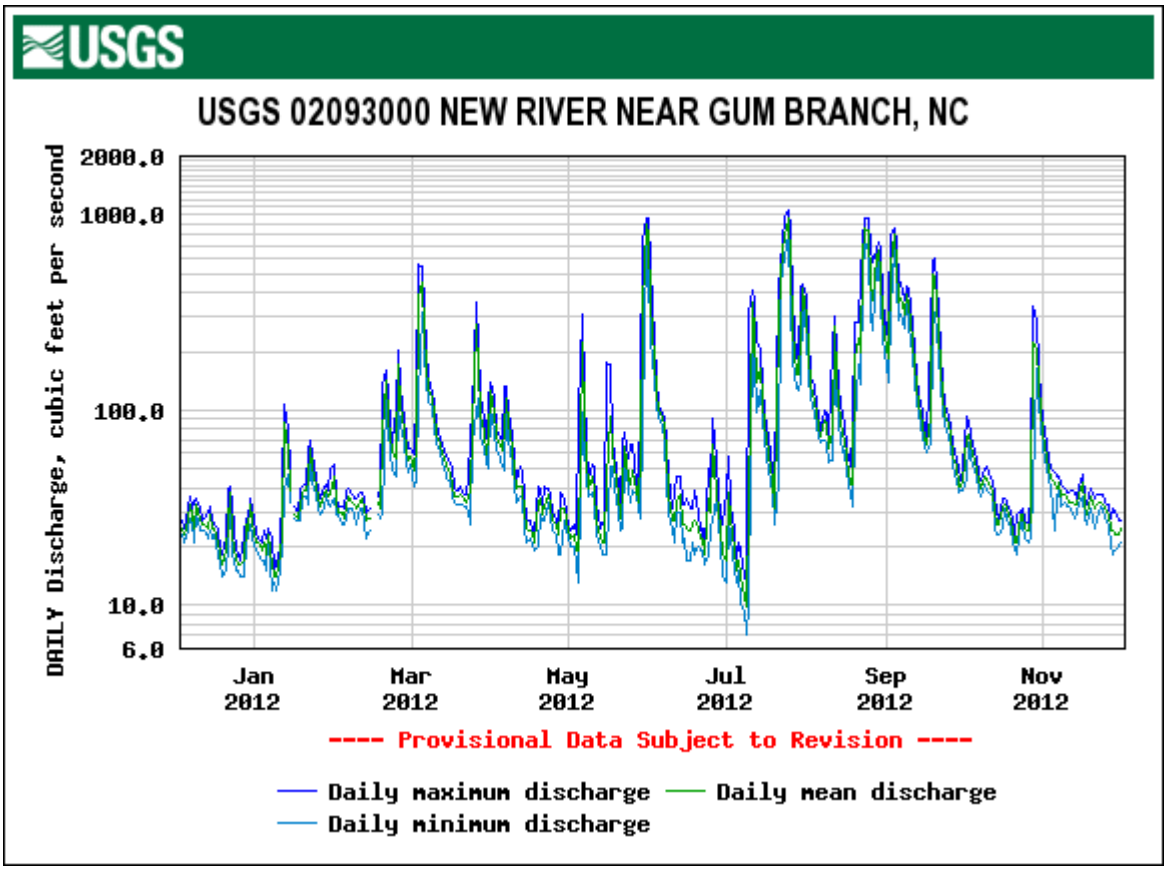

Figure 7-7. Sample measured data from a freshwater discharge gage.

Data will be applied as an input boundary condition in ADCIRC+SWAN simulations.

7.3.3 Assessment of Climate Change Impacts

Research Project CB-4 will predict the response of different scenarios of sea level rise and storminess on barrier island shoreline position and other coastal landforms (e.g., dune, beach, backbarrier environments). Similar to Research Project CW-4, we will use sea level rise estimates based on guidance from SERDP. Storminess scenarios will be drawn from results of SERDP Research Project RC-1702 and developed in consultation with SERDP. For conducting future scenarios, we also will obtain projections of freshwater discharge from Research Project TSP-2 (ESM).

7.3.4 Milestones

1. Conduct periodic and storm beach and nearshore morphology observations 2013–2017
   - Provide LiDAR–derived topography maps of the beach and frontal dunes 9/2016
   - Provide bathymetric charts of the Onslow Beach surf zone 10/2016
2. Initialize ADCIRC+SWAN and CSHORE-C15 models 2/2015
3. Predict sustainability of beach training ground under varying climate scenarios 6/2017

7.3.5 Deliverables

1.	Deliver maps of barrier island beach topography and storm change	9/2016
2.	Provide forecast results as maps of shoreline position and beach characteristics (e.g., slope, width, dune) under varying climate scenarios	9/2017
3.	Present results in a seminar to MCBCL personnel	9/2017
4.	Prepare and deliver the final Research Report	Draft 3/2017; final 9/2017

7.3.6 Planned Publications

Prepare a journal article addressing the methodology of the simplified, numerical model for predicting morphology change over climate-relevant time scales. The submission of this article is planned for fall 2016.

Prepare a journal article discussing the implications of climate change under varying scenarios of storminess and sea level rise on coastal environments and associated ecosystem. The submission of this article is planned for 2017.

7.4 Research Project CB-5: Linking Barrier Island Transgression Induced by Storms and Sea Level Rise to the Carbon Cycle, Changes in Ecosystem Function, and Management Decisions

Lead Investigator: Dr. Tony Rodriguez (UNC-IMS)

Supporting Researchers: Dr. Stephen Fegley (UNC-IMS), Dr. Brent McKee (UNC-Marine Sciences), one graduate student (Ph.D.), and one Technician

Technical Objectives/Goals: The technical objectives for Research Project CB-5 include measuring the (1) rate of island transgression, (2) transformation of organic carbon from initial accumulation in the backbarrier marsh to final erosion of peat in the shoreface, (3) duration and efficacy of carbon burial as the barrier rolls over the backbarrier marsh during transgression, (4) flux of carbon into the ocean as peat erodes in the shoreface, (5) contribution of barrier sand to backbarrier marsh accretion as the island moves landward, and (6) changes in habitat quality for flora, nesting sea turtles, and shorebirds, as well as the loss of military training area resulting from island rollover.

Research Questions: To develop an evolutionary model for barrier-island transgression focusing on the cycling of materials and the changes in island morphology and associated ecosystem services resulting from island rollover, we will address the following research questions:

1. How does the age, volume, and carbon content of the peat change with increasing distance from the salt marsh to the ocean?
2. What are the relationships between the rate of island transgression and the volume of peat preserved within the barrier and the flux of carbon to the ocean from the erosion of peat in the foreshore?
3. What are the differences in abundance of nesting shorebirds at young washover fans with no vegetation and older vegetated washover fans?
4. What are the relationships between sea turtle nest survivorship to hatching and backbeach width, elevation, and beach slope?

7.4.1 Background

In response to sea level rise, increased storminess, and reduced sediment supply, barrier islands migrate landward by aeolian processes and storm overwash (Leatherman and Williams, 1977), flood tidal delta formation (Leatherman, 1979; Riggs and Ames, 2007) and erosional shoreface retreat (Bruun, 1962; Dubois, 1995, Miselis and McNinch, 2006; Niedoroda et al., 1985; Pilkey et al., 1993; Rodriguez et al., 2001; Swift, 1976). This general conceptual model has been thoroughly tested from examining modern barriers (e.g., Moslow and Heron, 1978; Timmons et al., 2010; Wilkinson and Byrne, 1977) and barrier remnants preserved on the inner continental shelf (e.g., Belknap and Kraft, 1985; Rodriguez et al., 2004). However, it is unclear how the process of barrier rollover contributes to the coastal carbon budget and impacts the distribution and function of salt marsh and dune habitats. It is also unclear how the process will be modified by climate change and associated changes in the rate of sea level rise and storminess. In the absence of more detailed, quantitative data on these processes, management preparations, responses, and practices to preserve military training assets and environmentally sensitive habitats can only be informed by anecdotal information.

Transgressive barrier islands, such as the southern two-thirds of MCBCL's Onslow Island **(Figure 7-2**), sequester carbon principally through accretion of backbarrier marshes and peat burying this carbon below meters of sand by overwash and aeolian processes (**Figure 7-8**). These barriers also emit CO_2 when peat is buried in the marsh and eroded on the beach as the

labile components are oxidized. The deposition of washover fans (i.e., the landform created during overwash) provides substrates for salt marshes and dune slack flora (Johnston, 1998, is the mechanism of carbon burial, and creates important habitat for some nesting shorebirds (including the federally listed piping plover [*Charadrius melodus*]; Maslo et al., 2011). However, deposition of washover fans also adversely impacts MCBCL's infrastructure, including egresses, access roads, buildings, back-beach staging areas, and the ICW. In addition, the process of overwash produces a beach that presents a different landscape to nesting sea turtles with the potential to alter their choice of nesting location and influences nesting success in ways that lead to necessary changes in MCBCL's wildlife management practices involving decision rules about nest relocation practices (Mazaris et al., 2006; Pfaller et al., 2008; Rizkalla and Savage, 2011; Spanier, 2010).

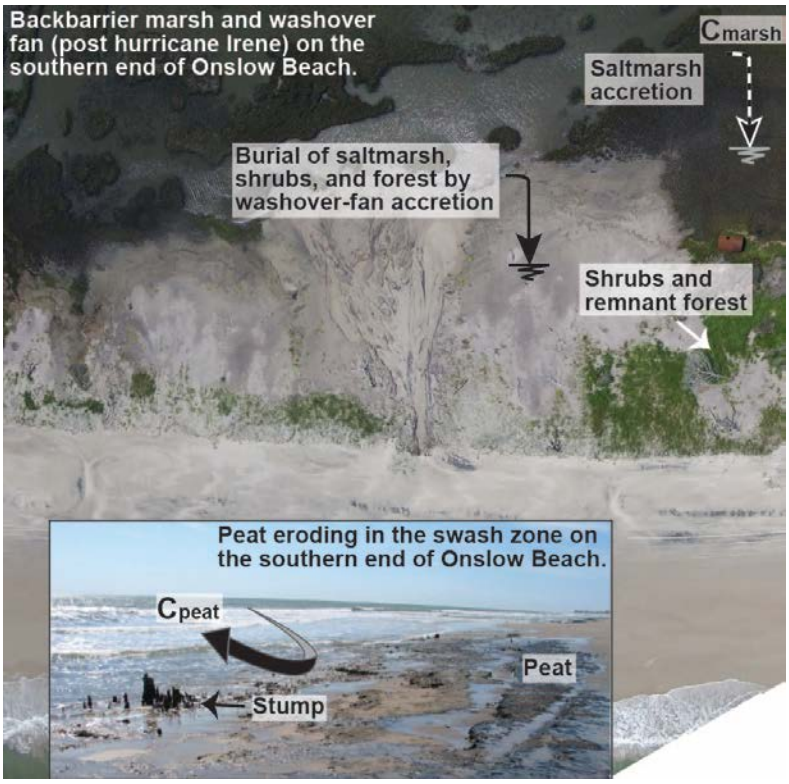

Figure 7-8. The southern two-thirds of Onslow Island is a typical transgressive barrier and ideal location for deriving a carbon budget, while examining the process of island rollover as it pertains to marsh accretion, marsh burial, island morphology, beach erosion, and ecosystem function.

The aerial photograph was taken June 6, 2012.

This research project builds on the monitoring and research efforts of DCERP1. During DCERP1, we learned that MCBCL military training activities at their present level have little impact on the historical washover fans (associated with Hurricane Fran in August 1996) and ancient washover fans (greater than 200 years old) that were mapped, as well as the associated fronting beach and intertidal areas. Research conducted by Rodriguez et al. (2012) shows significant variability in erosion rates and depths along Onslow Island at decadal and yearly time scales, which MCBCL manages by employing spatially defined restoration strategies (e.g., grass

planting, turtle nest relocation, sand-fence construction). Management of the amphibious training and recreational resource will become more challenging in the future because scientists have shown that the rate of sea level rise is increasing (Church and White, 2006; Jevrejeva et al., 2008; Rahmstorf, 2007). Another challenge is that tropical and extratropical storm intensity (Elsner et al., 2008; Emanuel 2005; Knuston et al., 1988) and frequency (Goldenberg et al., 2001; Webster et al., 2005) in the North Atlantic Ocean are also increasing (Carter and Draper, 1988), which will lead to increases in degradation of protective coastal dunes, more frequent overwash across Onslow Beach and other analogous DoD coastal installations, and more rapid erosion of peat on the beach.

7.4.2 Methods

7.4.2.1 Study Sites along Onslow Beach

The marsh at the southwestern end of the island (Transgressive Site) is fronted by an extensive washover fan, which initially formed in 1996 during Hurricane Fran, and low-elevation dunes (less than 3 m NAVD 88; Site 1; **Figure 7-2**). Sites 2 and 2.1 are areas that overwashed during Hurricanes Irene (August 2011) and Sandy (October 2012) depositing washover fans over the backbarrier marsh (**Figure 7-8** shows a photo of Site 2). The area of the island between Sites 1 and 4.1 has peat exposed on the beach for some period of every year. Areas around Site 3 consistently have peat exposed at the surface of the beach (**Figure 7-8**, inset photo), whereas the peat at the other sites is commonly covered by a thin (less than 1.0 m) veneer of sand. The marsh at the northeastern end of the island (Regressive Site) is fronted by a high-elevation dune ridge (greater than 10 m NAVD 88), which has not experienced overwash for more than a century (Yu, 2012). The backbarrier marsh is extensive in the southwest, extending approximately 750-m landward from the edge of the washover fan to the ICW. In the northeast, the backbarrier marsh is narrower than in the southwest, extending approximately 145-m landward from the dunes to dredge-spoil mounds that fringe the ICW. Marsh platforms at both sites are dominated by smooth cordgrass (*Spartina alterniflora*).

7.4.2.2 Barrier Morphologic Change

Sediment flux across the barrier, from the ocean shoreline to the backbarrier marsh, defines the landward translation of the island, burial of organic carbon, and the formation of new vegetated habitat. Deposition of washovers during storms buries carbon stored in vegetation and peat, but can also provide a new intertidal landscape for marsh colonization. In addition, after a storm overwashes a given island area, the connectivity between the beach and the backbarrier, in terms of sediment transport, increases at that location. Increased connectivity is due to the reduction in vegetation density, the resulting increase in aeolian sediment transport, the reduction in dune elevation, and the resulting increase in overwash potential from subsequent spring tides, storms, and wind- and current-driven increases in sea level. The connectivity between the backbarrier and beach will subsequently decrease if the dunes revegetate and storm-eroded sediment returns to the dunes; however, the time scale over which these processes operate and the changes in sediment flux that occur as the dune re-establishes elevation is unknown. In addition, increases in sea level rise and storminess may exceed the rate of ecological succession, limiting the role that plants play in stabilizing the dunes and dune fields. Understanding the relevant processes and their rates are necessary to constrain the barrier-island carbon budget (carbon burial).

Sediment connectivity between the beach and backbarrier will be investigated at a mature washover fan, an area of the island where the beach and backbarrier have recently become disconnected, and two recently deposited washover fans, where the beach and backbarrier remain connected. The connectivity between the beach and the backbarrier marsh at the washover fan that formed in 1996 in response to Hurricane Fran (Site 1) was examined during DCERP1. It was found that at least over the past 5 years at Site 1, the backbarrier was relatively disconnected from the beach and dunes. We will incorporate those data (e.g., aeolian sediment flux and sediment accretion) into this study. We have been monitoring sedimentation at washovers that initially formed in response to Hurricane Irene at Sites 2 and 2.1 since 2011 and will continue to process those data and examine changes at those sites during February 2013–September 2015. In addition, we will collect measurements of aeolian sediment flux at those sites. Both of those sites experienced significant deposition of washover sediment during Hurricane Sandy (October 2012) that buried and/or removed all of the new vegetation that had colonized the site since Hurricane Irene. In addition, we will examine Sites 3–4.1 during this project because those areas are vulnerable to future overwash (narrow low-elevation dune line), which may occur during the time frame of DCERP2.

We will derive the barrier morphologic changes from semi-annual laser scanning data from the southern portion of the barrier and will integrate this information with the DCERP1 monitoring results of morphologic changes. We will use a Riegl three-dimensional (3-D) LMSZ210ii terrestrial laser scanner (TLS) to collect topographic data. The TLS will be mounted onto a truck or a tripod for areas that are not easily accessible by vehicle. During data collection, the scanner rotates 360 degrees while collecting approximately 2 million spatial (x, y, and z) data points from laser returns. We use RTK-GPS–surveyed reflectors (five to eight reflectors per scan), positioned within the scan area, to georeference the data points to a global coordinate system (Universal Transverse Mercator [UTM]). Multiple scan positions are occupied at each site and merged into one data set. We will restrict beach surveying to 2 hours before and after low tide to maximize sub-aerial coverage. Error in the 3-D topographic data has been estimated to be ±3.0 cm, which includes a ±1.5-cm factory-estimated maximum instrument error and an average ±1.5-cm RTK-GPS error. The instrument reports RTK-GPS error as horizontal and vertical errors, and this varies based on factors such as the number of satellites, position of satellites, cloud cover, and other factors.

Detailed changes in beach topography, from the ocean shoreline to the estuarine shoreline, will allow us to directly measure accretion, erosion, and shoreline movements (**Figure 7-9**). We will use an algorithm included in the Merrick Advanced Remote Sensing (MARS) software package and manual editing to isolate ground points (x, y, and z data points) from the raw data. We will use Delaunay Triangulation to create surface-grid models from the ground points. Woolard (1999) and Woolard and Colby (2002) suggest that DEMs derived from airborne LiDAR most accurately represent coastal topography with a spatial resolution of 1–2 m. Given the high density of points that will be derived from the laser scans at each site in this study, we will use a 0.5-m grid spacing, which is generally much larger than the spacing of the laser returns, thus each grid node is based on an average of several topographic measurements. Focus site areas greater than 5 m^2 with no laser returns will not be included in the surface model; the areas will be defined with blanked grid nodes. We will import surface-grid files into Golden Software's Surfer 10.0 to generate contour maps and DEMs and to measure change.

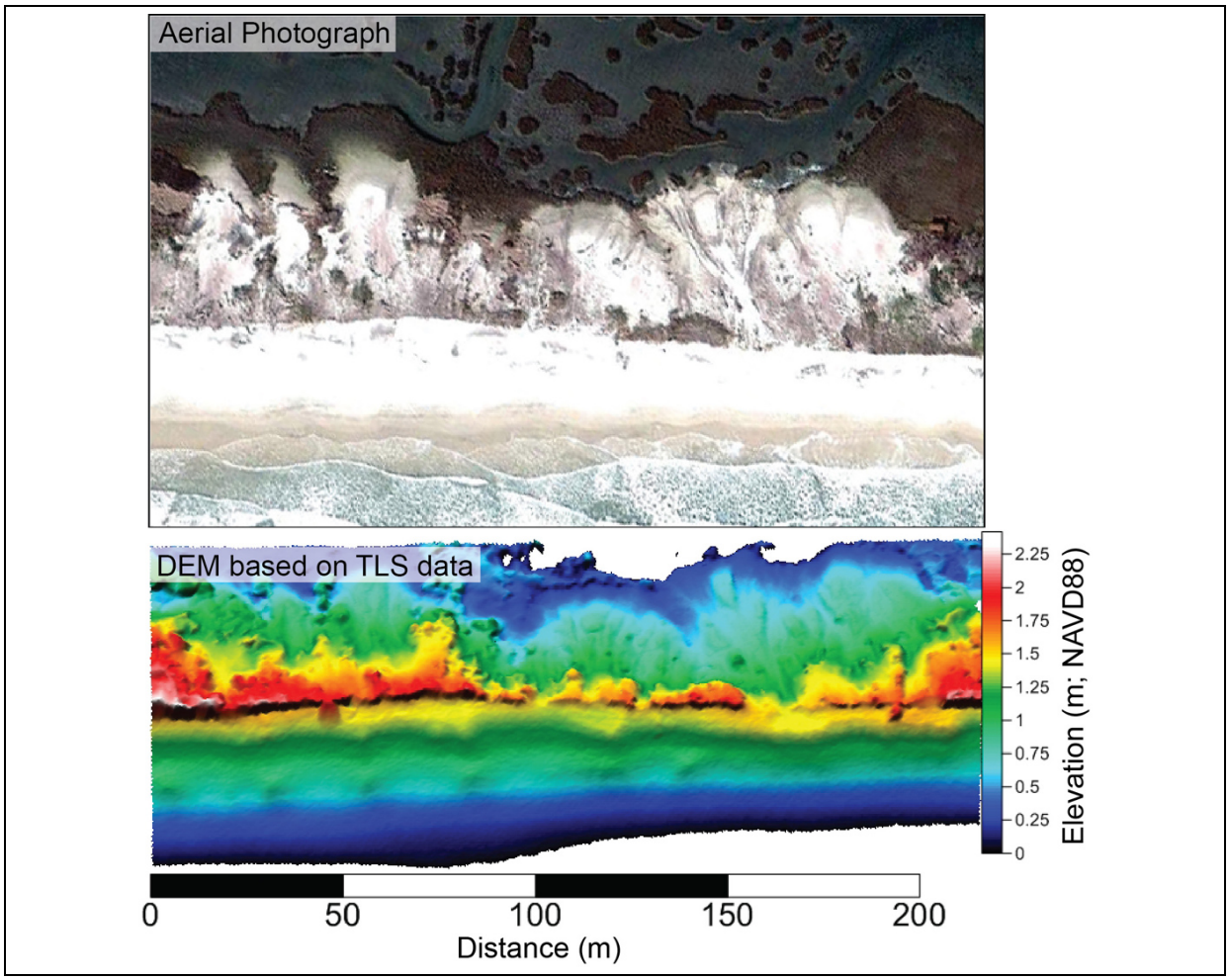

Figure 7-9. A DEM produced from TLS data collected after Hurricane Irene at Site 2.

Similar maps will be used for this study.

7.4.2.3 Aeolian Transport of Sediment Across the Barrier

We will use pitfall traps and periodic deployments of Guelph-Trent wedge traps and gaged sediment traps (Ridge et al., 2011) to directly measure aeolian sediment flux across the barrier. We will also continuously measure wind speed and direction and surface-sediment moisture at Site 1 and the offshore NOAA Buoy 41036 (located 50.0 km directly offshore of Onslow Beach) and at Sites 2 and 2.1 during specific wind events (**Figure 7-2**). Wind events are defined here as wind speeds greater than 6 m s^{-1} because that wind speed was shown at other beaches to have the potential for transporting sand 1.5–2.5 Φ (0.35–0.18 mm), which is similar to the grain size at Onslow Beach (Delgado-Fernandez and Davidson-Arnott, 2011; Ridge et al., 2011). In addition, during events, winds must be blowing from 55 degrees to 235 degrees, along and across the island from the ocean side because these are the most likely directions for delivering sand from the beach to the backbarrier marshes.

We will continuously obtain observations of wind speed and direction during the first 2 years of this research project at 10-minute intervals from NOAA Buoy 41036 and a HOBO anemometer at Site 1. We will compare daily wind speed and direction from these sensors because there is

expected to be some modification of the wind on the barrier due to topography and vegetation. We will use pitfall traps distributed from the foredune to the edge of the backbarrier marsh at Sites 2 and 2.1 to measure sediment flux across the barrier. We will construct pitfall traps from 3.8 cm in diameter × 61.0 cm–long polyvinyl chloride (PVC) pipe with a flexible pipe cap clamped on the bottom end and a 0.254-mm thick, shallow-cone-shaped collar glued to a 5-cm PVC coupler that slides onto the top end of the pipe. A 1.3-cm mesh plastic cloth is sandwiched between the PVC coupler and the pipe to prevent crabs from entering the trap. We will bury the pipe with the brass collar flush to the ground to prevent excessive scouring around the pipe. We will empty the traps generally three times per month and directly before and after some forecasted wind events. During select forecasted wind events, we will deploy Guelph-Trent wedge traps and gaged sediment traps at Sites 1, 2, and 2.1 across the barrier, distributed from the foredune to the edge of the backbarrier marsh. This methodology was developed during DCERP1 (for more details, see Ridge et al. [2011]; **Figure 7-10**). During these wind events, we will deploy HOBO anemometers approximately 50 cm above the ground surface at Site 2 to capture wind data closer to the bed: one at the foredune and another near the marsh. These data will enable direct comparison between wind speed and direction and sediment flux across the barrier during a single event. Comparisons between events that occur throughout the first 2 years of the project will elucidate the control of changing barrier morphology on wind-blown sediment flux as the backbarrier at Sites 2 and 2.1 become more disconnected from the beach due to increase in elevation of the dune and washover area and increase in vegetation density.

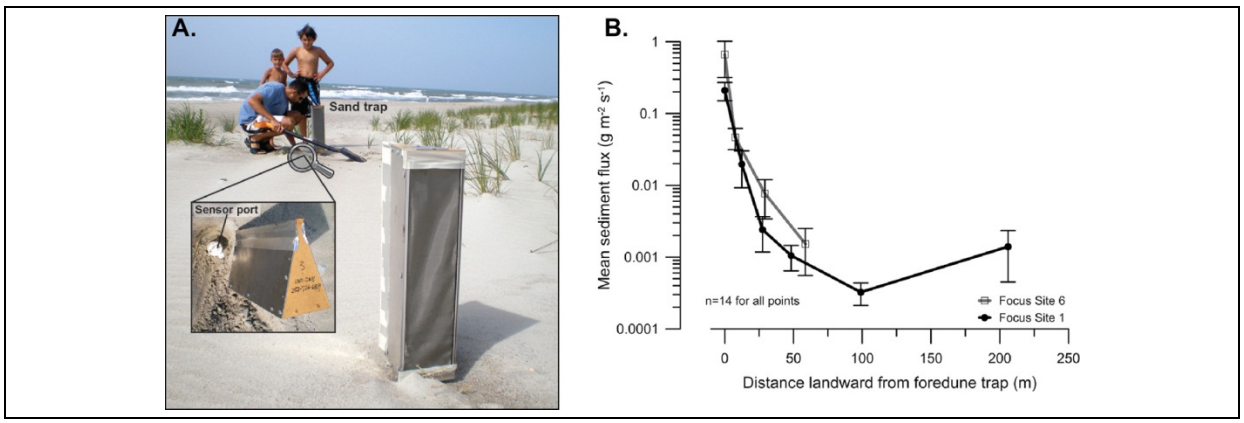

Figure 7-10. An example of a gauged Guelph-Trent wedge trap (A) and aeolian sediment flux measured from the foredune to the backbarrier marsh at Sites 1 and 6 during a 1-year study as part of DCERP1.

Site 6 is located at the northeastern end of Onslow Beach).

We will bag the sediment from the traps and return this to the laboratory for analyses, which include measuring mass and grain size. We will carry out grain-size analyses on subsamples using a sieve for the greater than 2-mm fraction and a CILAS laser-particle size analyzer for the 2,000- to 0.04-µm fraction. Detailed information on the CILAS 1180 can be found on the company's Web site at www.cilas.com. We can calculate sediment flux by knowing the duration of trap deployment, the mass and density of the sediment, and the dimensions and efficiency of the traps (**Figure 7-10**).

7.4.2.4 Character, Production, and Erosion of Peat

We will use core samples, in collaboration with Research Project CW-4 (**Figures 7-8 and 7-11**), to measure the accretion rate and composition of marsh peat and organic-rich sediment in the backbarrier (carbon storage); changes in peat and organic-rich sediment composition that occurs through time during accumulation, burial, and microbial degradation (carbon storage and transformation); and the erosion of peat and organic-rich sediment in the swash zone. We will collect two transects of closely spaced cores (vibracores; approximately 10 cores per transect), oriented perpendicularly to the shoreline from the backbarrier marsh to the foreshore, at Sites 1 and 2 (**Figures 7-2 and 7-11**). Based on cores collected during DCERP1, we know that peat and organic-rich sediment underlie this area of the barrier at a shallow depth (less than 1.0 m below the surface), and peat is commonly exposed on the foreshore. We will obtain an additional core transect from the northeastern portion of the island, extending landward from the marsh–dune boundary, which is close to where Research Project CW-4 and CW monitoring is working on measuring marsh accretion (**Figure 7-2**). This core transect does not extend onto the beach because results for DCERP1 indicate that underlying peat does not exist there. Peat was not exposed on the foreshore along the northeastern portion of the island during DCERP1, and it was not imaged at the nearshore with side-scan sonar and not imaged below the barrier using seismic and radar methods. Each core will sample the entire marsh or barrier lithosome down to an older unit (estuarine clay or old Pleistocene strata) that is not related to the barrier.

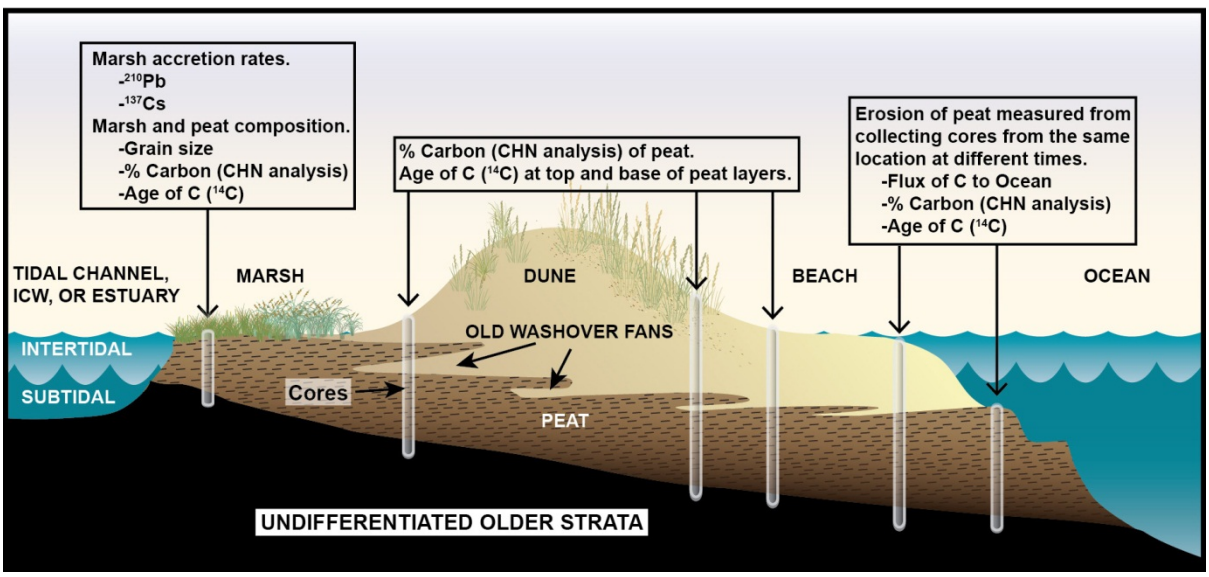

Figure 7-11. The schematic shows the coring strategy that will be used at the transect locations and the data that will be obtained from the cores.

We will use cores from the marsh to measure the composition of marsh and peat (grain size, % carbon) at different depths (no greater than 5-cm depth intervals), the age of the carbon being buried (^{14}C), and century-scale accretion rates (^{210}Pb and ^{137}Cs). We will measure percent carbon using CHN elemental analysis and sediment texture using a CILAS laser particle-size analyzer. ^{210}Pb geochronologies have been used to document rates of sediment accumulation in a variety of coastal environments. A constant supply of ^{210}Pb (22.3 year half-life) is delivered to these environments from the atmosphere; therefore, we can use sediment profiles of excess ^{210}Pb to

quantify the net accumulation rate over the past 100+ years and to characterize changes in accumulation rates during the time period. In addition, we can use ^{137}Cs (an impulse tracer produced from atmospheric nuclear tests) to establish geochronologies. ^{137}Cs was first introduced into the environment in significant amounts in the early 1950s and had peak input in 1963.

We will first determine the ^{210}Pb activities by using alpha particle spectrometry methods. ^{210}Po, the radiometric granddaughter of ^{210}Pb, is counted after methods described in DeMaster et al. (1985), McKee et al. (1983), and Nittrouer et al. (1979). Sediment samples from discrete intervals down-core (approximately every 1 cm) are freeze-dried, spiked with a ^{209}Po tracer (to determine and correct for chemical yield and counting efficiency), and leached with nitric and hydrochloric acids in a Teflon microwave digestion bomb. Polonium is spontaneously electroplated onto a stainless-steel planchet, and ^{210}Po/^{210}Pb concentrations are measured using silicon barrier detectors and an alpha spectrometer. Corrections are made for radioactive decay between times of collection and radiochemical counting. When using the alpha spectrometry method, excess ^{210}Pb activity (above that supported by effective parent ^{226}Ra) is determined by analyses of "background" total ^{210}Pb activities deep in the core (>>100 years old).

After examining the excess ^{210}Pb profile determined using alpha spectrometry, we will strategically select a subset of intervals downcore for analysis by direct gamma spectrometry for a direct and independent measurement of ^{210}Pb and ^{226}Ra and to determine ^{137}Cs activities. Samples analyzed by direct gamma counting are freeze-dried, packed into standardized vessels, sealed for 3 weeks for ^{222}Rn equilibration, and then counted for at least 24 hours. Sample sizes range between approximately 2 g and 40 g, depending on counting geometry (vial or Petri dish, respectively). Gamma counting is conducted on one of four low-background, high-efficiency, high-purity Germanium detectors (Coaxial-, BEGe-, and Well-types) coupled with a multi-channel analyzer. Detectors are calibrated using a natural matrix standard (IAEA-300) at each energy of interest in the standard counting geometry for the associated detector. Activities are corrected for self-adsorption using a direct transmission method (Cutshall et al., 1983). Total ^{210}Pb activity is directly determined by measuring the 46.5-KeV gamma photopeak. Supported levels of ^{210}Pb (^{226}Ra activity) is determined by measuring the gamma activity of ^{226}Ra granddaughters ^{214}Pb (295 and 352 KeV) and ^{214}Bi (609 KeV). Other gamma photopeaks of interest to this project are ^{137}Cs (661.7 KeV), ^{7}Be (477.6 KeV), and ^{234}Th (63.3 KeV).

We will use a constant initial concentration model (non-steady state) to determine sedimentation rates from a down-core distribution of excess ^{210}Pb activities (Appleby and Oldfield, 1992). We will use the down-core distribution of excess ^{210}Pb activities and assign a date of 1964 to the ^{137}Cs impulse peak (DeMaster et al., 1985) to establish a geochronology. Using this approach, we can employ changes in the slope of the excess ^{210}Pb profile down core, in conjunction with ^{137}Cs profiles, to document changes in sedimentation rates during the past 100+ years that result from changes in sediment supply, such as due to land-use changes (McKee et al., 2005; Ruiz-Fernandez et al., 2009).

We will use cores from the center of the island to measure the rate that the island is moving landward at century–millennial time scales and the composition of the peat preserved below the surface (**Figure 7-11**). Age dates (^{14}C) at the contact between marsh peat and barrier island sand should increase in age seaward. Comparing the age of this contact with the distance the sample is

away from the marsh–dune boundary should result in a measure of island transgression. We will employ the same methods used for the marsh cores to determine the composition of the peat.

We will directly measure erosion rates of peat in the foreshore through annual coring (Rodriguez et al., 2012) and erosion depths along Onslow Island from Sites 1 to 4.1 (**Figures 7-2 and 7-12**). At each site, three transects positioned approximately 100 m apart will be occupied. We will collect two cores at each transect, sampling the high intertidal and the middle intertidal zones of the foreshore. At each coring site in February 2013, we will use a gas-powered jackhammer to drive a Geoprobe macro-core sampling tool (1.22-m long; 5.4 cm in diameter) vertically into the ground its entire length. We will use a Trimble R8/5800 RTK-GPS receiver with average horizontal and vertical precisions of 0.015 m and 0.020 m, respectively, to survey core locations each year. We will also use the RTK-GPS (NAVD 88) to survey topographic profiles from the lower intertidal zone to the foredune at each core transect. We will use the RTK-GPS to reposition the 2013 coring locations, which will be flagged in 2014 and 2015, prior to collecting new cores. Cores collected after 2013 will be located between 5 cm and 10 cm away from the cores collected in 2013. We assume that this small distance makes spatial variations in the elevations of sedimentary beds and units negligible. We will bring cores back to the laboratory for photographing, describing, and sampling. We will compare core descriptions and photographs from 2014 and 2015 with the 2013 data set and will derive peat erosion by measuring the displacement depth of the prominent contact between the beach sand and the underlying peat or organic-rich sediment (**Figure 7-12**). Rodriguez et al. (2012) discuss this method of measuring the depth of erosion from observed differences in bedding and stratigraphy between cores collected at the same locations over a period of time. This information cannot be obtained from measuring rates of shoreline change. The grain size and carbon content of the peat sampled in the cores will allow for a direct assessment of the material that is being eroded and transported offshore.

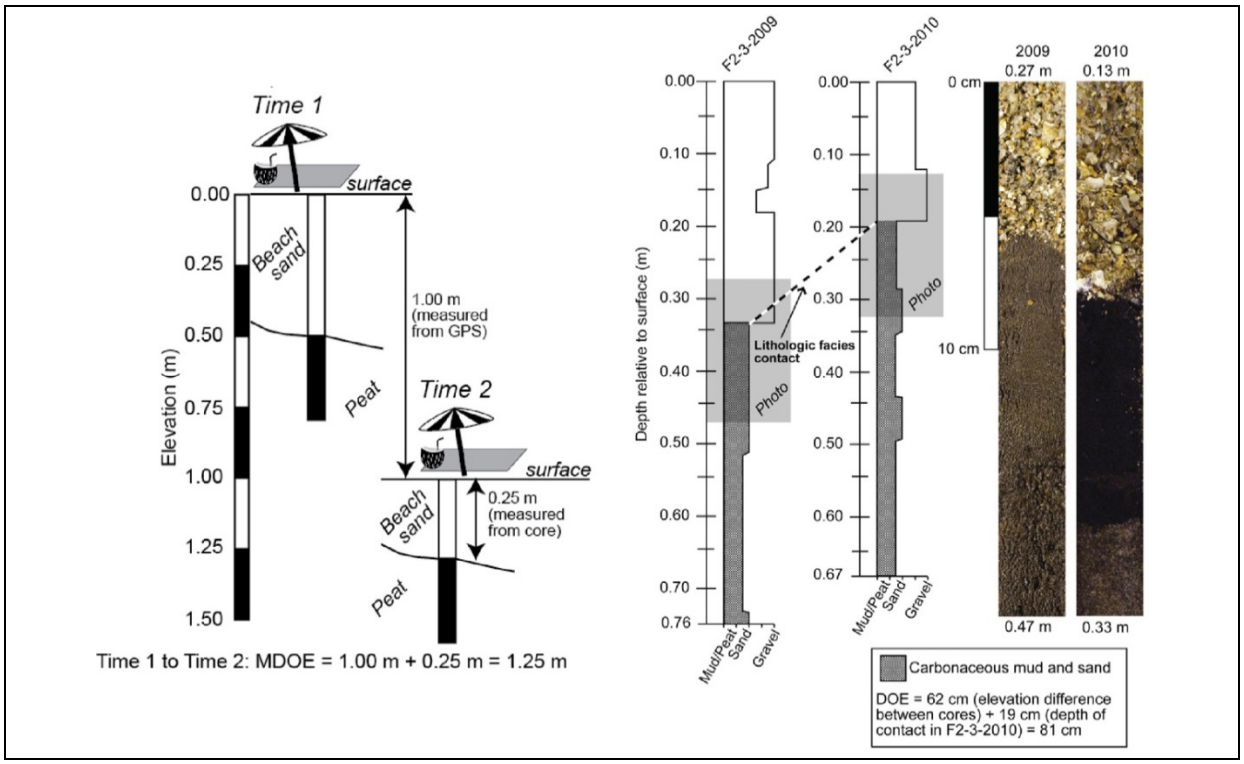

Figure 7-12. (Left) The schematic diagram and (right) core example at Site 2 shows our method of measuring erosion of peat and organic-rich sediment on the beach.

The maximum depth of erosion (MDOE) during a 1-year period is being shown.

7.4.2.5 Effects of Barrier Morphologic Change on Fauna and Flora of Management Interest

<u>Sea Turtle Nesting Activity</u>

Throughout sea turtle nesting season, MCBCL's EMD Threatened and Endangered species management staff will conduct daily surveys to make initial discovery and GPS location recordings of all sea turtle false crawls and nests. These individuals will be responsible for all management practices associated with maintaining the nests through hatching (e.g., installing anti-predation cages, relocating nests from the military training zone, post-hatching inventories) as well as recording all sea turtle nest data in a database to which we will have access.

Weekly, throughout sea turtle nesting season, we will visit the location of every false crawl and turtle nesting event occurring within the past week. We will gather coordinate data on the sea turtle nest elevations and nearby landscape morphology with high accuracy using a Trimble RTK-GPS to enable us to relate nest location and site-specific hatching success to elevation and dune-beach morphology (**Figure 7-13**). We will obtain x, y, and z coordinates in separate spatial grids established around the furthest landward point of each false crawl and around each nest. Each grid will consist of points contained within: (1) a 1-m diameter circle centered around the nest or most landward point of the false crawl; (2) an across-shore transect bisecting this circle extending from the low water mark to furthest extent of the foredunes; and (3) a parallel, transect extending over the same across-shore distance on either side of the central transect at a distance of 15 m. We will set the RTK-GPS to provide data at 0.25-m intervals. At several intervals

throughout the summer, especially after any storm events, we will revisit all of the false crawl and turtle nest locations and retake the coordinate data to determine the short-term and event-driven changes to surface dune-beach morphology.

We will use these data in two ways. First, we will use the data in conjunction with the results of ADCIRC and SWAN models produced during Research Project CB-4 to explore site-specific impacts of future changes in Onslow Beach morphology. The second use of the high accuracy spatial information will be direct tests of response variables (e.g., both mean and variation in elevation, slope, and distance to dune toe) to determine whether subtle or large changes in beach and dune landscape produced during the years of the study have detectable effects on the type of event (false crawl versus nest), the fate of the nest (e.g., inundation frequency, time to hatching), and the emergence success rate.

Figure 7-13. Turtle nest located between Sites 1 and 2.

We will measure the elevation and morphology of the surrounding beach for each nest and false crawl identified by MCBCL's EMD Threatened and Endangered personnel.

Shorebird Nesting

We plan to document how soon after creation, and under what environmental conditions, ground-nesting shorebirds use washover fans. We will use methodology modified from Karpanty and Fraser (2012) to compare the use of new (2011–2012) and old (1996) washover fans by shorebirds for nesting in each of two breeding seasons (late March through mid-July in 2013 and 2014). We will census weekly each of three washover fans (two produced by Hurricane Irene in 2011 and subsequently overwashed again in 2012 [Sites 2 and 2.1]), and one extensive overwash area produced by Hurricane Fran in (1996; Site 1) to identify the location of ground-nesting bird nests by direct inspection for the nests and via any behavioral clues (such as territorial defense or broken-wing displays) presented by adults. Ray (2011) documented that the Fran (old) overwash hosted ground-nesting Wilson's plovers (*Charadrius wilsonia*) and willets (*Catoptrophus semipalmatus*) in both 2008 and 2009. We will determine and record the GPS location of each nest. On subsequent weekly census trips to the washover fans, we will revisit each nest that has been discovered to determine its status.

After we find that the eggs of a nest have been abandoned, predated, or hatched, we will gather site-specific data on the vegetation and landscape. We will establish a 2-m × 2-m quadrat with the former nest site at the center. Within each quadrat, we will identify all plant species, estimate the percent cover of each species, measure the stem density of each species, and measure the vegetation height. We will also collect the same data from four equal-sized quadrats located 5 m

from the nest in each of four directions (two from an across-shore direction and two from an along-shore direction). We will then use an RTK-GPS to record spatial information on the local landscape covered by the five vegetation quadrats.

We will quantify bird foraging and bird predators on the landward margin of all three washover fans, adjacent to the salt marsh using Reconyx RapidFire Color digital cameras. Cameras will be affixed onto semi-permanent supporting frames and oriented to provide each one an unobstructed, 40-m view of the washover fan–salt marsh interface. We will download digital information biweekly. We will standardize the number of individuals of each species of bird and predator captured by the cameras on the basis of effort (time the cameras were operational) and will determine the timing and type of any activity with respect to time of day or night and in relation to weather events.

Ecological Succession in Washover Fans and Salt Marshes

We will use data collected from long-term fixed plots and short-term random quadrats to quantify changes to the flora assemblages occurring in overwashed terrestrial and salt marsh communities. The fixed plots were already established in both the Irene and Fran washover fans. Each plot is 5 m × 20 m (with the long axis oriented along-shore), with the southwest corner anchored on a permanent marker (we also have GPS locations for these corners). The plots occur at intervals (from 5–25 m, depending upon the width of the island and the occurrence of specific plant associations) on transects that begin at the primary dunes and extend into the salt marsh on the back of the barrier. Two parallel transects spaced approximately 0.5 km apart extend across the old Fran washover fan, and three parallel transects spaced approximately 50 m apart extend across each of two new Irene washover fans. These plots have been sampled previously using a modification of the N.C. Carolina Vegetation Survey methodology (Peet et al., 1998) in which every species occurring within the confines of the plot is identified and its percent cover is estimated. We will resample each of the plots on each of the transects seasonally (early March, mid-July, and late October) in both 2013 and 2014 to sample annual and perennial species with different growth and blossoming schedules.

Long-term plots have the ability to reveal successional trajectories in floral assemblages and associated rates of community change but, because they are fixed in space, they do not enable us to gather data in locations that receive overwash in the future that do not overlap the existing boundaries of the long-term plots. At both of the Irene washover fans, we have documented subsequent overwash events that cover only part of the area of each overwash. For us to quantify short-term (days to weeks) effects of overwash on existing communities within areas experiencing different physical regimes, we will supplement our long-term data with replicate, haphazardly located 2-m × 2-m plots strategically situated to sample sites patently overwashed and nearby sites that have not been overwashed after each overwash event has occurred. Within these plots, we will gather the same quantitative information on the vegetation as previously described in the ground-nesting bird study. We will also take replicate, vertical, 5 cm in diameter cores within and outside overwashed locations to determine the depth of sediment over the pre-existing vegetation layer.

7.4.3 Assessment of Climate Change Impacts

Assuming climate change and associated responses in the rates of sea level rise and storminess continue, the processes will impact the barrier by increasing the frequency and extent of overwash and accelerating island transgression. Both of those processes affect the burial and erosion of carbon-rich peat on the island, which are being measured as part of Research Project CB-5. Predictions of future storm conditions will be based on results from SERDP Research Project RC-1702 and will be developed in consultation with SERDP. Research Projects CB-4 is producing predictions of island morphology and shoreline positions under different storm (e.g., using conditions that are 25-, 50-, and 100-percent stormier than the previous 100 years) and sea level rise scenarios. Research Project TSP-2 will use those results, integrated with the barrier island carbon budget derived from this study, to project the carbon budget into the future.

Research Project CB-5 is closely tied with Research Project CW-4 because both are addressing salt marsh accretion and associated carbon sequestration. We will coordinate our core transects so that they are positioned close to where Research Project CW-4 is measuring marsh accretion and vegetation. We will assist Research Project CW-4 with collecting their sediment cores; in addition, data related to sediment accretion based on radiometric analyses and carbon composition will be shared. The quantity of carbon exported into the ocean via the erosion of carbon-rich sediment and peat on the beach will be scaled, based on the results of Research Project CB-4, to estimate carbon release under different sea-level and storminess scenarios. This information will be used to determine the overall coastal/estuarine budget for the NRE area. The utility of the island as a nesting ground for sea turtles and shorebirds under different sea-level and storminess scenarios will be assessed from the observed patterns in ecological succession (Research Project CB-5) and the predicted changes in the width of the backbeach and aerial extent of washover fans (Research Project CB-4). Therefore, Research Projects CB-4 and CB-5 are operating under the same assumptions and information regarding overwash.

7.4.4 Intended Study Areas

The study area will be Onslow Island, focusing on the overwash fans on the southern two-thirds of the island.

7.4.5 Milestones

1.	Produce maps of barrier morphologic change	9/2013, 9/2014, 9/2015
2.	Complete core transects across barrier and carbon analyses of peat	1/2015
3.	Measure erosion of peat deposits on the forebeach	3/2013, 2/2014, 2/2015
4.	Measure accretion of peat in backbarrier marsh	1/2015
5.	Integrate results with Research Project CW-4 and report on patterns observed in ecological succession, bird use of washover fans, and sea turtle nesting	Annually
6.	Integrate results with Research Project CB-4	2/2015, 2/2016
7.	Complete research studies of sea turtle and shorebird nesting behavior and provide nest locations and elevations to the Base	1/2014, 1/2015

8. Complete research of primary ecological succession in the marsh and washover fans 1/2014
9. Complete measurements of aeolian-sand transport across the barrier 1/2016

7.4.6 Deliverables

1. Deliver maps of barrier morphologic change 9/2013, 9/2014, 9/2015
2. Contribute to the development of a carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5) Draft 3/2015; final 3/2017
3. Deliver barrier island carbon budget and decision-support maps 1/2017
4. Prepare and deliver the final Research Report 3/2017

7.4.7 Planned Publications

Submit a journal article describing beach changes that occurred around the sea level anomaly in 2009–2010 caused by oceanographic forcing. Our results show that this sea level anomaly caused more erosion and landward shoreline movement than what is typically experienced during a tropical or extra-tropical storm. The submission of this article is planned of September 2013.

Submit a journal article discussing changes in barrier overwash that occurred around A.D. 1865 when the rate of relative sea level rise increased from −0.1 mm/y to +2.1 mm/y. The submission of this article is planned for December 2013.

Submit a journal article describing washover-fan evolution and impacts to backbarrier marshes and associated carbon burial at temporal scales ranging from months to decades. The submission of this article is planned for July 2015.

7.5 Literature Cited

Appleby, P.G., and F. Oldfield. 1992. Application of lead-210 to sedimentation studies. Pp. 731–779 in *Uranium-Series Disequilibrium: Applications to Earth, Marine and Environmental Sciences*. Edited by M. Ivanovich and R. Harmon. Clarendon Press: Oxford, UK.

Belknap, D.F., and J.C. Kraft. 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. *Marine Geology 63*:235–262.

Benton, S.B., C.J. Bellis, J.M. Knisel, M.F. Overton, and J.S. Fisher. 2004. 1998 *Long-Term Average Annual Erosion Rate Update: Methods Report (March 18)*. North Carolina Division of Coastal Management, North Carolina Coastal Resources Commission. Page 23.

Booij, N., R.C. Ris, and L.H. Holthuijsen. 1999. A third-generation wave model for coastal regions, Part I, Model description and validation. *Journal of Geophysical Research C4*(104):7649–7666.

Brodie, K.L., and J.E. McNinch. 2011. Beach change during a nor'easter: Relationships to wave steepness and inner surf zone dissipation. Pp. 1360–1374 in *The Proceedings of the Coastal Sediments 2011* 1. Edited by J.D. Rosati, P. Wang, and T.M. Roberts.

Browder, A., and J.E. McNinch, 2006, Linking framework geology of the nearshore: Correlation of paleo-channels with shore-oblique sandbars and gravel outcrops. *Marine Geology 231*:141–162.

Brown, A.C., and A. McLachlan. 1990. *Ecology of Sandy Shores*. Elsevier: Amsterdam, The Netherlands.

Bruun, P. 1962. Sea level rise as a cause of shore erosion. *Proceedings of the American Society of Civil Engineers, Journal of the Waterway Harbors Division 88*:117–130.

Carter, D.J.T., and L. Draper. 1988. Has the northeast Atlantic become rougher? *Nature 332*:494.

Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea level rise. *Geophysical Research Letters 33*, L0160.

Cleary, W.J. 1996. Inlet Induced Shoreline Changes: Cape Lookout-Cape Fear. Pp. 41–50 in *Environmental Coastal Geology: Cape Lookout to Cape Fear, NC: Carolina Geological Society Fieldtrip Guidebook*. Edited by W.J. Cleary. Carolina Geological Society.

Cutshall, N.H., I.L. Larsen, and C.R. Olsen. 1983. Direct analysis of ^{210}Pb in sediment samples: Self-absorption corrections. *Nuclear Instruments and Methods in Physics Research 206*:309–312.

Delgado-Fernandez, I., and R. Davidson-Arnott. 2011. Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events. *Geomorphology 126*:217–232.

DeMaster, D.J., B.A. McKee, C. Nittrouer, Q. Jiangchu, and C. Guodong. 1985. Rates of sediment accumulation and particle reworking based on radiochemical measurement from continental shelf deposits in the East China Sea. *Continental Shelf Research 4*:143–158.

Dietrich, J.C., S. Tanaka, J.J. Westerink, C.N. Dawson, R.A. Luettich Jr., M. Zijlema, L.H. Holthuijsen, J.M. Smith, L.G. Westerink, and H.J. Westerink. 2012. Performance of the unstructured-mesh, SWAN+ADCIRC model in computing hurricane waves and surge. *Journal of Scientific Computing 52*(2):468–497.

Dietrich, J.C., M. Zijlema, J.J. Westerink, L.H. Holthuijsen, C. Dawson, R.A. Luettich, Jr., R. Jensen, J.M. Smith, G.S. Stelling, and G.W. Stone. 2011. Modeling hurricane waves and

storm surge using integrally coupled, scalable computations. *Journal of Coastal Engineering 58*:45–65.

Dietrich, J.C., S. Bunya, J.J. Westerink, B.A. Ebersole, J.M. Smith, J.H. Atkinson, R.E. Jensen, D.T. Resio, R.A. Luettich Jr., C.N. Dawson, V.J. Cardone, A.T. Cox, M.D. Powell, H.J. Westerink, H.J. Roberts. 2010. A high-resolution coupled riverine flow, tide, wind, wind wave, and storm surge model for southern Louisiana and Mississippi, Part II: Synoptic description and analysis of Hurricanes Katrina and Rita. *Monthly Weather Review 138*:378–404.

Dubois, R.N. 1995. The transgressive barrier model- an alternative to two-dimensional volume balanced models. *Journal of Coastal Research 11*:1272–1286.

Egbert, G.D., A.F. Bennett, and M.G.G. Foreman, 1994. TOPEX/POSEIDON tides estimated using a global inverse model. JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. C12, P. 24,821, 1994 doi:10.1029/94JC01894.

Elsner, J.B., T.H. Jagger, and K.-B. Liu. 2008. Comparison of hurricane return levels using historical and geological records. *Journal of Applied Meteorology & Climatology 47*:368–374.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature 436*:686–688.

Foxgrover, A.C. 2009. *Quantifying the overwash component of barrier island morphodynamics: Onslow Beach, NC*. Master's thesis. The College of William and Mary, Williamsburg, VA.

Fraser, J.D., S.E. Keane, and P.A. Buckley. 2005. Prenesting use of intertidal habitats by piping plovers on South Monomoy Island, Massachusetts. *Journal of Wildlife Management 69*:1731–1736.

Godrey, P.J., and M.M. Godrey. 1976. Barrier island ecology of Cape Lookout National Seashore and vicinity, North Carolina. *National Park Service Scientific Monograph Series*, Number 9.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez, and W.M. Gray. 2001. The recent increase in Atlantic hurricane activity: Causes and implications. *Science 293*:474–479.

Harris, W.B., S. Mendrick, and P.D. Fullagar. 2000. Correlation of onshore-offshore Oligocene through lower Miocene strata using $^{87}Sr/^{86}Sr$ isotopic ratios, north flank of Cape Fear Arch, North Carolina, USA. *Sedimentary Geology 134*:49–63.

Houser, C., C. Hapke, and S. Hamilton. 2008. Controls on coastal dune morphology, shoreline erosion, and barrier island response to extreme storm. *Geomorphology 100*:223–240.

Jevrejeva, S., J.C. Moore, A. Grinsted, and P.L. Woodworth. 2008. Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters 35*.

Johnston, M.K. 1998. *The Inherited Geologic Framework of the New River Submarine Headland Complex, North Carolina, and Its Influence on Modern Sedimentation.* Master's thesis, University of North Carolina at Wilmington, Wilmington, NC. Page 83.

Karpanty, S. and J. Frazer. 2012. Understanding the top-down and bottom-up drivers of shorebird nest success and habitat use in relation to beach management practices on Marine Corps Base Camp Lejeune. In *DCERP1 Final Research Report*. SERDP Project Number RC-1413. 85 p.

Knuston, T.R., R.E. Tuleya, and Y. Kurihara. 1988. Simulated increase of hurricane intensities in a CO^2–warmed climate. *Science 279*:1018–1020.

Leatherman, S.P. 1979. Migration of Assateague Island, Maryland, by inlet and over-wash processes. *Geology 7*:104–107.

Leatherman, S.P., and A.T. Williams. 1977. Lateral textural grading in overwash sediments. *Earth Surface Processes 2*:333–341.

Luettich, R.A., Jr., J.J. Westerink, and N.W. Scheffner. 1992. *ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves Coasts and Estuaries, Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL*. Dredging Research Program Technical Report DRP-92-6. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS. 137 pages.

Maslo, B., S.N. Handel, and T. Pover. 2011. Restoring beaches for Atlantic coast piping plovers (*Charadrius melodus*): A classification and regression tree analysis of nest-site selection. *Restoration Ecology 19*:194–203.

Mazaris, A.D., Y.G. Matsinos, and D. Margaritoulis. 2006. Nest site selection of loggerhead sea turtles: The case of the island of Zakynthos, W Greece. *Journal of Experimental Marine Biology and Ecology 336*:157–162.

McKee, B., A.S. Cohen, D.L. Dettman, M.R. Palacios-Fest, S.R. Alin, and G. Ntungumburanye. 2005. Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: II. Geochronologies and mass sedimentation rates based on C-14 and Pb-210 data. *Journal of Paleolimnology 34*:19–29.

McKee, B.A., C.A. Nittrouer, and D.J. DeMaster. 1983. The concepts of sediment deposition and accumulation applied to the continental shelf near the mouth of the Yangtze River. *Geology 11*:631–633.

McNinch, J.E. 2004. Geologic control in the nearshore: Shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. *Marine Geology 211*(1–2):121–141.

McNinch, J.E., K.L. Brodie, H.M. Wadman, K.K. Hathaway, R.K. Slocum, R.P. Mulligan, J.L. Hanson, and W.A. Birkemeier. 2012. Observations of wave run-up, shoreline hot-spot erosion, and sound-side seiching during Hurricane Irene at the Field Research Facility. Shore & Beach *80*(2).

Miselis, J.L., and J.E. McNinch. 2006. Calculating shoreline erosion potential using nearshore stratigraphy and sediment volume: Outer Banks, North Carolina. *Journal of Geophysical Research-Earth Surface 111*, F02019. 15 pages.

Moslow, T.F., and D.S. Heron. 1978. Relict inlets: Preservation and occurrence in the Holocene stratigraphy of southern Core Banks, North Carolina. *Journal of Sedimentary Petrology 48*:1275–1286.

Niedoroda, A.W., D.J.P. Swift, A.G. Figueiredo Jr., and G.L. Freeland. 1985. Barrier island evolution, middle Atlantic shelf, U.S.A. Part II: Evidence from the shelf floor. *Marine Geology 63*:363–396.

Nittrouer, C.A., R.W. Sternberg, R. Carpenter, and J.T. Bennett. 1979. The use of Pb-210 geochronology as a sedimentological tool: Application to the Washington coastal shelf. *Marine Geology 31*:297–316.

Peet, R.K., T.R. Wentworth, and P.S. White. 1998. A flexible, multipurpose method for recording vegetation composition and structure. *Castanea 63*:262–274.

Pfaller, J.B., C.J. Limpus, and K.A. Bjorndal. 2008. Nest-site selection in individual loggerhead turtles and consequences for doomed-egg relocation. *Conservation Biology 23*:72–80.

Pilkey, O.H., R.S. Young, S.R. Riggs, A.W.S. Smith, H.Y. Wu, and W. D. Pilkey. 1993. The concept of shoreface profile of equilibrium—a critical review. *Journal of Coastal Research 9*:255–278.

Plant, N.G., K.T. Holland, and J.A. Puleo. 2002. Analysis of the scale of errors in nearshore bathymetric data. *Marine Geology 191*(1–2):71–88.

Plant, N.G., R.A. Holman, and M.H. Freilich. 1999. A simple model for inter-annual sandbar behavior. *Journal of Geophysical Research 104*(C7):15755–15776.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea level rise. *Science 315*:368–370.

Ray, K. 2011. Factors Affecting Wilson's Plover (*Charadius wilsonia*) Demography and Habitat Use at Onslow Beach, Marine Corps Base Camp Lejeune, North Carolina. M.S. thesis, Virginia Tech, Blacksburg, VA.

Reynolds-Fleming, J.V., R.A. Luettich, and J.G. Fleming. 2012. Comparative hydrodynamics during events along a barrier island: Explanation for overwash. *Estuaries and Coasts*. doi: 10.1007/s12237-012-9578-8.

Ridge, J.T., A.B. Rodriguez, S.R. Fegley, R. Browne, and D. Hood. 2011. A new "pressure sensitive" method of measuring aeolian sediment transport using a Gauged Sediment Trap (GaST). *Geomorphology 134*:426–430.

Riggs, S.R., and D.V. Ames. 2007. *Effect of storms on barrier island dynamics, Core Banks, Cape Lookout National Seashore, North Carolina, 1960–2001*. U.S. Geological Survey Scientific Investigations Report 2006-5309. Page 73.

Riggs, S.R., S.W. Snyder, D. Ames, and P. Stille. 1999. Chronostratigraphy of upper cenozoic phosphorites on the North Carolina continental margin and oceanographic implications for phosphogenesis. Pp. 369–385 in *Marine Authigenesis: From Global to Microbial: Journal of Sedimentary Research Special Publication Number 66*. Edited by C.R. Glenn, C.R., and J. Lucas.

Riggs, S.R., W.J. Cleary, and S.W. Snyder. 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology 126*:213–234.

Rizkalla, C.E., and A. Savage. 2011. Impact of seawalls on loggerhead sea turtle (*Caretta caretta*) nesting and hatching success. *Journal of Coastal Research 27*:166–173.

Rodriguez, A.B., P.L. Rodriguez, and S.R. Fegley. 2012. One-year along-beach variation in the maximum depth of erosion resulting from irregular shoreline morphology. *Marine Geology 291–294*:12–23.

Rodriguez, A.B., J.B. Anderson, F.P. Siringan, and M. Taviani. 2004. Holocene evolution of the east Texas coast and inner continental shelf: Along-strike variability in coastal retreat rates. *Journal of Sedimentary Research 74*:406–422.

Rodriguez, A.B., M.L. Fassell, and J.B. Anderson. 2001. Variations in shoreface progradation and ravinement along the Texas coast, Gulf of Mexico. *Sedimentology 48*:837–853.

Ruiz-Fernandez, A., C. Hillaire-Marcel, A. de Vernal, M.L. Machain-Castillo, L. Vasquez, B. Ghaleb, J. Aspiazu-Fabian, and F. Paez-Osuna. 2009. Changes of coastal sedimentation in the Gulf of Tehuantepec, South Pacific Mexico, over the last 100 years from short-lived radionuclide measurements. *Estuarine Coastal and Shelf Science 82*:525–536.

Schupp, C.A., J.E. McNinch, and J.H. List. 2006. Shore-oblique bars, gravel outcrops and correlation to shoreline hotspots. *Marine Geology 233*:63–79.

Spanier, M.J. 2010. Beach erosion and nest site selection by the leatherback sea turtle *Dermochelys coriacea* (Testudines: Dermochelyidae) and implications for management

practices at Playa Gandoca, Costa Rica. *International Journal of Tropical Biology 58*:1237–1246.

Swift, D.J.P. 1976. Coastal sedimentation. Pp. 255–310 in *Marine Sediment Transport and Environmental Management*. Edited by D.J. Stanley, and D.J.P. Swift. John Wiley and Sons: New York, NY.

Timmons, E.A., A.B. Rodriguez, C.R. Mattheus, and R. DeWitt. 2010. Transition of a regressive to a transgressive barrier island as a function of back-barrier erosion, climate change, and low sediment supply, Bogue Banks, North Carolina, USA. *Marine Geology 278*:100–114.

Webster, P.J., G.J. Holland, J.A. Curry, and H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science 309*:1844–1846.

Wells, J.T., and C.H. Peterson. 1986. Restless ribbons of sand: Atlantic and Gulf coastal barriers. U.S. Fish and Wildlife Services' National Wetlands Research Center. Slidell**:** 24

Wilkinson, B.H., and J.R. Byrne. 1977. Lavaca Bay—Transgressive deltaic sedimentation in central Texas estuary. *American Association of Petroleum Geologists Bulletin 61*:527–545.

Woolard, J.W. 1999. Volumetric change of coastal dunes using airborne LiDAR, Cape Hatteras National Seashore, North Carolina. Master's thesis East Carolina University, Greenville, NC. 109.

Woolard, J.W., and J.D. Colby. 2002. Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LiDAR: Cape Hatteras, North Carolina. *Geomorphology 48*:269–287.

Yates, M.L., R.T. Guza, and W.C. O'Reilly. 2009. Equilibrium shoreline response: Observations and modeling. *Journal of Geophysical Research 114*:C09014. 16 pages.

Yu, W. 2012. *Impacts of Storms and Sea Level Rise on Coastal Evolution Between Two Capes: Onslow Bay, North Carolina*. Master's thesis, Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC.

8.0 Terrestrial Module

8.1 Introduction

The terrestrial ecosystem refers to the gradient of vegetation from salt marsh at the estuary margin, through brackish/freshwater marsh, to the longleaf pine savannas and pocosins (shrub bog) that dominate the terrestrial environments on MCBCL (Wells, 1942; Christensen, 2000). The gradients between these habitat types differentiate the terrestrial ecosystem of the coastal zone from that of inland sites, such as Fort Benning, where dry longleaf pine savannas and bottomland hardwoods dominate. Most of the rare species characteristic of coastal terrestrial ecosystems, including species of concern on MCBCL, are found in the transitional zones along these gradients. The research proposed for this module will be carried out at a variety sites distributed across MCBCL.

Variation in the biota and ecosystem processes, including net primary production (NPP) and net ecosystem production (NEP), along these gradients is driven by variation in hydrology, soils, and fire behavior. Human activities on MCBCL, including military training, forest cutting and thinning, and prescribed burning (PB), also contribute to that variation. Salt marsh ecosystems are inundated daily with saline waters, and freshwater/brackish marsh ecosystem soils are frequently saturated with waters of lower salinity. Pocosin vegetation occurs on poorly drained organic soils and experiences infrequent (greater than 40 years), high-intensity fires. Over the long term (greater than 100 years), these wetlands are generally assumed to be slowly accumulating peat and, therefore, are carbon sinks (Christensen, 2000). Longleaf pine savannas generally occur on shallow organic and mineral soils; the depth of the water table in these ecosystems varies from a few centimeters to more than a meter, depending on topography, creating a gradient between dry upland savannas and wet flatwoods. The locations of transitions from one ecosystem to another along this gradient are often influenced by disturbance histories, particularly their respective fire regime (Garren, 1943; Christensen, 1981). These variations have significant effects on plant composition and diversity (Walker and Peet, 1984), as well as net primary production (Christensen, 2000). Net carbon flux into or out of these ecosystems varies through time in response to patterns of change associated with disturbances such as fire, hurricanes and forest cutting. The average amount of carbon stored over decades and centuries on similar landscapes is determined by the frequency and severity of these disturbances (Mitchell et al., 2009), but these relationships have not been quantified for longleaf pine ecosystems. For over two decades, MCBCL managers (and their counterparts at many other southeastern military installations) have pursued a vigorous program to convert most of the pine acreage into high quality foraging habitat for RCWs, and to be able to quantify habitat quality for plant and animal species in general. More recently, interest has grown in opportunities for managing ecosystems on military installations so as to maximize the sequestration and storage of carbon (Zhoa et al., 2010).

Decades of fire suppression in southern pine stands have resulted in the accumulation of a dense midstory of hardwood vegetation and a thick layer of soil organic matter (Varner et al., 2005), which has impeded the regeneration of longleaf pine on two fronts. First, the accumulation of a hardwood midstory impedes the recruitment of longleaf pine seedlings, which regenerate best in an open, park-like savanna (Brockway and Outcalt, 1998). Second, significant litter accumulation can also limit the regeneration of longleaf pine seedlings and the many herbaceous

layer species endemic to longleaf savannas by shading the seed bank, changing the microclimate of the forest floor, and eventually increasing the pool of soil carbon. Consequently, reversing the trend of encroachment by cohorts of hardwoods throughout the forest midstory and reducing the accumulation of both litter accumulations and soil carbon will be necessary if longleaf restoration efforts are to be successful (Brockway et al., 2009).

Figure 8-1 illustrates the important processes and management interventions influencing carbon storage on the terrestrial MCBCL landscape. Longleaf pine stands are typically managed to provide optimal habitat for a diverse array of plant and animal species, most notably the RCW. Frequent (approximately 3-year return interval) PB is central to such management. Such stands may or may not be selectively cut through time, removing some of the larger trees and encouraging new recruitment. Large areas of successional loblolly pine at MCBCL and other installations are managed in an even-aged fashion, with clear-cut harvests at rotation intervals of 40 years or longer. Wherever possible, these sites are replanted in longleaf pine following harvest. Mechanical treatments are also used at MCBCL and other military installations throughout the Southeast (Knapp et al., 2011) to create savanna-like conditions and improve wildlife habitat. Mechanical treatments are also used for more traditional silvicultural purposes such as precommercial thinning. These treatments can provide the added benefit of reducing the wildfire severity to a level more commensurate with the low-severity wildfires and prescribed fires typical of longleaf pine stands (Varner et al., 2005). Mechanical treatments consist of a one-time harvest and mulching of midstory hardwood species. Mulched biomass is thereafter left on the forest floor, some of which will be combusted during prescribed fire(s), leaving the remainder to decompose. Thus, midstory mulching should, over the long-term, be considered to be a net loss of carbon storage, albeit a small loss, with the added benefit of a potential reduction in the risk of higher severity wildfires in the future. However, such reductions in wildfire severity do not necessarily result in an increase in long-term carbon storage. Reducing the amount of carbon lost in a fire requires the removal of a much greater amount of carbon, since most of the carbon stored in forest biomass (stem wood, branches, coarse woody debris) remains unconsumed even by high-severity wildfires. In many Western U.S. forests, fuel reduction treatments often result in a reduction in ecosystem carbon storage and may thus be counterproductive to climate change mitigation efforts (Campbell et al., 2012; Mitchell et al., 2009). Less is known about the carbon storage impacts of one-time midstory removals conducted in southeastern pine forests. However, research in longleaf pine flatwood systems has shown that although carbon may be lost initially, rates of CO_2 uptake after the fire can be quickly recovered (Whelan et al., 2013).

If midstory removals result in a reduction in long-term storage, installation management may be faced with a dilemma. Future mandates for the protection of species such as the RCW may take priority over managing installations for climate change mitigation efforts, and such management could have a significant effect (positive or negative) on carbon stores. In any case, the effects of variations in restoration management, including variations in thinning protocols, fire season, and return intervals on carbon flux and storage need to be understood to provide maximum flexibility in meeting habitat restoration and carbon sequestration goals within the constraints of costs and personnel resources.

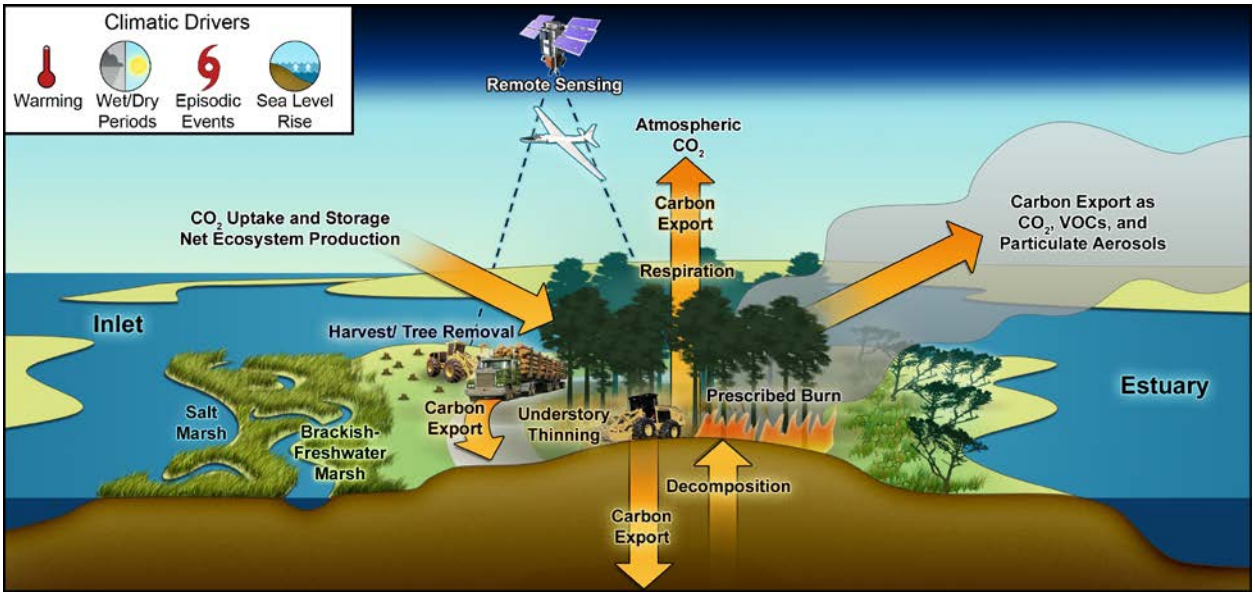

Figure 8-1. Conceptual model for the Terrestrial Module.

The two new research projects proposed for the Terrestrial Module (**Table 8-1**) constitute an integrated program designed to provide a greater understanding of how natural and human disturbances, including wildfire, PB, and various cutting practices, affect plant and animal habitat quality and carbon sequestration and storage at the scale of individual forest stands and across larger landscapes. Evaluation of the impact of potential future climate change scenarios on these relationships is an important goal of these projects. These two new research projects build upon the terrestrial monitoring and research projects completed in DCERP1 and will also be supplemented by follow-on work on Research Project T-1 which looks at changes in terrestrial community structure after the disturbance of a second prescribed burn application (**Table 8-1**). Decision support tools aimed at improving flexibility for forest management aimed at carbon sequestration and ecosystem biodiversity goals in the context of uncertain future climates are central goals for Research Projects T-3 and T-4.

Table 8-1. The Terrestrial Module research projects, senior researchers, outcomes and benefits to MCBCL, and the duration of project

Project	Research Project Title	Senior Researchers and Duration
T-1 Supplemental[a]	*Effects of Different Understory Restoration Management Options on Terrestrial Ecosystem Plant and Arthropod Communities*	**Senior Researcher:** Norman Christensen
	Outcomes and benefits: 1. Completion of DCERP1 Research Project T-1 experimental field sampling and analyses. This project will provide an assessment of the impacts of variation in management protocols for thinning and prescribed fire and variations in site conditions on specific restoration outcomes, including plant and arthropod diversity and their relation to target species such as the RCW and Bachmann's sparrow (*Peucaea aestivalis*).	**Duration:** 5/2015–6/2017

(continued)

Table 8-1. The Terrestrial Module research project, senior researcher, outcomes and benefits to MCBCL, and the duration of project (continued)

Project	Research Project Title	Senior Researchers and Duration
T-1 Supplemental[a] (continued)	*Effects of Different Understory Restoration Management Options on Terrestrial Ecosystem Plant and Arthropod Communities (continued)*	**Senior Researcher:** Norman Christensen
	Outcomes and benefits (continued): 2. In addition to preparing and submitting a report to MCBCL resource managers outlining experimental findings, we will host a 2-day workshop on strategies for restoration of longleaf pine ecosystems for staff at MCBCL and other appropriate DoD installations.	**Duration:** 5/2015–6/2017
T-3	*Forest Management, Species Habitat, and Implications for Carbon Flux and Storage*	**Senior Researchers:** Norman Christensen and Stephen Mitchell
	Outcomes and benefits: 1. Use LANDIS model simulations to quantitatively assess the effects of prescribed fire regimes, wildfire severity (% overstory mortality), fuel consumption, and restoration thinning protocols on carbon storage and flux at the stand level and across the MCBCL landscape Calibration and simulation of longleaf pine systems will be informed by previously collected field data as well as the concurrent work of Research Project RC-2115. 2. Assess the effects of potential future climate change scenarios on the relationships among the natural and human disturbances and patterns of carbon storage and flux. 3. Assess the possible tradeoffs between forest management to maximize long-term carbon stores and management aimed at restoration of species habitat. 4. Develop a decision-support tool (in collaboration with Research Project TSP-1) to improve management flexibility in the context of potentially competing or complementary goals (e.g., carbon and endangered species management).	**Duration:** 3/2013–6/2017
T-4	*Impacts of Climate Change on Management of Red-Cockaded Woodpeckers at MCBCL*	**Senior Researcher:** Jeffrey Walters
	Outcomes and benefits: 1. Improved RCW DSS Tool for MCBCL and Fort Bragg (both in North Carolina) 2. Improved ability to integrate carbon sequestration goals and RCW recovery goals despite climate change 3. Improved understanding of likely changes in dynamics of MCBCL RCW population in response to climate change.	**Duration:** 3/2013–6/2015

8.2 Knowledge Gaps in Conceptual Model and Research Needs

The research program in the Terrestrial Module focuses primarily on critical knowledge gaps related to 4 major issues in MCBCL's management of terrestrial habitats.

1. The impact of variation in natural and human disturbance regimes on carbon storage and flux in MCBCL forest ecosystems needs to be quantified. These impacts have been successfully evaluated in different forest ecosystems in other regions where intensive field studies have provided the necessary input data for simulation models such as LANDIS. Monitoring and research data gathered in DCERP1 make it possible for us to adapt LANDIS for such evaluations across MCBCL.

2. The effects of variation in forest management protocols (PB and understory/midstory thinning) on plant, arthropod and avian species composition, diversity and habitat quality must be evaluated. Resolution of this uncertainty was the central goal of experimental research initiated by Research Project T-1 in DCERP1. However, the DCERP1 funding period permitted evaluation of these effects for only the first year following the initiation of experimental treatments, and it was understood that additional sampling of experimental plots needed to occur during the DCERP2 timeframe in order to obtain a fuller understanding of these effects. That sampling will be completed in year 3 of this project.

3. The nature and extent of tradeoffs between forest management aimed at habitat restoration and biodiversity conservation versus management focused on carbon storage needs to be evaluated. This will be done by integrating our understanding gained during DCERP1 and additional sampling in DCERP2 (item 2 above) of different forest management practices and disturbances on plant, arthropod and avian diversity, composition and habitat quality with the results of the simulation studies (item 1 above).

4. Understanding of the effects of potential climate change scenarios on these patterns and interactions is needed to inform future forest management decisions. Research Project CC-1 will provide projections of future climate for a range of different CO_2 emission scenarios for the MCBCL region that will be used to parameterize LANDIS simulations and thereby estimate these effects. Projected daily climate variables will include, among other things, estimates of minimum and maximum temperature, rainfall, and photosynthetically active radiation.

As these four critical knowledge gaps are addressed by the Terrestrial Module, we will revise the conceptual models as appropriate for the module and each research project respectively to clarify information for other users.

8.3 Research Project T-3: Forest Management, Species Habitat, and Implications for Carbon Flux and Storage

Lead Investigator: Dr. Norman L. Christensen (Duke University)

Supporting Researchers: Dr. Stephen Mitchell (Duke University) and Peter Harrell (Duke University)

Technical Objectives/Goals:

1. Provide MCBCL managers with the information and tools needed to monitor and manage carbon stores, while supporting military training goals and restoring and maintaining key elements (e.g., biodiversity, endangered species habitat) of longleaf (*Pinus palustris*) and loblolly pine (*Pinus taeda*) ecosystems. Data from monitoring and research studies conducted during DCERP1 will provide most of the data necessary to calibrate simulation models of forest change and carbon storage in the context of MCBCL management practices, including harvest (clear cutting), overstory and midstory thinning, and prescribed fire and wildfire regimes. These models will be the basis for development of decision-support tools that enhance management flexibility with respect to tradeoffs between conservation and carbon management goals and in the context of climate change.
2. Assess potential impacts of different climate-change scenarios on terrestrial carbon stores in relation to forest management practices. Projected daily climate variables will include, among other things, estimates of minimum and maximum temperature, rainfall, and photosynthetically active radiation.
3. Transfer knowledge gained during our studies to managers at MCBCL and other military installations on similar landscapes. The team will develop decision tools for use by natural resource managers for auditing carbon stores and planning around stand and landscape management objectives in collaboration with Research Project TSP-1 as part of its common SDSS.

Research Questions:

1. At the level of individual stands, how do different forest management scenarios influence carbon stores in the near term (<10 years), intermediate term (10–70 years), and long term (>70 years)?
2. At the level of the MCBCL landscape, how do variations in the application of different management scenarios influence carbon stores in the near term (<10 years), intermediate term (10–70 years), and long term (>70 years)?
3. How will likely scenarios of climate change affect stand and landscape level changes in carbon storage associated with variations in forest management scenarios?

8.3.1 Background

To provide improved military training conditions and protect biodiversity (most notably populations of the federally listed RCW (*Picoides borealis*), conservation of existing longleaf pine stands and the restoration of the longleaf pine habitat are among the primary objectives of natural resource managers at MCBCL and other military installations in the southeastern United States. In addition, some successional forests are managed in an even-aged manner with clear-cut harvests to meet more traditional silvicultural goals. A detailed conceptual framework for such management in pine-dominated ecosystems is presented in **Table 8-2**.

Table 8-2. A conceptual framework for model studies of the effects of alternative management practices on forest carbon storage.

Note that these are general scenarios, and the details of harvest rotation, woody debris, and slash management, and the frequency of prescribed burns may be varied.

Management Treatment	Description	Likely Impacts on Carbon Stores	Management Context
No Management Loblolly pine—no thinning, prescribed fire or cutting	Loblolly pine stands with dense shrubby undergrowth are left unmanaged.	Individual tree growth continues. Overstory tree biomass peaks and declines as a consequence of thinning-related mortality. Understory/midstory biomass, woody debris, and forest floor continue to accumulate, increasing the probability of wildfires.	This management scenario is unlikely and purely hypothetical. It is included here to examine the potential role of fuel accumulation and increased wildfire risk on carbon stores.
Commercial Harvest Cycle Loblolly pine—no thinning or prescribed fire, clear-cut at 25 or 60 years depending on management objectives	Loblolly pine stands with dense shrubby undergrowth are left unmanaged. Sites are clear-cut when pines reach approximately 25 years for pulp fiber or 60 years for saw timber, and residual understory is burned. Loblolly seedlings are then sown across the site on 10-ft centers (435 trees per acre) and allowed to regrow.	Individual tree growth continues. In the 25-year rotation case, clear-cutting is performed while the stand is in the early thinning phase of development and live biomass is still accumulating. In the 60-year rotation case, clear-cutting is performed towards the end of the thinning phase when net live biomass accumulation is nearing zero or perhaps even negative. This process could be interrupted by wildfires or by clear-cutting. The stands would subsequently be re-established for future commercial harvest.	This is representative of management in loblolly and slash pine for pulp fiber and saw timber across the Southeastern Coastal Plain. It is used on MCBCL for the management of pine stands that are not slated for restoration to longleaf pine (e.g., on wet sites with soils high in organic matter).
Longleaf Savanna Restoration I Loblolly pine—understory/ midstory thinning	Shrubs and understory trees (up to 8 inches dbh) are thinned and masticated with debris left onsite. The site is prescribe burned 1-year following thinning and every 3 years thereafter. Longleaf pine seedlings are planted in the understory. After mature loblolly pines reach 70–80 years, stands are selectively cut to encourage new longleaf recruitment and to maintain an uneven-aged population of live trees and snags (potential RCW habitat), although thinning may occur at various times before the age of 70 years, depending on stand development.	Immediate conversion of live woody shrubs and trees (and large woody debris) to woody fragments on forest floor. Some of this woody debris and most of the accumulated litter are consumed during the first prescribed burn. Residual below-ground biomass decays. Growth of thinning-released overstory trees increases. Although a 3-year return time prescribed fire increases net primary production of the herb layer, it also consumes the majority of above-ground biomass with each fire event. The net effect on net carbon storage through time is not clear.	This practice is used across MCBCL in loblolly pine stands in which restoration of longleaf pine savanna is the long-term goal. It is hoped that the intermediate stages in which loblolly pine is still the canopy dominant will provide habitat for longleaf pine endemics such as the RCW.

(continued)

Table 8-2. A conceptual framework for model studies of the effects of alternative management practices on forest carbon storage. (continued)

Management Treatment	Description	Likely Impacts on Carbon Stores	Management Context
Longleaf Savanna Restoration II Loblolly pine—clear-cut followed by longleaf pine restoration	Overstory trees (>10 inches dbh) are cut at the base, and boles are removed from the site. Smaller trees, branches, and leafy materials may be windrowed or dispersed and be burned or allowed to decay in situ. Sites are typically burned in the season following logging. Longleaf pine seedlings are then sown across the site on 10-ft centers (435 trees per acre). Once longleaf pine seedlings reach 12–15 ft, a 3-year return interval prescribed burn program can be initiated. After 70–80 years, stands are selectively cut to encourage new longleaf recruitment and to maintain an uneven-aged population of live trees and snags (potential RCW habitat), although thinning may occur at various times before the age of 70 years, depending on stand development.	Removal of overstory boles represents a significant immediate change in stored carbon. Also an immediate conversion of live small tree, branch, and leaf biomass to dead woody debris. Below-ground biomass gradually decays. Herbs and shrub biomass increases as longleaf pine seedlings grow. Above-ground carbon storage in understory herbs and shrubs is subsequently regulated by prescribed fire. Although 3-year return time prescribed fire increases net primary production of the herb layer, it also consumes the majority of above-ground biomass with each fire event. The net effect on net carbon storage through time is not clear.	Restoration of longleaf pine savanna is the long-term goal for these stands. Although intermediate stages will not likely provide habitat for longleaf pine savanna endemic species, this restoration protocol may restore longleaf pine as the dominant canopy species more quickly than the understory/ midstory thinning treatment. This method is employed at MCBCL and across the longleaf range.
Maintenance of Mature Longleaf Pine Savanna	Sites are dominated by large (>20 inches dbh), uneven-aged longleaf pines with a diverse understory of grasses, herbs, and low shrubs. Prescribed burns are typically applied on a 3-year rotation. Individual tree mortality and recruitment is episodic and related to disease or to infrequent disturbance events such as hurricanes. Sites may be selectively cut, removing some trees to encourage new establishment and maintain an uneven aged population of live trees and snags (potential RCW habitat).	Carbon storage in understory biomass varies in relation to the return intervals of prescribed burns. Deaths of large trees from disease or storm events and selective cutting result in significant transfer of carbon from live to dead pools.	Longleaf pine–dominated stands currently exist in various stages of maturity on MCBCL. The goal here is restoration of uneven-aged stands dominated by large (>24 inches dbh, basal area = 15–25 m^2/ha) old trees and high-quality RCW habitat. Fire is the primary tool for maintenance, and some selective cutting may also occur.

Climate influences the frequency and severity of disturbances, as well as the trajectory of post-disturbance changes. Thus, persistent changes in temperature, precipitation, and evapotranspiration may significantly affect both long-term carbon storage and dynamics. Studies in other pine-dominated ecosystems suggest midstory and understory thinning aimed at fuel reduction significantly decreases carbon storage in the long term because wildfires consume a

relatively small fraction (less than 30%) of carbon stored in stems wood, branches, coarse woody debris (Campbell et al., 2012; Mitchell et al., 2009). As an alternative to midstory and understory thinning and prescribed fire, MCBCL forest management includes clear-cutting and overstory thinning, although neither treatment is performed with the primary objective of reducing fire severity. These practices have even more significant impacts on carbon stores through time. Thus, the effects of variations in restoration management, including variations in thinning protocols and in fire season and return intervals, on carbon flux and storage need to be understood to provide maximum flexibility in meeting habitat restoration and future potential carbon sequestration goals within the constraints of costs and personnel resources. Additionally, future climate may alter the carbon stores on the MCBCL ecosystem, but the interaction between climatic variables is not straightforward. An increase in temperature, for example, may lengthen the growing season, but this will not increase carbon uptake if there is an associated decrease in soil moisture resulting from increased evapotranspiration resulting from higher temperatures. Furthermore, higher temperatures could also result in higher decomposition rates and may alter the balance between photosynthesis and respiration.

8.3.2 Methods

8.3.2.1 Field Data Collection

DCERP1 vegetation monitoring data from 95 pine-dominated stands on MCBCL will provide important inputs for the LANDIS-II model, including species composition, tree density, size class distribution, and seedling abundance. These 95 stands represent most of the scenarios described in **Table 8-2** for a wide range of site conditions. Additional data from sites with under-represented management histories (i.e., clear-cuts and sites that have experienced different burning regimes) will be added to this existing data set to ensure that the full range of MCBCL management practices is represented. These data will be used to estimate live biomass carbon, dead biomass carbon, and soil and litter carbon so that total stand carbon can be estimated. Data on the carbon storage dynamics from Research Project RC-2115 will also be used in model calibration and verification, particularly its work on the dynamics of root decomposition because there is little existing data on this significant component of the longleaf pine carbon cycle. Research Project RC-2115 will gather data on carbon storage in longleaf pine forests in MCBCL, Fort Benning (in Georgia), and Fort Polk (in Louisiana) and will use them to calibrate a stand-level model for the longleaf pine ecosystems at these installations. In addition to providing data on above- and below-ground carbon storage in longleaf pine ecosystems, the work of Research Project RC-2115 should provide us with valuable data on below-ground taproot decomposition rates in longleaf pine ecosystems. We will also be able to compare its model projections to those of the LANDIS model. As discussed below, this information will also be used to evaluate the effects of multiple management activities and climate change scenarios on long-term stores of carbon in MCBCL terrestrial ecosystems.

Additionally, SERDP's Research Project RC-2118 will be performing simulations of longleaf pine stands at Fort Benning under three different management scenarios: carbon storage maximization, longleaf pine restoration, and fire risk reduction. Although Research Project RC-2118 differs from our work because it focuses exclusively on the management of longleaf pine, its findings might allow for both projects to develop a broad synthesis on the effectiveness of forest restoration efforts and their impacts on carbon storage in southeastern pine ecosystems. It

is too early to say how we will be able to utilize the work of Research Project RC-2118. However, MCBCL may be able to benefit from findings of Research Project RC-2118 on fire risk reduction in longleaf pine forests because most of the work we have conducted at MCBCL has focused on the effects of fire risk reduction in loblolly pine forests, and there are some areas of MCBCL in which longleaf pine have been fire suppressed. We are also interested in examining the longleaf pine carbon maximization scenarios of Research Project RC-2118 and comparing them to the carbon storage scenarios at MCBCL in Research Project RC-2115 and ours as well.

Accordingly, we are planning to share our respective findings to examine any differences in the impacts of management (fire, thinning) on carbon storage potential in the two locations. Although both MCBCL and Ft. Benning support and manage for longleaf pine ecosystems, they contain different variations of longleaf types across their ranges. Comparisons of management actions and resulting carbon consequences will allow for investigation into the possibility of generalizing carbon storage in longleaf pine sites. However, as previously stated, it is too early to say how we will be able to utilize the work of Research Project RC-2118.

8.3.2.2 The LANDIS II Model

We will use LANDIS-II v6 (hereafter referred to as LANDIS) to simulate the effects of clear-cut harvest, midstory reduction, and prescribed burns (single or repeated) on total ecosystem carbon storage under a variety of climatic change scenarios (He and Mladenoff, 1999; Mladenoff, 2004; Scheller et al., 2011). LANDIS simulates ecosystem processes while accounting for the presence and absence of tree species though simulating a cohort structure in a network of individual cells of user-designated size and resolution. LANDIS stratifies the heterogeneous landscape into land types based on climate (annual variation in temperature and rainfall), soil, and terrain attributes. Within the simulation, the size of an individual cell typically represents the resolution of the underlying GIS data, such as layers developed from a digital elevation model (DEM), in which the number of cells is typically designed to accommodate the landscape of interest. Thus, LANDIS can simulate change at the scale of individual stands, and it can also simulate change across landscapes composed of stands in different stages of succession following different management practices. Seed dispersal is a spatial process simulated at the landscape level. During DCERP1, we developed the landscape database needed to run LANDIS (i.e., estimates of live tree, midstory and understory biomass, woody debris, and soil and litter carbon). By using our previously collected stand-level data in conjunction with landscape-level community classifications, land-cover and land-use change data, and forest inventory data, we will be able to simulate the MCBCL and surrounding ecosystems under a broad range of forest management actions (i.e., understory and midstory thinning, timber harvest, and prescribed burning) and climate-change scenarios over annual and multi-decadal time scales.

Model Calibration—Estimates of live biomass carbon, dead biomass carbon, soil and litter carbon provide estimates of total stand carbon storage for all of our experimental loblolly pine plots and our control longleaf pine plots and will guide model calibration. We will use existing allometric equations to estimate below-ground carbon storage for loblolly pine. For longleaf pine, we will use both existing allometric equations and below-ground carbon storage data from Research Project RC-2115. The model will also simulate root decomposition rates, which we will derive from the work of RC-2115. Estimates of loblolly pine root decomposition rates are

readily available in the literature, but there is a lack of studies on the dynamics of taproot decomposition in longleaf pine. For the latter, we will use estimates of root decomposition for longleaf pine forests provided by Research Project RC-2115 to aid our model calibration.

The MCBCL landscape is divided into several compartments with different management and natural disturbance histories, and these differences are reflected in the carbon stores in each compartment. We will provide a spatially explicit representation of carbon stores across the MCBCL ecosystem by using LiDAR (Light Detection and Ranging) data collected from MCBCL. LiDAR data provide estimates of forest canopy heights and tree density that can be used for estimates of forest biomass. Previous utilization of LiDAR at MCBCL was used to characterize the RCW habitat and can provide a foundation for model calibration (Smart et al., 2012). Once the model has been calibrated, we will use the LiDAR data to validate the model. We will also validate the model by comparing it to our field-based estimates of carbon storage in live biomass, dead biomass (including forest floor fuels), and soils. Field-based estimates of carbon storage provided by Research Project RC-2115 will also be used in model validation. Model validation will determine whether a re-calibration of the model is needed.

Management Scenarios—We have selected management scenarios likely to be used by MCBCL, as well as management scenarios used at greater frequencies by agencies across the southeast, including rotation harvests for maximum timber yield, thereby giving our work relevance beyond the MCBCL ecosystem. At the stand level, forest management treatments will include the following:

1. Loblolly pine: No treatment (stands representing a variety of conditions undergo natural succession with no management intervention)
2. Longleaf pine: No treatment (stands representing a variety of conditions undergo natural succession with no management intervention)
3. Loblolly pine: Clear-cut harvest and replanting (rotations to be based on MCBCL management objectives)
4. Loblolly pine: Midstory and understory thinning.

These management scenarios are described in more detail in **Table 8-2**. Applications of prescribed burns and harvesting across the MCBCL landscape will be performed within the forest community types that typify each management action; simulation of pocosin ecosystems, for example, would not be treated with controlled burns every 3 years. LANDIS does not simulate midstory and understory thinning treatments per se, but the model can simulate harvests that select for certain diameter sizes. Therefore, harvest for trees with diameters of 8 inches or less will simulate the midstory and understory thinning treatment. Harvested materials in the simulated thinning treatments will be left on the ground to emulate the woody debris that is left on the forest floor.

Prescribed burn regimes will include dormant and growing season burns at intervals relevant to MCBCL managers (the current prescribed burn return interval target is every 3 years). LANDIS simulations based on return times of 1, 3, 5, and 10 years will inform managers about the potential flexibility they might have in the application of different prescribed burn intervals, as well as their impacts on long-term carbon storage.

LANDIS allows a user to divide the landscape up into fire regime units, which are associated with different fire frequencies and fire weather, so that differences in fire regimes can be represented across a heterogeneous MCBCL landscape. We will group the prescribed fires into different size classes according to different sizes of prescribed burns throughout the MCBCL landscape within the dynamic fire extension, while keeping fire severities constant for prescribed fires. Fire sizes and severities can be constrained to different levels by varying the mean fire size, the standard deviation of the fire size, the maximum fire size parameter(s), rate of spread, critical surface fire rate of spread, and the severity calibration factor. Fire severities for prescribed fires will be low (i.e., no overstory tree mortality) because the installation fire staff and managers are unlikely to set fires under meteorological conditions conducive to high-severity crown fires.

Our analysis could also help determine the degree of midstory and understory fuel accumulation as a result of different levels of fire suppression, as well as the effects of understory fuel accumulation on fire severity. In collaboration with MCBCL forest management staff, we will finalize the specific details of management scenarios. Nevertheless, the general categories of management practice are clear.

Additionally, Research Project RC-2118 will be performing simulations of longleaf pine stands at Fort Benning under three different management scenarios: carbon storage maximization, longleaf pine restoration, and fire risk reduction. Although Research Project RC-2118 differs from our work because it focuses exclusively on the management of longleaf pine, its findings might allow for both projects to develop a broad synthesis on the effectiveness of forest restoration efforts and their impacts on carbon storage in southeastern pine ecosystems.

LANDIS Harvest Extension—The Harvest extension in LANDIS allows multiple stand-level treatments to be modeled simultaneously across a landscape such as MCBCL. Using this extension, LANDIS represents stands as groups of cells that are prioritized for harvest using one of four user-specified ranking algorithms that use criteria related to forest management objectives (Gustafson et al., 2000). Cells within a selected stand are harvested according to the species and age cohort removal rules specified in a prescription. These flexible removal rules allow simulation of a wide range of prescriptions such as prescribed burning, thinning, single-tree selection, and clear-cutting. The different cutting practices produces differences in species and size-class composition, average patch sizes (for patches defined by forest type or by size class), and amount of forest edge across the landscape.

LANDIS Dynamic Fuel System and Dynamic Biomass Fuel System Extensions—LANDIS has two extension options available for simulating fuel and fire dynamics. The first fuel extension option, called the *Dynamic Fuel System* extension, uses species age, conifer mortality, and post-disturbance information at each cell to classify every active cell into a season-independent fuel type (Sturtevant et al., 2009). The second fuel extension option, called the *Dynamic Biomass Fuel System* extension, is identical to the Dynamic Fuel System; however, the Dynamic Biomass Fuel System calculates species values and uses cohort biomass in addition to the previously mentioned variables to classify fuel types. The Dynamic Biomass Fuel System also requires the use of a succession extension that calculates above-ground biomass for every cohort. Both extensions are capable of recognizing recent disturbance history and both produce maps of fuel types, percent conifer, and percent dead conifer (Sturtevant et al., 2009). For now, we believe that the Dynamic Biomass Fuel System extension will be ideal for simulating fire

dynamics because it allows the presence of biomass to be incorporated into fire behavior. Our calibration of prescribed fires will recognize that hardwood accumulation does not result in higher severity prescribed fires. This is because the installation does not set prescribed fires in stands with a hardwood midstory when meteorological conditions and fuel moisture are conducive to the propagation of a crown fire. We also recognize that the fuel module for LANDIS was developed with western and northern latitude North American fuel scenarios in mind, where biomass and fuels recovery occurs on the order of decades rather than years. However, LANDIS has been successfully calibrated for pine forests of the Atlantic Coastal Plain that are subject to naturally occurring wildfires and are treated with prescribed burns (Scheller et al., 2008 and 2011), providing us with a valuable and tested reference point.

8.3.2.3 Climate Change Scenarios

Projected Climate Data for LANDIS Simulations—Research Project CC-1 will provide projections of future climate for a range of different CO_2 emission scenarios. LANDIS uses climate data on a monthly time step. Meteorological driven data include maximum and minimum temperature, standard deviations of monthly temperature, and monthly precipitation, with the latter two standard deviations computed from a moving average of other years on a 10-year time step. Meteorological data are generated based on the monthly averages and standard deviation of monthly data provided for every year. Thus, driving meteorological data used by LANDIS are month specific, allowing the model to respond to inter-annual differences in both temperature and precipitation.

LANDIS Century Extension for Climatic Effects on Biogeochemical Cycling—We will use the LANDIS Century extension (Scheller et al., 2011) to account for above- and below-ground biogeochemical processes and their response to climatic change. The Century model (Parton et al., 1987 and 1993) links above-ground processes of stand dynamics to below-ground processes of soil carbon and nitrogen dynamics. The Century extension runs on much of the same meteorological data required by the PnET extension. Driving data consist of average minimum monthly temperature, average monthly maximum temperature, standard deviation of monthly temperatures, average annual precipitation, and standard deviation of annual precipitation. Within the Century extension, each species-age cohort has an associated leaf biomass, above-ground wood biomass, coarse root biomass, and fine root biomass (Scheller et al., 2011). The size of each cohort component is a function of net primary productivity, carbon allocation, and mortality. Annual fraction leaf and fine root mortality is modeled as the inverse of leaf longevity and occurs during a user-designated month. Monthly fraction of above-ground wood and coarse root mortality is user determined and includes all forms of wood mortality, including thinning and loss of branches. In addition, age-related mortality will substantially reduce above-ground biomass after a cohort reaches 80% of maximum longevity(Scheller and Mladenoff, 2004).

LANDIS PnET Extension for Probabilistic Species Establishment—The PnET model extension can calculate the probability of establishment (P_{EST}) under changing climatic conditions. The P_{EST} is calculated at an annual time step and is dependent upon climatic driving data. Establishment of a species can only occur following a disturbance or at a succession time step. P_{EST} is based on the minimum of the following limiting factors: (1) growing degree days, (2) species-specific drought tolerance (in response to soil moisture) and (3) minimum January temperature. Of the variables determining P_{EST}, drought tolerance (in response to soil moisture)

is a key variable that could alter the regenerative capacities of coastal plain pine forests. Thus, although the Century extension simulates the effects of climatic change on ecosystem processes, the LANDIS PnET extension simulates the effects of climatic change on species recruitment. Of particular interest are the effects of drought on the future colonization of pine species adapted to widely differing hydrologic gradients.

Effects of Hurricanes—The Harvest extension could, in theory, be used to mimic the effects of a hurricane by simulating the cutting, but not the removal, of overstory cohorts that would be the most susceptible to hurricane winds. We also note that LANDIS has a wind extension to simulate wind dynamics that simulates blowdown on susceptible cohorts. The susceptibility of a cohort is a user-determined function of age and species, whereby each species has an age at which it is increasingly susceptible to wind blowdown. However, the wind module operates stochastically and, whether it is suitable for simulating episodic, hurricane-type disturbances at MCBCL, is unknown at present and can only be resolved through testing. Thus, although we recognize the benefits of incorporating hurricane-type disturbances, we cannot state how well the model can reproduce them for MCBCL. We hope to resolve this in the early stages of model testing and calibration.

8.3.2.3 Technology Transfer

LANDIS will be developed so as to facilitate use by MCBCL managers for auditing carbon stores and planning around stand and landscape management objectives. Specifically, we will integrate LANDIS into the common SDSS in collaboration with Research Project TSP-1. Our objective is to develop a Terrestrial Carbon Assessment Decision-Support Tool (TCAT) that can be used to assess the tradeoffs between forest management to maximize long-term carbon stores and other forest management objectives, including prescribed burning, habitat restoration, and tree harvest. Working with Research Project TSP-1, we will provide managers at MCBCL and other installations with similar vegetation with a tool that will facilitate auditing of carbon stores and evaluation of different management protocols on likely changes in carbon stores through time.

8.3.3 Assessment of Climate Change Impacts

Research Project T-3 will use local climate data provided by Research Project CC-1 to drive LANDIS model simulations. This model responds to climatic changes through an incorporation of species-specific parameters for drought tolerance, phenology, and germination, all of which are responsive to temperature, solar radiation, and precipitation (average monthly values). Similarly, LANDIS can account for changes in growth rates that might accompany climatic change, as well as the changing establishment probabilities for each species, thereby allowing for a dynamic representation of potential changes in species composition and growth that may occur under a changing climate.

8.3.4 Milestones

1. Initiate the calibration of LANDIS to DCERP1 field data and GIS data 3/2013
2. Complete calibrations and begin initial model simulations 6/2013
3. Conduct minimal field sampling to fill any calibration gaps 6/2013–8/2013

4. Refine the model and simulations and analyze simulation data 9/2013–12/2014
5. Conduct a field campaign for vegetation and arthropods on experimental plots 5/2015–8/2015
6. Prepare decision-support tool (TCAT) for loading into SDSS with Research Project TSP-1 9/2015–12/2015
7. Analyze data from the field campaign 9/2015–2/2016
8. Prepare and submit a manuscript on the impact of forest management practices on carbon stores 3/2016–8/2016
9. Prepare and deliver a report on experimental results to MCBCL staff 3/2016–8/2016
10. Complete simulation runs and prepare and submit manuscript(s) based on the results of the model simulations. Note: The completion of these simulations could be sooner, depending upon the availability of climate data from Research Project CC-1. 11/2016–12/2016
11. Prepare and deliver a Final Report 9/2016–6/2017
12. Prepare and submit a manuscript on the impact of climate change on coastal plain ecosystems 3/2017–7/2017

8.3.5 Deliverables

1. Deliver draft manuscripts on results of the LANDIS model simulations to RTI and to MCBCL staff. Note: Model results are contingent upon the delivery of climate data from Research Project CC-1. 8/2016
2. Working with Research Project TSP-1, we will provide managers at MCBCL and other installations with similar forest types with a tool (TCAT) that will facilitate auditing of carbon stores and evaluation of different management protocols on likely changes in carbon stores through time. 12/2015
3. Prepare and deliver the final Research Report. Draft 3/2017; final 6/2017

8.3.6 Planned Publications

Submit a journal article on the impacts of different forest management practices on carbon stores in coastal plain (including MCBCL) ecosystems. Planning is contingent upon the availability of projected climate data from Research Project CC-1. Submission of the article is planned for August 2016.

Submit a journal article on the potential impacts of climatic change on coastal plain (including MCBCL) ecosystems. Planning is contingent upon the availability of projected climate data from Research Project CC-1. Submission of the article is planned for July 2017.

8.4 Research Project T-4: Impacts of Climate Change on Management of Red-Cockaded Woodpeckers at MCBCL

Lead Investigator: Dr. Jeffrey Walters (VA Tech)

Supporting Researcher: One Postdoctoral student (Sara Zeigler)

Technical Objectives/Goals: The overarching goal of Research Project T-4 is to provide MCBCL managers with information they will require to continue to integrate recovery of the endangered RCW that drives management of the terrestrial ecosystem, with military training and carbon sequestration goals as climate changes. Specific objectives are as follows: (1) evaluating the possible impacts of climate change on the demography of RCWs; (2) using simulation modeling to assess how the dynamics of the RCW population on MCBCL may be altered by effects of climate change on RCW demography and forest structure; (3) providing MCBCL with a modeling tool that will allow Base managers to make additional assessments of how management activities might impact the RCW population on current and future landscapes; and (4) providing a refined version of this same tool to an additional North Carolina installation (i.e., Fort Bragg).

Research Questions:

1. Based on current linkages between weather and RCW productivity, how are projected changes in weather due to climate change predicted to alter RCW productivity on MCBCL and Fort Bragg?
2. Based on simulation modeling, how are projected changes in RCW demography and longleaf pine habitat due to climate change predicted to alter RCW population growth on MCBCL?

8.4.1 Background

The primary conservation objectives for the terrestrial environment of MCBCL managers are to restore the longleaf pine ecosystem and recover the RCW within that system, while supporting the military training mission. These same objectives apply to five other large, heavily used DoD installations across the southeastern region of the United States. DoD has had great success in meeting these objectives, while continuing to support the military training mission, recovering two RCW populations and increasing others (including the population at MCBCL; **Figure 8-2**), but climate change presents a challenge to this continued success. When faced with changing habitat selection pressures such as those resulting from a changing climate, only a few outcomes are possible for populations: dispersal to a new habitat where the selection pressure is similar to the old habitat; remaining in place, but altering some traits in response to the selection pressure via phenotypic plasticity; adapting to the new selection pressure by changing genotype frequencies (i.e., microevolution); or local extinction (Gienapp et al., 2008; Holt, 1990). Latitudinal and altitudinal range shifts in response to climate change are widely documented (e.g., Walther et al., 2002), but little is known of responses of species that persist in populations in habitat islands with few emigration possibilities. The RCW is such a species, and its inability to move is exacerbated by its extreme habitat specialization (Walters, 1991). RCWs must respond to climate change in situ and avoid the outcome of local extinction, which requires an understanding of how RCW population dynamics will change and adjusting management strategies appropriately. Adjusting for climate change will require greater management flexibility than currently exits and integrating RCW recovery with the emerging goal of increasing carbon sequestration (see Research Project T-3).

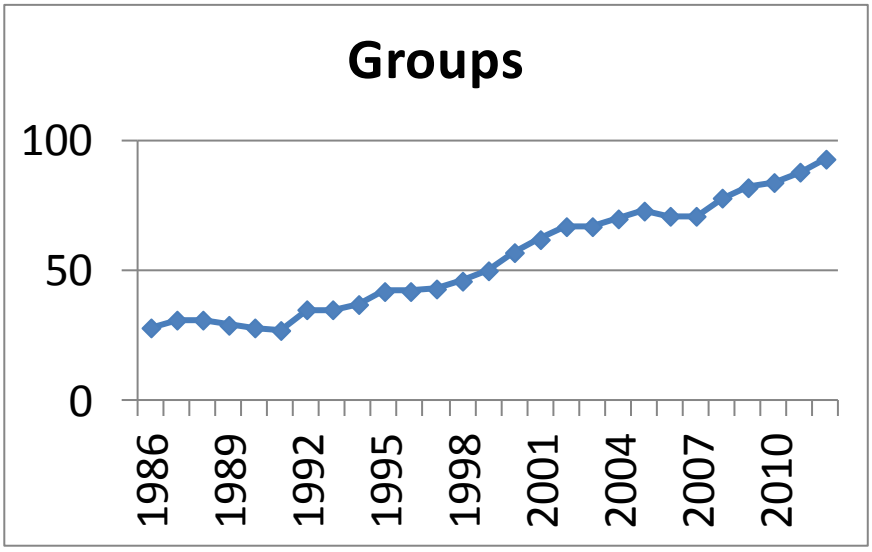

Figure 8-2. The number of groups of RCWs on MCBCL from 1986 to 2012.

During a previous SERDP research project (RC-1472), we developed the RCW DSS Tool for general use on DoD installations with RCW populations. The RCW DSS Tool is an individual-based, spatially explicit RCW population model that includes interactions with the landscape in several forms and is regularly used by MCBCL staff. This tool currently includes two options with respect to RCW demography: a coastal option based on the MCBCL population, and an inland option based on the North Carolina Sandhills (Fort Bragg) population. The DSS Tool also has two landscape options: a land-cover option and an RCW matrix option. In the land-cover option, the quality of habitat associated with each RCW group is a simple function of the age of pine stands. In the RCW matrix option, habitat quality is determined by habitat quality scores produced by the tool the U.S. Fish and Wildlife Service currently uses to evaluate RCW foraging habitat (i.e., the RCW matrix). To develop the RCW DSS further as part of another current SERDP project (RC-1696), we are adding the capability for a dynamic landscape. In both current existing landscape options, the landscape is static except for aging of the pine canopy. However, the new version of the RCW DSS will have the capability for habitat features that affect RCW habitat quality scores to change over time as a function of succession, disturbance, and management.

In another project funded by non-SERDP sources, Dr. Walters is conducting a region-wide assessment that includes MCBCL documenting changes in life history features such as clutch size, laying date and productivity over time, and exploring the linkages between these life history features and climate change. Research Project T-4 will provide the capability to project impacts of climate change on RCW demography (Objective 1). We will produce a coastal version of the improved RCW DSS with a dynamic landscape resulting from Research Project RC-1696 for MCBCL (Objective 3) and an inland version for Fort Bragg (Objective 4). We will use forest structure and dynamics projections resulting from Research Project T-3 to construct future landscapes on which to run simulations of RCW population dynamics under various possible future climate scenarios using the new, MCBCL version of the RCW DSS (Objective 2).

8.4.2 Methods

All of the data required to carry out the project are available from other projects in which the PI is involved. Thus the project consists entirely of modeling work. The computer programmer who built the RCW DSS in Research Project RC-1472 and the postdoctoral associate who built the forest dynamics model in RC-1696 will be collaborating on Research Project T-4; therefore, making adjustments of the RCW DSS necessary to produce an MCBCL-specific tool will be a straightforward task in terms of programming. The RCW DSS currently runs, and will continue to run, as an ArcGIS extension. The forest dynamics model constructed in RC-1696 is a state-transition model (the Path Landscape Model, formerly known as the Tool for Exploratory Landscape Scenario Analyses [TELSA]), **Figure 8-3**). Producing a version of the forest dynamics model appropriate for MCBCL will also be straightforward, involving only removing specific states and transitions (i.e., those involving sand pine), replacing the Eglin landscape with the MCBCL landscape, and adjusting a few model parameters to reflect (i.e., probabilities of hurricanes and fire) disturbance regimes on MCBCL (Objective 3). Producing a version for Fort Bragg (Objective 4) will be similarly straightforward. Because the MCBCL tool will run in an ArcGIS environment, it will easily be incorporated into the modeling framework being developed by Dr. Patrick Halpin under Research Project TSP-1.

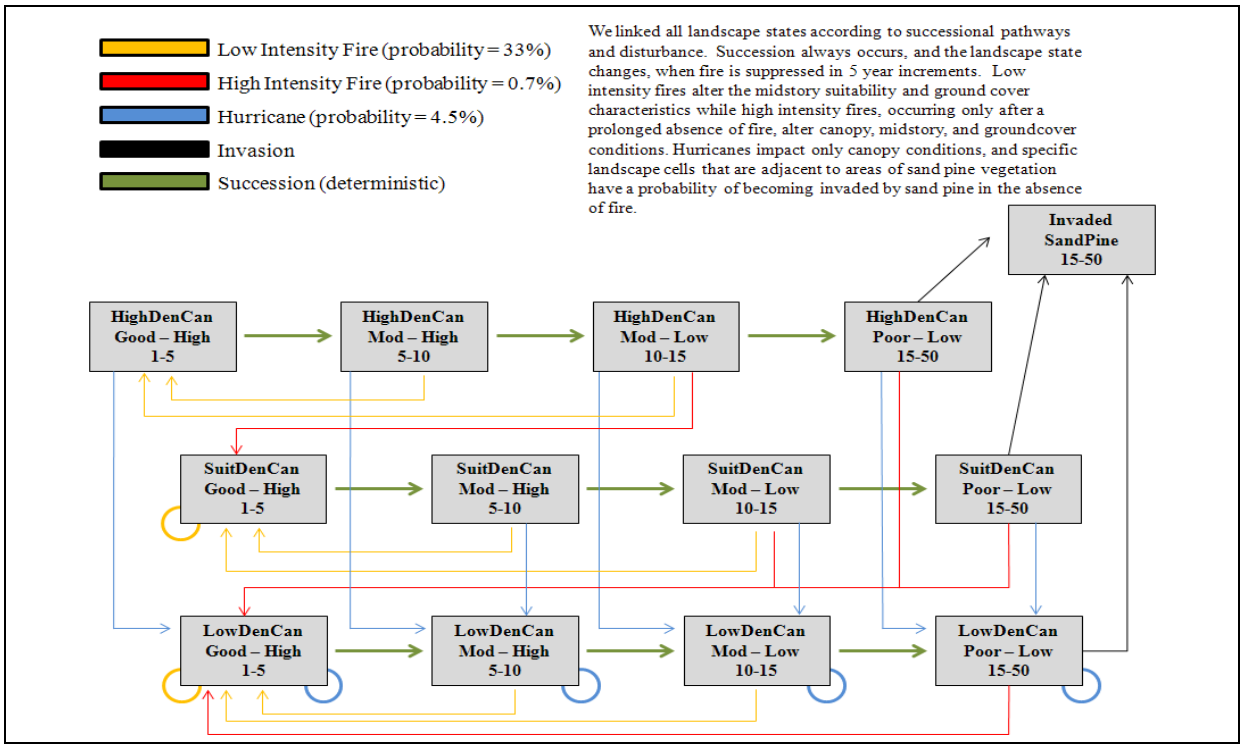

Figure 8-3. Draft version of the state-transition model for longleaf forest dynamics.

We will collaborate with Research Project CC-1 to explore the potential effects of climate change on RCW demography. Relationships between climate and RCW demography are emerging from current research by Ms. Vicki Garcia, a Ph.D. student in the PI's laboratory. Ms. Garcia has already documented which demographic parameters are changing (for previous documentation of advances in laying date, see also Schiegg et al., 2002), and she is currently analyzing relationships of those parameters to weather, including linkages to not only monthly

averages in precipitation and temperature, but also weather events (e.g., 10 consecutive days of daily high temperatures above 32°C) and demography. Based on these linkages and projected climate scenarios provided by Research Project CC-1, we will compute expected future means and variances in key demographic parameters and will use these data to evaluate the possible effects of climate change on RCW demography and to run scenarios of future RCW population dynamics. The two model parameters involved are productivity, expressed in terms of fledglings produced by an RCW group in a year and annual survival rates of breeders, helpers, and fledglings. We will select future demographies and durations of model runs based on available climate date and to compare population performance under projected these future climates to that under current conditions.

8.4.3 Assessment of Climate Change Impacts

Research Project T-4 will investigate the projected impact of climate change on local populations of endangered RCWs at MCBCL and at Fort Bragg in North Carolina. We will evaluate both effects due to impacts on RCW demography related to the linkages between weather and productivity and effects due to habitat change. We will use long-term demographic data from MCBCL and Fort Bragg to analyze the linkages between weather and productivity, which will be conducted in collaboration with Research Project CC-1. We will use simulation modeling, built on a foundation provided by other SERDP funding, to evaluate population dynamics, an analysis that will also use the results from Research Project T-3 to project landscape dynamics. We will conduct this task in collaboration with Research Project CC-1.

8.4.4 Milestones

1.	Deliver the RCW DSS Tool with a user's guide to MCBCL managers and transition the tool to Fort Bragg	7/2014
2.	Prepare and deliver the final Research Report	6/2015

8.4.5 Deliverables

1.	Deliver the RCW DSS Tool and user's guide to MCBCL	July 2014
2.	Deliver the RCW DSS Tool and user's guide for Fort Bragg	March 2015
3.	Prepare and deliver the final Research Report	Draft 3/2015; final 6/2015

8.4.6 Planned Publications

Submit a journal article with the tentative title of "Effects of Local Habitat Processes on RCW Population Dynamics in a Changing World." In this article, we will examine how differences in productivity, fire regime, and RCW vital rates in longleaf pine ecosystems at Eglin AFB, MCBCL, and Fort Bragg translate into differences in RCW population growth rates at each site. We will also examine how projected site-specific changes in climate may affect vital rates, and (ultimately) population growth rates of RCWs. We are planning to submit this article to *Ecological Applications*. Submission of the article is planned for December 2014.

8.5 Research Project T-1-Supplemental: Effects of Different Understory/Midstory Restoration Management Options on Terrestrial Ecosystem Plant and Arthropod Communities

Note: The DCERP1 funding period only permitted evaluation of effects for the first year following the initiation of experimental treatments, and it was understood that additional sampling of experimental plots needed to occur during the DCERP2 timeframe to obtain a fuller understanding of treatment effects. That sampling will be completed in Year 3 of DCERP2.

Lead Investigator: Dr. Norman L. Christensen (Duke University)

Supporting Researchers: Dr. Stephen Mitchell (Duke University)

Technical Objectives/Goals:

1. This project will complete field sampling of vegetation and arthropods in experimental plots established in DCERP1 Research Project T-1. The specific objectives for Research Project T-1 were to measure the impacts of understory and midstory thinning (mechanical operations with HydroAx equipment) in different seasons (growing versus dormant) on forest herb layer cover, composition, production, and arthropod composition and diversity. Experimental treatments were installed in 2009 and burned in 2010 or 2011. Vegetation, arthropods and birds were sampled during the 2011 growing season. This was only the second growing season following treatment. Although a few trends were evident in differences among treatments and sites, it was our expectation that significant treatment differences (if any) would not be fully apparent for several years. Therefore, it was part of the plan for Research Project T-1 plan experimental plots would be sampled once more during the 2015 growing season. These results will bear directly on MCBCL forest management objectives, including the following:
   - Restoration of the longleaf pine habitat
   - Recovery of RCW populations
   - Conservation of native biological diversity
   - Support for military maneuvers (e.g., expanding the available training area by opening the understory, facilitating troop movement)
   - Promotion of sustainable forest management
   - Improved knowledge on fire and fuel management.
2. Transfer knowledge gained during our studies to managers at MCBCL and other military installations on similar landscapes. The team will present information garnered from this experiment to MCBCL and other installations via a workshop focused on longleaf pine ecosystem restoration.

Hypotheses:

1. Herbaceous cover, productivity, and species diversity will increase with increasingly aggressive measures to remove understory hardwood shrubs and trees and control the reproduction of these trees and shrubs (mechanical thinning, herbicide and mechanical thinning plus herbicide).
2. These effects will vary depending on the season of mechanical thinning (growing season versus dormant season).
3. Forest management activities will have their greatest impacts on species richness and composition in moister sites compared to drier sites.
4. Changes in the composition, productivity, and diversity of the herbaceous community will be highly correlated with variations in the composition of insect and bird communities.

8.5.1 Background

The terrestrial vegetation of North Carolina's lower coastal plain is known for its diversity across a wide range of spatial scales. MCBCL lands capture much of that variation. At the landscape scale, geomorphic variations such as relict dune and estuarine deposits and subtle changes

(±1 m) in elevation of the soil surface relative to the shallow water table produce remarkable variations in ecosystem structure, composition and processes. Within a few kilometers of the coast, vegetation composition is heavily influenced by salt aerosol and maritime climatic gradients. In pre-settlement times, inland vegetation varied along a continuum from shrub bog (pocosin) wetlands on deep peat soils to pine-dominated flatwoods with an understory of shrubs on poorly drained mineral soils and longleaf pine savannas on well-drained sands (Christensen, 2000). There was nearly complete turnover of plant species composition from one end of this gradient to the other. Some of these ecosystems display remarkable species richness and high levels of species endemism at very local scales. For example, longleaf pine savannas may support more than 60 vascular plant species per square meter and more than 120 species per hectare; Walker and Peet, 1983).

Ecosystem composition and structure was also heavily influenced by variations in pre-settlement fire regimes along this gradient. Pocosins typically experience intense, crown-killing fires at return intervals of more than 40 years, whereas longleaf pine savannas are maintained by light surface fires at intervals of 1–5 years (Bailey et al., 2007; Christensen, 1981, 1992, and 2000). The relative amount and distribution of pocosin, flatwood and savanna ecosystems on pre-settlement landscapes was heavily influenced by the frequency and behavior of fire. Repeated, low severity fires can maintain savanna on very moist soils with relatively high amounts of organic matter. Indeed, it is just these situations that support the highest plant species richness at small (m^2) spatial scales. It is also these sites that support a number of unique endemic species, including several insectivorous plant species. On all but very well-drained sites, the absence of fire for periods longer than 5–6 years results in the invasion of shrubs and a variety of understory trees. This invasion also changes the amounts and distribution of fuels such that subsequent fires are likely to be severe enough to kill and even consume canopy trees.

Today, post-settlement land use and disturbance influence the mosaic of terrestrial ecosystems on lower coastal plain landscapes such as on MCBCL. Except for the wettest and driest sites, forests on much of this landscape were cleared for agriculture during the eighteenth and nineteenth centuries (Crowley, 1996). Longleaf pine savannas that were not cut were heavily managed for naval stores (Early, 2004). Much of this farmland was abandoned in the years following the Civil War and Reconstruction up to World War II; post abandonment succession generally produced an even-aged overstory of loblolly pine with an understory dominated by shrubs and understory trees on all but the driest sites (Christensen, 2000). Fire was not only excluded from these forests, but the successional changes promoted understory vegetation and fuels that are comparatively difficult to burn (Nowacki and Abrams, 2008). In the period from 1940 to 1960, large tracts of such land were acquired by timber companies who managed them to maintain loblolly pine dominance.

Across the Southeast United States, this history of land use led to the transformation of more than 95% of the land once dominated by longleaf pine savanna to loblolly pine dominated flatwoods. Even where longleaf pine remained, fire suppression often led to the invasion of woody understory plants and the loss of endemic plant and animal species. In many places, longleaf pine ecosystems are represented by relatively small and often isolated stands.

Altered fire regimes and habitat loss and fragmentation have contributed to the significant number of plant and animal species found in communities dominated by longleaf pine that are

currently listed as threatened or endangered under the Endangered Species Act. The RCW is probably most notable among these listed species. These listings, along with general concerns about the loss of longleaf pine habitat, have been the impetus for restoration of loblolly pine flatwoods to longleaf pine savannas. Indeed, maintenance and restoration of longleaf pine habitat and, hopefully, associated populations of RCWs have been prominent objectives of forest management over much of the MCBCL landscape.

In some parts of MCBCL, restoration has taken the form of clear-cutting, followed by planting of longleaf pine and eventual re-establishment of an appropriate prescribed fire program. Restoration of mature longleaf pine habitat by this approach will, of course, require many decades. As an alternative strategy to accelerate habitat restoration, MCBCL staff have implemented mechanical thinning treatments to remove understory and midstory hardwoods (generally stems less than 20 cm dbh) and open savanna-like stand structures and understory composition and fuels that are more typical of longleaf pine ecosystems (**Figure 8-4**). Such management is currently being applied to hundreds of MCBCL acres each year. Variations on this management theme include different seasons (growing and dormant) of mechanical control of the woody understory. Restoration of low severity, high frequency fire regimes is a key objective. Therefore, all thinned areas receive a late winter or early spring prescribed fire in the year following treatment.

Figure 8-4. A typical loblolly pine site prior to understory/midstory thinning (left). HydroAx in action (center) mulching woody stems <20 cm dbh. A typical site following understory/midstory thinning (right).

The effects of restoration treatments on understory vegetation are especially relevant because the composition of this community is a major determinant of RCW habitat quality (USFWS, 2003). The needs of RCWs are well known, but virtually nothing is known about the relationships between the diversity and composition of the plant communities and the diversity and composition of avian communities (USFWS, 2003). Arthropods play an important role in determining habitat quality for many bird species, but the effects of restoration treatments on arthropod diversity and composition are largely unknown.

Research Project T-1 will provide an understanding of the relationships among trophic levels that may influence avian habitat (particularly RCW). This research focuses on the following data gaps:

- Effects of variations in understory forest restoration techniques
- Impacts of forest restoration management on herbaceous communities and the interaction of those activities with fire management

- Linkages between restoration of herbaceous communities and habitat for insect and bird communities
- Improved understanding of the variations in these effects among different site conditions within the general loblolly pine plantation forest type.

8.5.2 Methods

8.5.2.1 Experimental Design and Study Sites

In 2008, stands that were slated for forest restoration (i.e., understory/midstory thinning treatment) were identified by MCBCL staff. These stands or restoration treatment units were dominated in the canopy by 50–60 year-old loblolly pine, with a dense midstory of woody trees and shrubs. Based on general appearance, soil series, and dominant species, stands were designated as either mesic (well-drained soils, dominated by loblolly pine and some longleaf pine), wet-mesic (moister soils dominated by loblolly pine only), and high pocosin (wet, organic soils dominated by loblolly and with some pond pine).

Each experimental treatment block included three 1-ha treatment plots: (1) no woody understory and midstory removal control (C), (2) dormant season mechanical understory and midstory removal (D), and (3) growing season mechanical understory and midstory removal (G). Dormant season (D) treatments were installed during January and February, and growing season (G) treatments were installed in June and July of 2009. Restoration treatment units were selected so as to establish three blocks in each of the mesic, wet-mesic and high pocosin designations for a total of nine blocks. However, one of the wet-mesic blocks was lost to wildfire in 2009, leaving eight blocks (**Figure 8-5**). All treatments were to receive non-growing season prescribed burns at 3-year intervals. The original plan was to complete the first post-treatment burns between December 2009 and April 2010. However, because of unfavorable weather conditions in 2010, only two out of the eight treatment areas could be burned during that year. Post-treatment burns on the remaining plots were completed between February and April 2011.

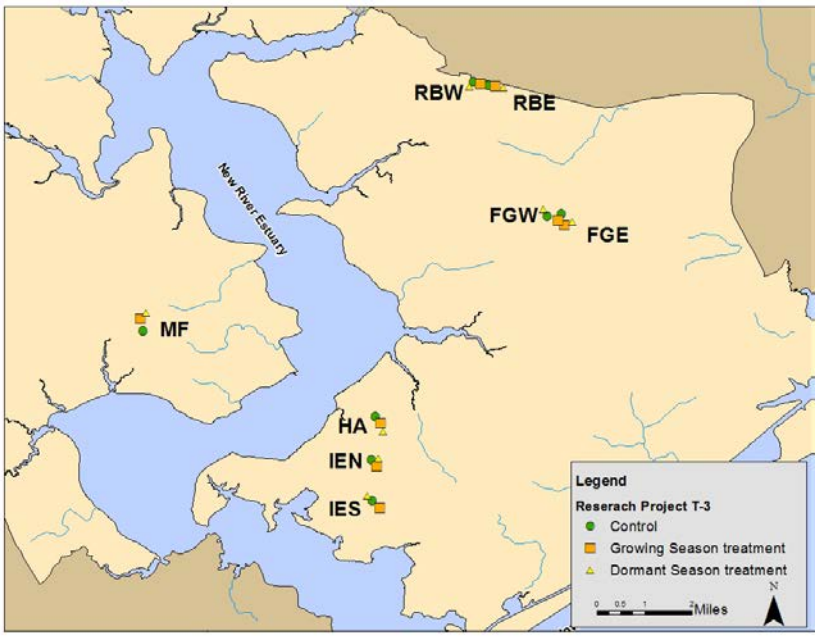

Figure 8-5. The location of experimental blocks and treatment plots for Research Project T-1-supplemental on MCBCL.

MCBCL staff had designated blocks IES, FGE, and FGW as high pocosin, blocks MF, IEN, and HA as wet mesic, and blocks RBE and RBW as mesic.

8.5.2.2 Vegetation, Arthropod, and Bird Sampling

Prior to treatment applications, woody stems 1–20 cm dbh were censused by species and diameter class in each of the three 1-ha experimental plots in each of the eight blocks. The 1–20 cm dbh size range was selected because these are the stems typically removed in the thinning treatment. Within an 8-m radius of each of the five randomly located points in each plot, dbh and species identity were recorded for each stem ≥5 cm dbh. All stems less than 5 cm were recorded by species and dbh along a 1- × 8-m transect traversing each point. In the year after prescribed burning, each experimental plot was censused for vegetation species abundance and diversity, cover of herbs, and biomass of woody plants using the Carolina Vegetation Survey methodology (Peet et al., 1998).

Arthropod (primarily insects and spiders) populations were monitored in pitfall, yellow pan, and Malaise traps (Malaise, 1937; Provencher et al., 2001a and b). Arthropods were euthanized and identified in the laboratory to the lowest taxon possible. Insect identification was conducted in collaboration with Drs. Andy Deans and Matthew Bertone of the Department of Entomology at North Carolina State University. The arrangement of vegetation and arthropod samples is shown in **Figure 8-6**. Bird composition and abundance were assessed from point count samples located at the center of each treatment plot at several times throughout the breeding season in conjunction with Research Project T-2. The details of avian sampling methods are described in the *DCERP1 Final Research Report* (RTI, 2013).

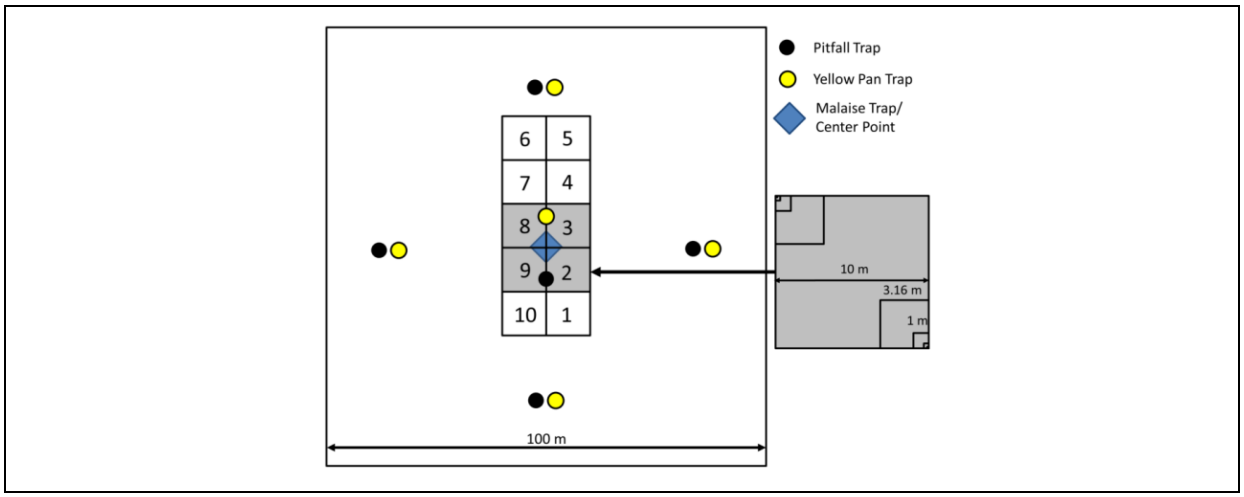

Figure 8-6. The arrangement of vegetation sample plots (the numbered rectangle) and arthropod traps in individual 1-ha experimental plots.

8.5.2.3 Soils

Soil samples were collected from each experimental plot during the growing season following treatment and prescribed burning. Using a 5 cm in diameter piston corer, a uniform sample of the top 0–10 cm of mineral soil (soil beneath layers of litter and duff) was collected at each of four points located 10 m from the center point of each experimental plot. Each soil sample was subsequently analyzed by Brookside Laboratories (New Knoxville, OH). Soil pH as measured using a glass electrode in a 1:1 slurry of soil and distilled water (McLean, 1982). Percent soil organic matter was determined by weight loss after ignition at 360°C. P (phosphorus), K (potassium), Ca (calcium), Mg (magnesium), Mn (manganese), Zn (zinc), B (boron), Cu (copper), Fe (iron), Al (aluminum), S (sulfur), and Na (sodium) were extracted according to Mehlich (1984). P concentrations in the Mehlich extractant were measured colorimetrically; concentrations of other elements were determined by plasma emission spectroscopy. Cation exchange capacity was measured by summation of all cations as milliequivalents/100 g soil (Ross, 1995). Several of these soil features have been shown to have a high correlation with the distribution of many coastal plain plant species (Christensen, 2000; Christensen et al., 1988; Peet, 2006; Walker and Peet, 1983).

8.5.2.4 Statistical Analyses

Data for monitoring and experimental plots were analyzed using standard statistical tools for product-moment correlation and analysis of variance provided in the data analysis and graphics system R (Venables et al., 2011). Non-metric multidimensional scaling (NMS) ordination (Kruskal and Wish, 1978) was used to analyze trends in species composition in monitoring and experimental plots. Each NMS axis represents a component of variation in the multivariate data set that is similar to a principal components axis (PCA). However, NMS ordination is much better suited for use with non-normal species composition data than PCA. Plots with similar scores for a particular NMS axis are more similar to one another with respect to the trends in species composition represented by that axis than stands with less similar scores. Our NMS analyses used the Sørenson dissimilarity metric for 1000 iterations to derive two-dimensional ordination axes, which represent the main axes of compositional variation. We ran PC-ORD with

random starting configurations for 100 runs with real data with a maximum of 1,000 iterations per run, and a stability criterion of 0.00001. Indicator species analysis (Dufrêne and Legendre, 1997), and correlation and regression tree analyses (McCune et al., 2002) were used to identify those species and site measures that are most highly correlated to variations in species composition represented in the NMS ordination (McCune and Grace, 2002).

We used structural equation modeling (SEM) to evaluate the correlational relationships among the composition of vegetation, arthropod, and breeding bird communities for experimental plots and the 21 additional DCERP1 Research Project T-2 plots. There are several features of SEM that are different from most classical methods of statistical analyses. First, unlike many classical statistical techniques, SEM is not intended to test and/or reject null hypotheses. Instead, the purpose of SEM is to test theoretical relationships among different variables and competing models. Second, the calculation of the degrees of freedom in the model comes from having more known values (from the covariance matrix of the data) than estimated values (required by the model). Models in which all possible pathways are specified are saturated and possess 0 degrees of freedom; nonzero degrees of freedom permit the testing of model structure (Grace et al., 2010). Third, chi-square (χ^2) statistics that yield a p-value <0.05 are considered a *poor* model fit, whereas higher p-values are considered a stronger fit. However, good-fitting SEMs do not prove causal relationships (Bollen, 1989). Inferences about the sign and strength of directional paths in SEM can only be made if sound theory guides both the model building and the model fitting processes (Grace, 2006). Fourth, SEM allows several correlated variables to be represented collectively as a composite variable. A composite variable is a special type of variable that is completely specified by two or more causal indicators (Grace and Bollen, 2008). We combined soil pH, cation exchange capacity, and % soil organic matter (Table 1) into a single, composite variable of soil characteristics. Non-composite variables that are directly observed are referred to as manifest variables.

8.5.2.5 Measurements in DCERP2

We will evaluate experimental outcomes 6-years after the application of longleaf pine restoration treatments during the 2015 growing season. These plots will be burned again in 2014 as part of MCBCL's typical 3-year rotation. We will also sample pre- and post-fire woody stems and ground fuels within each 1-ha experimental treatment plot, using our previously established 20-m × 50-m (0.1-ha) plots in each 1-ha plot. As previously described, we will sample overstory and understory vegetation using the Carolina Vegetation Sampling protocol (Peet et al., 1998). To sample ground fuels, we will re-establish our 50-m fuel sampling line down the center transect of each 0.1-ha plot to sample fine fuels and coarse woody debris by size class, using line intercept transects (e.g., Harmon and Sexton, 1996). We will resample both the stems (>1 cm dbh) and ground fuels after the fires, which will give us an estimate of fire-caused mortality and ground fuel consumption. We will sample and identify arthropods as previously described. We will use the multivariate and SEMs previously described to analyze data.

During each fire, we will collect various measurements of fire behavior, such as flame length, fire temperature, and rates of spread. Rates of spread and flame length will be measured with an infrared camera on loan from the laboratory of Dr. Leda Kobizar at the University of Florida. We will measure temperatures using fine-wire thermocouples, although video taken from the infrared camera could also provide coarse estimates of temperature.

8.5.3 Results to Date

8.5.3.1 Pre- and Post-Treatment Variation in Vegetation, Arthropod, and Bird Communities

Pre- and post-treatment data for stem density and basal area for woody stems, and post-treatment % canopy cover in each treatment plot are displayed in **Table 8-3**. Although stem density varied considerably among treatment plots (5,500 to 57,000 stems/ha for the 1-4 cm dbh size class and 130 to 1,390 stems/ha for the 5-20 cm dbh size class), it was considerably higher than the average for longleaf pine stands that have been prescribe burned at regular intervals (e.g., <1,000 stems/ha for the 1–4 cm dbh size class and <100 stems/ha for the 5–20 cm size class). Basal area for 1–20 cm stems accounted for 15% to more than 70% of total stand basal area; in longleaf stands basal area of 1–20 cm stems generally accounts for less than 15% of total basal area.

Table 8-3. Summary of pre-treatment and post-treatment vegetation data for T-1 experimental plots in DCERP1.

Pre-treatment basal area data could not be gathered for treatment plots FGE-C and FGW-C owing to military training activities. Blocks are ordered left to right as high pocosin (FGE, FGW and IES), wet mesic (IEN, HA and MF) and mesic (RBE and RBW).

		Pre-Treatment			Post-Treatment				
Blk-Trt	**Age (year)**	**Stems <5 cm**	**Stems 5–20 cm**	**Basal Area stems 1–20 cm dbh**	**Stems <5 cm**	**Stems 5–20 cm**	**Stems >20 cm**	**% Canopy Cover**	**Total Basal Area**
FGE-C	50	N/A	N/A	N/A	1,820	620	220	37.34	26.2
FGE-D	50	10,250	770	6.02	610	130	190	47.45	19.6
FGE-G	50	21,250	190	4.01	110	40	200	100	19.6
FGW-C	50	N/A	N/A	N/A	1,530	640	180	99.99	25.6
FGW-D	50	11,000	520	5.06	650	140	210	54.68	19.6
FGW-G	50	22,000	370	4.64	130	30	190	52.8	19.6
IES-C	60	46,750	510	11.5	300	80	220	100	19.7
IES-D	60	6,000	1,390	11.65	590	180	170	60.92	18.5
IES-G	60	11,750	130	2.46	380	240	120	59.92	13.5
IEN-C	50	57,000	120	13.42	1,730	340	110	61.65	7.6
IEN-D	50	10,750	770	8.2	840	160	120	60.2	10.2
IEN-G	50	16,250	420	4.31	220	0	220	94.48	17.6
HA-C	53	27,750	610	14.52	1,130	300	110	66.75	18.1
HA-D	53	16,500	600	6.06	80	10	80	58.19	8.4
HA-G	53	9,000	340	3.07	350	30	80	79.44	8.4
MF-C	63	34,500	480	8.64	2,100	670	130	68.7	21.3
MF-D	65	6,500	820	7.71	300	50	250	61.95	23.6
MF-G	65	11,500	260	2.53	440	130	190	58.75	16.5
RBE-C	60	12,750	610	9.72	2,060	650	90	96.36	23.8
RBE-D	64	5,500	1,330	9	980	100	140	69.39	18.4
RBE-G	64	10,500	300	2.45	190	10	80	59.88	13.3
RBW-C	56	11,500	380	4.38	1,060	220	230	96.63	26
RBW-D	56	6,000	650	4.63	850	170	120	44.62	22.1
RBW-G	56	9,500	210	2.72	170	20	130	64.63	19.1

As expected, density of 1–20 cm dbh stems was considerably less than pre-treatment density in all post-treatment plots. In nearly all cases, understory stem density was reduced by more than 90%. This was true even for control plots because they had been prescribe burned (PB) in either 2010 or 2011 along with the thinned plots. There were no significant differences among blocks (F=0.98, DF=7, P >0.48); however, there were significant differences among treatments (F=47.56, DF=2, P <0.00001). Specifically, stem density was uniformly highest in control plots, lower in dormant season thinning plots and lowest in growing season thinned plots **(Figure 8-6)**.

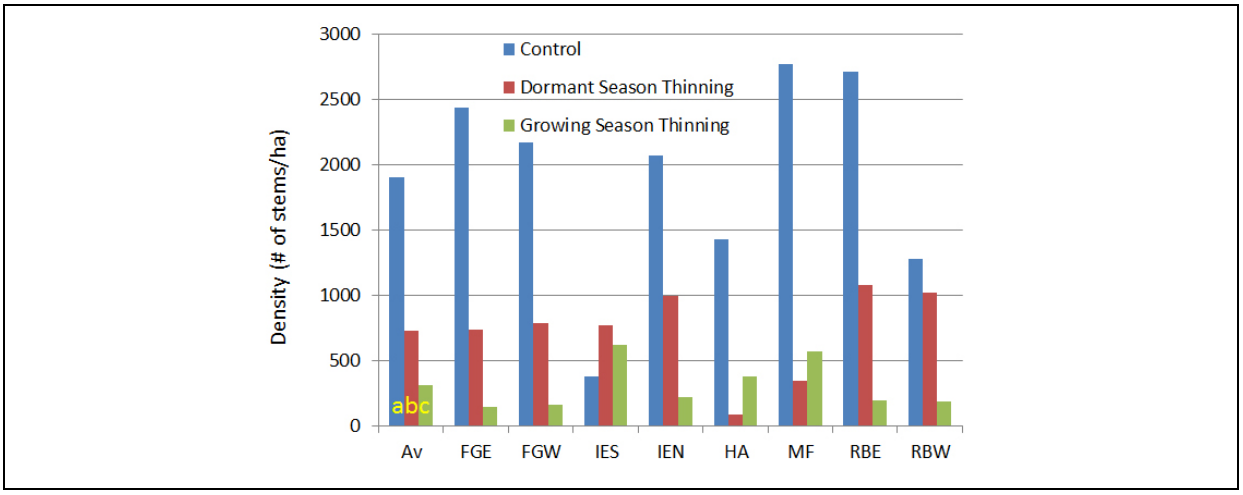

Figure 8-6. Post-treatment 1–20 cm dbh stem density by block and treatment.

Blocks are ordered left to right as high pocosin (FGE, FGW and IES), wet mesic (IEN, HA and MF) and mesic (RBE and RBW). There are no significant differences among blocks. Treatments, however, are significantly different from one another (P <0.05, Duncan's Multiple Range Test) as indicated by the lower case yellow letters in the average (Av) bars.

These results indicate that growing season thinning may be more effective than dormant season thinning in reducing understory hardwood density, at least in the short term. If these differences persist, it would suggest that there is an added restoration benefit to growing season compared to dormant season thinning.

The pattern of change in the IES block is noteworthy. In this block only, post-treatment 1–20 cm stem density was actually lower in the control treatment than in either the dormant or growing season thinning treatments. This was a direct consequence of the fact that the prescribed fire in IES-C was far more severe than in any of the other blocks or treatments.

Canopy cover (%) was uniformly highest in control plots compared to thinned treatment plots. However, there was no significant difference between dormant and growing season thinning in this regard.

Species richness (number of taxa per 0.1 ha) for plants, arthropods and plants is displayed in **Figure 8-7.** Total plant species richness (number of species per 0.1 ha) ranged from as low as 7 in FGW-C, a pocosin plot, to as high as 41 in HA-D, a wet-mesic plot. There were significant differences among treatment blocks (F=5.43, DF=7, P <0.005). In general, high pocosin blocks (FGE, FGW, and IES) and one wet mesic block (IEN) had fewer species than other blocks. There was also a highly significant treatment effect (F=14.50, DF=2, P <0.0005); the control

treatments had fewer species than either of the thinning treatments. There was no significant difference between the thinning treatments.

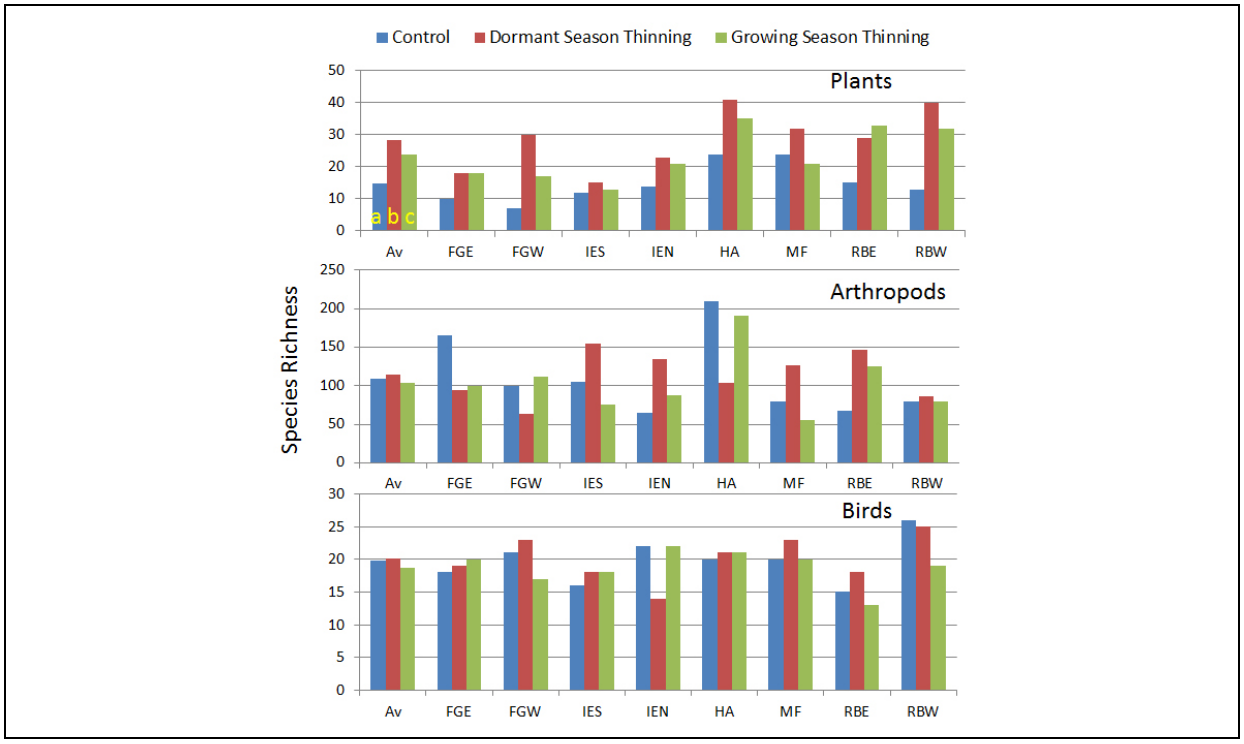

Figure 8-7. Post-treatment species richness of plants (number per 0.1 ha), arthropods (number trapped per site) and birds (number identified per site) by block and treatment.

Blocks are ordered left to right as high pocosin (FGE, FGW, and IES), wet mesic (IEN, HA, and MF) and mesic (RBE and RBW). "Av" represents the average for each treatment across all blocks. There are significant differences in plant species richness among blocks. Furthermore, the control treatment had significantly lower species richness than either of the thinning treatments ($P < 0.05$, Duncan's Multiple Range Test) as indicated by the lower case yellow letters in the average bars. There are no differences among blocks or treatments for either arthropods or birds.

Although they represent only the second growing season following treatment, these results are consistent with our Hypothesis 1 that understory/midstory thinning will increase herbaceous species diversity. This increase in plant species richness in thinned treatment plots is notable because it occurs in the growing season following treatment applications and prescribed burning. It is very likely a consequence of increased light to the understory owing to diminished canopy cover, reduced amounts of litter and diminished competition from understory shrubs. Differences between growing season and dormant season thinning treatments were not evident (Hypothesis 2).

There were no significant differences among either blocks or treatments in species richness of either arthropods or birds. However, within and among block variation was much higher for arthropod than for bird species richness. The Malaise, yellow pan, and pitfall traps sample insect populations in a small area (probably within 5–10 m of the traps) compared to the bird point counts that sample populations over a much larger area (greater than 50 m). This is the most likely explanation for the high sample to sample variance among arthropods compared to birds.

Compositional variation in the community of plants among treatment plots based NMS ordination is displayed in **Figure 8-8**. Also included in this graph are the 11 longleaf pine dominated stands that were simultaneously surveyed for arthropods and birds. There is a clear separation of the loblolly dominated experimental plots with generally low Axis 1 NMS scores from the longleaf dominated plots with generally higher Axis 1 NMS scores. Experimental plots are arrayed as a continuum from high pocosin with low Axis 2 NMS scores to wet mesic with intermediate Axis 2 scores and mesic plots with high Axis 2 scores. Species diversity in the wettest block (IES) remains low and none of the species typical of longleaf pine stands occur here. Thus, such very wet areas may be poor candidates for restoration. These results are contrary to our Hypothesis 3 that thinning and PB will have their greatest impacts on vegetation species richness and composition in wetter sites compared to drier sites.

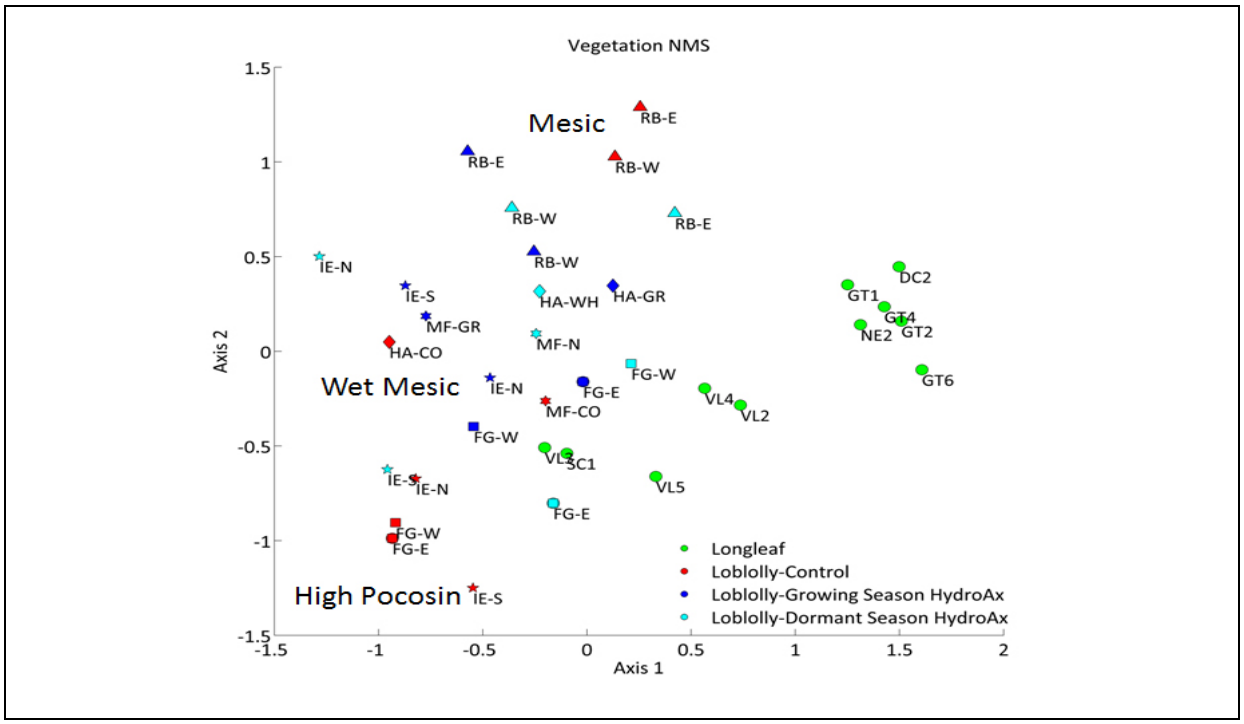

Figure 8-8. NMS ordination of plant species composition in 24 T-1 experimental plots (red, blue and azure symbols) and 11 longleaf pine dominated plots (green symbols).

Each treatment block is represented by a different shape symbol.

For any given block, thinning treatments tend to be located more toward the middle of Axis 2. However, with just a single sample in time, it is not possible to determine if this represents a genuine shift in species composition. Future measurements of these same plots will allow us to plot actual trajectories of change.

Compositional variation in the community of birds among treatment plots based on NMS ordination is displayed in **Figure 8-9**. Although the graph is oriented differently, the general arrangement of plots relative to one another is remarkably similar. In this case, longleaf pine stands have low Axis 1 scores and loblolly dominated stands have high Axis 1 scores. (Note: Unlike principal components analysis, the sequence of NMS axes is random and bears no relationship to the amount of compositional variation for which they account.) As with the plant

community ordination, loblolly dominated stands are arrayed as a continuum from mesic stands with high Axis 2 scores to wet mesic stands with intermediate Axis 2 scores and high pocosin stands with low Axis 2 scores. There are no obvious trends among treatments within blocks.

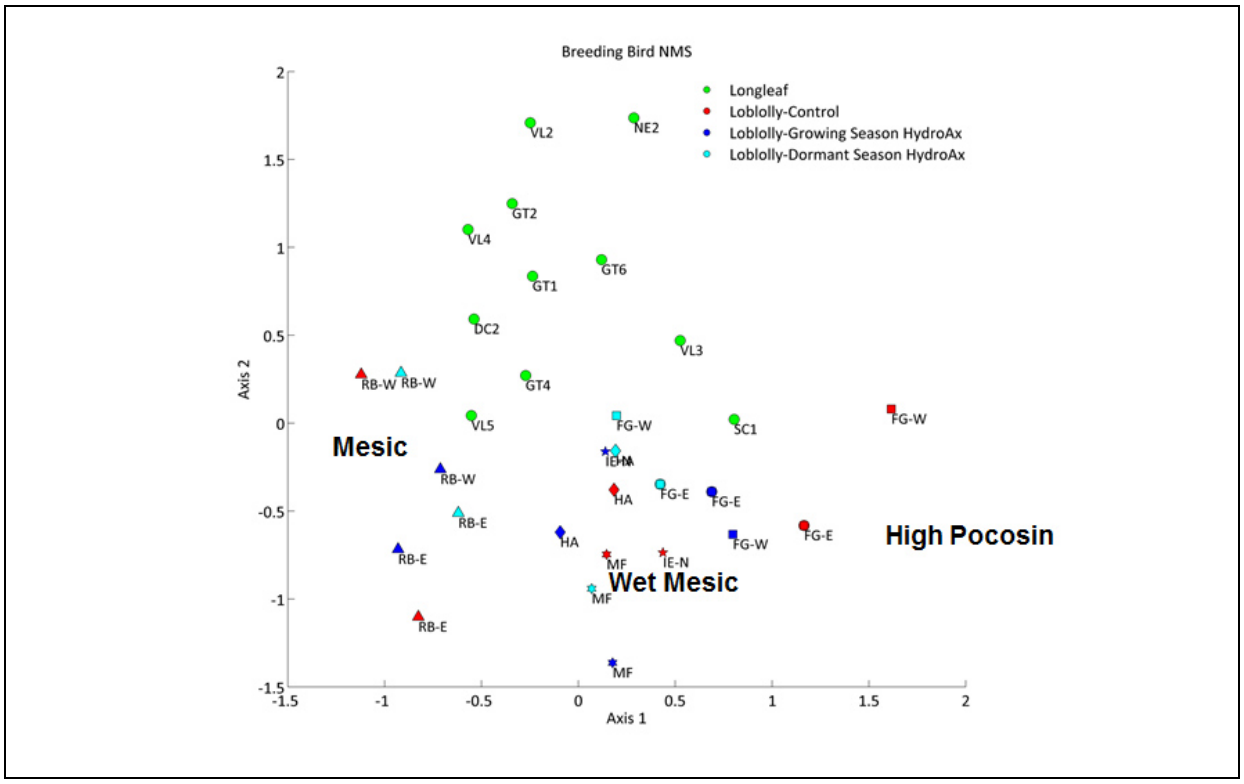

Figure 8-9. NMS ordination of bird species composition in 24 T-1 experimental plots (red, blue, and azure symbols) and 11 longleaf pine dominated plots (green symbols).

Each treatment block is represented by a different shape symbol.

Compositional variation in the community of arthropods among treatment plots based on non-metric multidimensional scaling ordination is displayed in **Figure 8-10**. In this ordination the separation of longleaf and loblolly pine stands is less clear, but longleaf dominated stands generally have lower Axis 2 scores than loblolly dominated stands. Among loblolly pine stands there was no discernible pattern among either blocks or treatments.

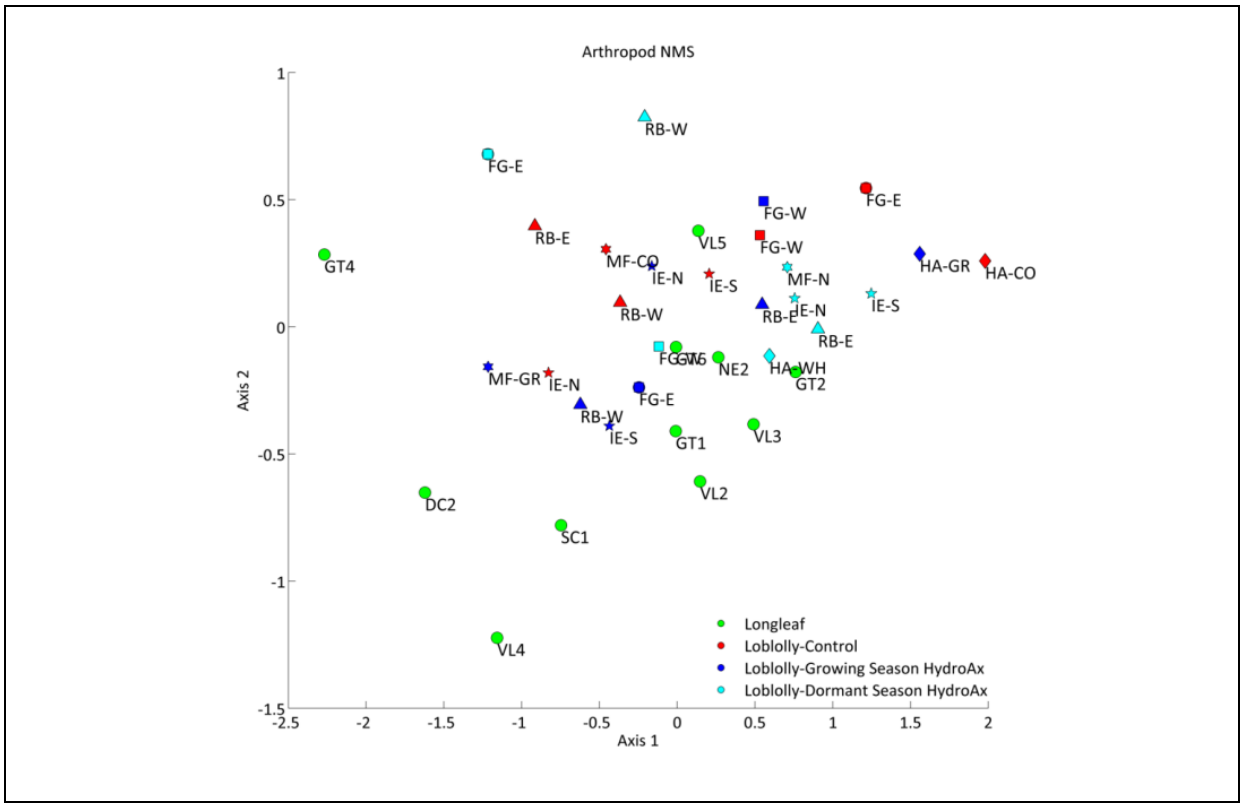

Figure 8-10. NMS ordination of arthropod species composition in 24 T-1 experimental plots (red, blue, and azure symbols) and 11 longleaf pine-dominated plots (green symbols).

Each treatment block is represented by a different shape symbol.

We analyzed the relationships among soil characteristics, plant, arthropod, and bird species composition for the stands above using an SEM (**Figure 8-11**). We excluded plots that lacked arthropod data as well as plots with a hardwood midstory (to separate the effects of midstory structure from the effects of soils, vegetation, and arthropods on breeding birds. The model provided a good fit to the data (X^2=1.99, DF=5, P=0.85); a non-significant P-value indicates that there are no significant deviations between the model and the data. The general rationale for this model is that plant species composition is significantly influenced by the properties of soils, and that both arthropod and avian community composition are influenced by the composition of the plant community. We also hypothesized that avian community composition is influenced by the composition of the arthropod community.

Within SEMs, the strengths of associations between variables are represented as path coefficients, which are standardized regression coefficients (Grace and Bollen, 2005). *Partial* coefficients ($\gamma_{partial}$) represent the change expected if a predictor is varied (in standard deviation units) and are identical to correlation coefficients. Thus, partial coefficients measure the predicted sensitivity of the response variable to one or more predictor variables. *Semi-partial* coefficients ($\gamma_{semipartial}$) are the square root of the unique variance explanation of a predictor variable on a response variable; they are a measure of covariance between the predictor variable and the response variable that is independent of any other variable (Grace and Keeley, 2006). In other words, the semipartial coefficient represents the unique influence of a specific variable that is uncorrelated with any other variable.

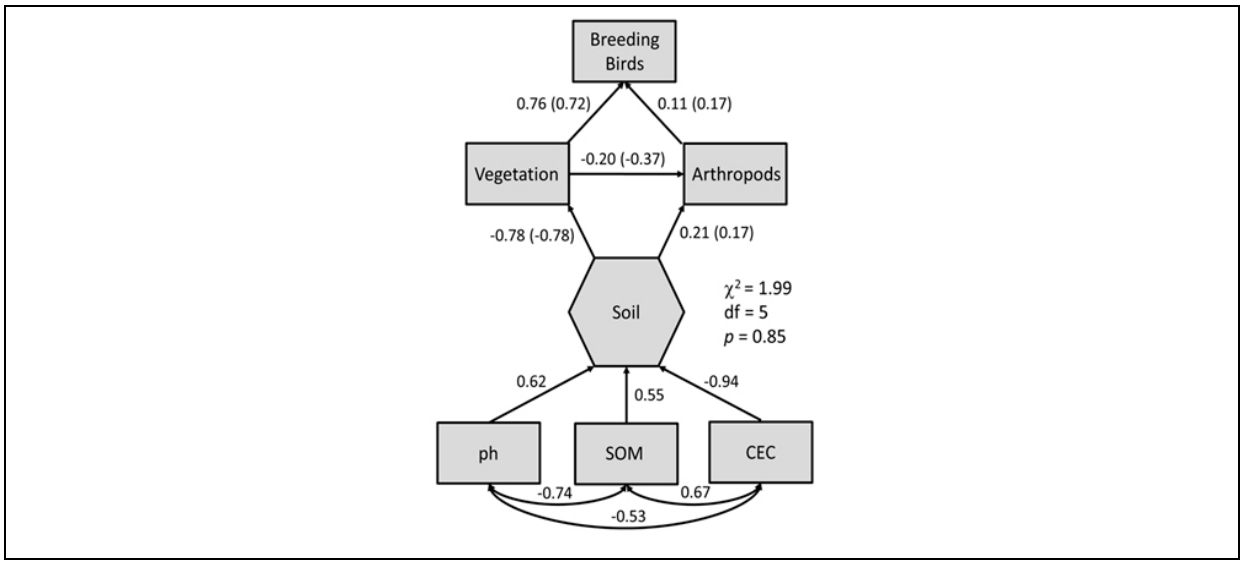

Figure 8-11. SEM for HydroAxed experimental plots and longleaf pine plots.

The direction of the arrow is the assumed direction of influence. Numbers indicate partial path coefficients and numbers in parentheses indicate semipartial path coefficients. Positive coefficients indicate positive correlations and negative coefficients indicate negative correlations between model components.

The path coefficient between the composite soil variable and vegetation composition is quite strong ($\gamma_{partial}$=−0.78). Path coefficients ($\gamma_{partial}$) represent the change expected in a variable such as vegetation composition if the predicting variable, in this case the composite soil variable, varies; it is equivalent to a correlation coefficient. The path coefficient from vegetation to birds is also quite strong ($\gamma_{partial}$=0.76). In SEMs that included arthropod species composition, path coefficients linking arthropods to soils, vegetation to birds were much weaker. For example, the partial path coefficient for arthropods on birds was only 0.11. The partial path coefficient for vegetation to arthropods is somewhat stronger ($\gamma_{partial}$=−0.20). The semipartial path coefficient, a measure of the covariance of the response variable independent of any other variable, is even stronger (−0.37).

The weak correlations between arthropod community richness and composition and other ecosystem components may be a consequence of several factors. Although it is possible that the diversity and composition of the assemblage of arthropods are determined by factors other than those influencing the diversity and composition of plants and birds, other issues associated with the sampling and identification of arthropods are undoubtedly important. Sampling procedures for plants and birds are well established and potential sampling errors are well understood and easily quantified. This is not the case for arthropods. Although we used three rather different trapping methods, it is still likely that we sampled only a portion of the total community of arthropods, and that our sample was biased by those species that are most attracted to these trap types. Furthermore, pan, pitfall, and Malaise traps typically sample the arthropod community from a relatively small area (within 5-10 m) compared to point counts for birds (> 50 m). Unfortunately, it is not possible to quantify sampling error or bias for these animals.

Our results thus far do signify very strong relationship between soil characteristics and vegetation composition and between vegetation composition and avian community composition, and thus support in part our Hypothesis 4. They are indicative of likely causal relationships

among these different model components, and they provide assurance that management strategies focused on particular ecosystem components such as the restoration of plant community composition are likely to have favorable effects on other ecosystem components.

We will summarize research findings and relevant management recommendations from the DCERP1 Research Project T-1 and the DCERP2 Research Project T-3 resampling experiment in a report to MCBCL resource managers.

8.5.4 Milestones

1.	All plots are burned	12/2013–4/2014
2.	Conduct a field campaign for vegetation and arthropods on experimental plots	5/2015–8/2015
3.	Analyze data from the field campaign	9/2015–2/2016
4.	Prepare and submit manuscripts from experimental plots	3/2016–8/2016
5.	Prepare and deliver a report on experimental results to MCBCL staff	3/2016–8/2016
6.	Conduct a 2-day workshop on longleaf pine restoration	11/2016–12/2016
7.	Prepare and deliver a Final Report	9/2016–6/2017

8.5.5 Deliverables

1.	Deliver field campaign data to DCERP MARDIS	2/2015
2.	Deliver draft manuscripts regarding experimental plots	3/2016–8/2016
3.	Deliver presentation slides and handouts for a longleaf pine restoration workshop	10/2016
4.	Deliver a Final Report	Draft 3/2017; final 6/2017

8.5.6 Planned Publications

Submit a journal article on linkages between soil, vegetation, and breeding bird composition. This article is planned for May 2013.

Submit a journal article on the role of natural disturbance on vegetation in coastal plain pine forests. This article is planned for May 2013.

Submit a broad, review article on the impacts of longleaf pine restoration treatments among different taxonomic groups. This article is planned for October 2013.

Submit a journal article on the relationships between vegetation and arthropod community composition. This article is planned for October 2016.

8.6 Literature Cited

Bailey, A.D., R. Mickler, and C. Frost. 2007. Presettlement fire regime and vegetation mapping in Southeastern Coastal Plain forest ecosystems. Pp. 275–286 in *The Fire Environment—Innovations, Management, and Policy Conference Proceedings*, Destin, FL. March 26–30. Edited by B.W. Butler, and W. Cook. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Bollen K.A. 1989. *Structural Equations with Latent Variables*. John Wiley & Sons: New York.

Brockway, D.G., and K.W. Outcalt. 1998. Gap-phase regeneration in longleaf pine wiregrass ecosystems. *Forest Ecology and Management 106*(2–3):125–139.

Brockway, D.G., K.W. Outcalt, B.L. Estes, and R.B. Rummer. 2009. Vegetation response to midstorey mulching and prescribed burning for wildfire hazard reduction and longleaf pine (Pinus palustris Mill.) ecosystem restoration. *Forestry 82*(3):299–314.

Campbell, J.L., M.E. Harmon, and S.R. Mitchell. 2012. Can fuel reduction treatments really increase forest carbon storage in the western U.S. by reducing future fire emissions? *Frontiers in Ecology and the Environment 10*:83–90.

Campbell, J., D.C. Donato, D. Azuma, and B. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, United States. *Journal of Geophysical Research—Biogeosciences 112*:G04014.

Christensen, N.L. 1981. Fire regimes in southeastern ecosystems. Pp. 112–136 in *Fire Regimes and Ecosystem Properties*. Edited by H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners. U.S. Department of Agriculture, Forest Service, General Technical Report WO-26. 594 pages.

Christensen, N.L. 1992. Variable fire regimes on complex landscapes: Ecological consequences, policy implications, and management strategies. Pp. ix–xiii in *Fire in the Environment*. Edited by T. Waldrop, U.S. Department of Agriculture, Forest Service, General Technical Report SE-69.

Christensen, N.L. 2000. Vegetation of the Coastal Plain of the southeastern United States. Pp. 397–448 in Vegetation of North America (2nd Edition). Edited by M. Barbour and W.D. Billings. Cambridge University Press.

Christensen, N.L., R.B. Wilbur, and J.S. McLean. 1988. *Soil-Vegetation Correlations in Pocosins of Croatan National Forest, North Carolina*. U.S. Fish and Wildlife Service, Fort Collins, CO.

Cohen, S., R. Braham, and F. Sanchez. 2004. Seed bank viability in disturbed longleaf pine sites. *Restoration Ecology 12*(4):503–515.

Crowley, A.E. 1996. *This Land, This South: An Environmental History*. University of Kentucky Press: Lexington, KY.

Cunningham, P., et al. 2013. *DCERP1 Final Research Report.* Prepared for SERDP.

Early, L.S. 2004. *Looking for Longleaf*. University of North Carolina Press: Chapel Hill, NC.

Gienapp, P., C. Teplitsky, J.S. Alho, J.A. Mills and J. Merila. 2008. Climate change and evolution: Disentangling environmental and genetic responses. *Molecular Ecology 17*:167–178.

Grace, J.B., T.M. Anderson, H. Olff, and S.M. Scheiner. 2010. On the specification of structural equation models for ecological systems. *Ecological Monographs 80*:67–87.

Grace, J., and K. Bollen. 2008. Representing general theoretical concepts in structural equation models: The role of composite variables. *Environmental and Ecological Statistics 15*:191–213.

Grace, J.B. 2006. *Structural Equation Modeling and Natural Systems*. Cambridge University Press: Cambridge, UK.

Grace, J.B., and J.E. Keeley. 2006. A structural equation model analysis of postfire plant diversity in California shrublands. *Ecological Applications 16*:503–514.

Grace, J.B., and K.A. Bollen. 2005. Interpreting the results from multiple regression and structural equation models. *Bulletin of the Ecological Society of America 86*:283–295.

Gustafson, E.J., S.R. Shifley, D.J. Mladenoff, K.K. Nimerfro, and H.S. He. 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. *Canadian Journal of Forest Research 30*:32–43.

Harmon, M.E., and J. Sexton. 1996. *Guidelines for Measurements of Woody Detritus in Forest Ecosystems*. U.S. LTER Publication Number 20. U.S. LTER Network Office, University of Washington, College of Forest Resources, Seattle, WA. 73 pages.

He, H.S., and D.J. Mladenoff. 1999. Spatially explicit and stochastic simulation of forest-landscape fire disturbance and succession. *Ecology 80*(1):81–99.

Holt, R.D. 1990. The microevolutionary consequences of climate change. *Trends in Ecology and Evolution 5*:311–315.

Kirk, W.D.J. 1984. Ecologically seIective coIoured traps. *Ecological Entomology 9*:35–41.

Knapp, B.O., G.G. Wang, H. Hu, J.L. Walker, and C. Tennant. 2011. Restoring longleaf pine (Pinus palustris Mill.) in loblolly pine (Pinus taeda L.) stands: Effects of restoration

treatments on natural loblolly pine regeneration. *Forest Ecology and Management 262*(7):1157–1167.

Kruskal, J.B., and M. Wish. 1978. *Multidimensional Scaling*. Sage Publications: Beverly Hills, CA.

Malaise, R. 1937. A new insect-trap. *Entomologisk Tidskfirt 58*:257–271.

McCune, B., and J.B. Grace. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, OR.

McCune, B., J.B. Grace, and D.L. Urban. 2002. *Analysis of Ecological Communities*. MjM Software Design, Gleneden Beach, OR.Mitchell, S.R., M.E. Harmon, and K.E.B. O'Connell. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. *Ecological Applications 19*(3):643–655.

McLean, E.O. 1982. Soil pH and lime requirement. Pp. 199–223 in *Methods of Soil Analysis, Part 2.* Agronomy Monograph 9, Second edition. Edited by A.L. Page, R.H. Miller, and D.R. Keeney. ASA and SSSA: Madison, WI.

Mehlich, A. 1984. Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. *Communications in Soil Science and Plant Analysis 15*:1409–1416.

Mladenoff, D.J. 2004. LANDIS and forest landscape models. *Ecological Modelling 180*(1):7–19.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. *Nature 463*:747–756.

Nowacki, G.J., and M.D. Abrams. 2008. The demise of fire and the "mesophication" of forests in the eastern United States. *Bioscience 58*:124–138.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J.I. Kinyamario. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles 7*(4):785–809.

Peet, R.K., T.R. Wentworth, and P.S. White. 1998. A flexible, multipurpose method for recording vegetation composition and structure. *Castanea 63*(3):262–274.

Peet, R.K., T.R. Wentworth, and P.S. White. 1998. A flexible, multipurpose method for recording vegetation composition and structure. *Castanea 63*(3):262–274.

Provencher, L., B.J. Herring, D.R. Gordon, H.L. Rodgers, G.W. Tanner, J.L. Hardesty, L.A. Brennan, and A.R. Litt. 2001a. Longleaf pine and oak responses to hardwood reduction techniques in fire-suppressed sandhills in northwest Florida. *Forest Ecology and Management 148*:63–77.

Provencher, L., B.J. Herring, D.R. Gordon, H.L. Rodgers, K.E.M. Galley, G.W. Tanner, J.L. Hardesty, and L.A. Brennan. 2001b. Effects of hardwood reduction techniques on longleaf pine sandhill vegetation in northwest Florida. *Restoration Ecology 9*:13–27.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal 51*:1173–1179.

Ross, D. 1995. Recommended soil tests for determining exchange capacity. Pp. 62–69 in *Recommended Soil Testing Procedures for the Northeastern United States*. Northeastern Regional Bulletin #493. Edited by J.T. Sims, and A. Wolf. Agriculture Experiment Station: University of Delaware, Newark, DE.

Scheller, R.M., and D.J. Mladenoff. 2004. A forest growth and biomass module for a landscape simulation model, LANDIS: design, validation, and application. *Ecological Modelling 180*(1):211–229.

Scheller, R.M., D. Hua, P.V. Bolstad, R.A. Birdsey, and D.J. Mladenoff. 2011. The effects of forest harvest intensity in combination with wind disturbance on carbon dynamics in Lake States Mesic Forests. *Ecological Modelling 222*(1):144–153.

Scheller, R.M., S. Van Tuyl, K. Clark, N.G. Hayden, J. Hom, and D.J. Mladenoff. 2008. Simulation of forest change in the New Jersey pine barrens under current and pre-colonial conditions. *Forest Ecology and Management 255*:1489–1500.

Schiegg, K., G. Pasinelli, J.R. Walters, and S.J. Daniels. 2002. Inbreeding and experience affect response to climate change by endangered woodpeckers. In *Proceedings of the Royal Society of London (B)* 269:1153–1159.

Shipley, B. 2000. *Cause and Correlation in Biology: A User's Guide to Path Analysis, Structural Equations, and Causal Inference*. Cambridge University Press: Cambridge, UK.

Smart, L.S., J.J. Swenson, N.L. Christensen, and J.O. Sexton. 2012. Three-dimensional characterization of pine forest type and red-cockaded woodpecker habitat by small-footprint, discrete-return LiDAR. *Forest Ecology and Management 281*:100–110.

Sturtevant, B.R., R.M. Scheller, B.R. Miranda, D. Shinneman, and A. Syphard. 2009. Simulating dynamic and mixed-severity fire regimes: A process-based fire extension for LANDIS-II. *Ecological Modelling 220*:3380–3393.

USFWS (U.S. Fish and Wildlife Service). 2003. *Red-cockaded Woodpecker (Picoides borealis) Recovery Plan: Second Revision*. U.S. Fish and Wildlife Service, Atlanta, GA.

Varner, J.M., D.R. Gordon, E. Putz, and J.K. Hiers. 2005. Restoring fire to long-unburned Pinus palustris ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology 13*(3):536–544.

Venables, W.N. 2011. *An Introduction to R: Version 2.13.2*. Available at http://cran.r-project.org/doc/manuals/R-intro.pdf. Accessed June 13, 2012.

Walker, J., and R.K. Peet, 1983**.** Composition and species diversity of pine-wire grass savannas of the Green Swamp, North Carolina. *Vegetatio 55*:163–179.

Walters, J.R. 1991. Application of ecological principles to the management of endangered species: The case of the red-cockaded woodpecker. *Annual Review of Ecology and Systematics 22*:505-523.

Walther, G.-R. E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J-M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature 416*:389–395.

Whelan, A., R.J., Mitchell, C. Staudhammer, and G. Starr. 2013. Cyclic occurrence of fire and its role in carbon dynamics along and edaphic moisture gradient in longleaf pine ecosystems. *PloS ONE 8*(1):e54045.

Zhao, S., S. Liu, Z. Li, and T. L. Sohl. 2010. Federal Land Management, Carbon Sequestration, and Climate Change in the Southeastern U.S.: A Case Study with Fort Benning. Environmental Science & Technology 44:992-997.

9.0 Climate Change

9.1 Introduction

Climate change is a potential long-term challenge that could impact DoD's management of terrestrial, coastal, and aquatic/estuarine resources. There are also fundamental challenges in identifying the specific climate factors that drive ecosystem processes and in projecting changes to these climate factors into the future at ecosystem process scales. Research Project CC-1 attempts to address both of these challenges (**Table 9-1**).

Table 9-1. Climate Change Module research project, senior researcher, outcomes and benefits to MCBCL, and duration of the project

Project	Research Project Title	Senior Researcher and Duration
CC-1	*Development of Uniform Historical and Projected Climate to Support Integrated Coastal Ecosystem Research*	**Senior Researcher:** Ryan Boyles
	Outcomes and benefits: 1. Identify relevant climate variables and thresholds relative to key ecosystem process models 2. Gain an objective understanding of the historical variability of climate over the MCBCL study region 3. Develop methods to produce integrated climate history and future scenarios for the study region at relevant ecosystem process scales 4. Document the climatological data and spatial and temporal scales used in all DCERP process models	**Duration:** 3/2013–10/2017

9.2 Research Project CC-1: Development of Uniform Historical and Projected Climate to Support Integrated Coastal Ecosystem Research

Lead Investigators: Drs. Ryan Boyles (NCSU)

Supporting Researcher: Adrienne Wootten (NCSU)

Technical Objectives/Goals: The main goal of Research Project CC-1 will be to develop uniform and consistent historical and projected climate inputs to support the RTI DCERP2 Team's research and ecosystem modeling efforts. Specific objectives of this research project include the following:

1. Integrate climate change data and science into the RTI DCERP2 Team's research process through extensive engagement with team researchers and installation managers
2. Identify and document critical climate variables (at the appropriate temporal and spatial scales for the ecosystem module modeling efforts) and thresholds for the ecosystems being studied
3. Develop uniform historical climate data and future climate scenarios for consistent use across the entire RTI DCERP2 Team at ecosystem process scales sufficient to adequately test and evaluate ecosystem process models. This climate data will be based on input from RTI DCERP2 Team researchers and will be derived from results of ongoing research efforts by other SERDP–funded climate change studies (i.e., Research Projects RC-1702 and RC-2206). In consultation with SERDP, other appropriate climate information may be used.

Research Questions:

1. Which methods are appropriate to scale available data sets to the extent and resolution needed by DCERP research modules?
2. Which methods are appropriate to produce consistent representation of future climate between independently produced data sets (e.g., downscaled air temperature, precipitation, winds, sea-surface temperature, storminess, sea level) at the range temporal and spatial scales needed?

9.2.1 Background

Extreme events across the southeastern United States have the potential to change dramatically with climate change over the next century. Research indicates an increase in the frequency of extreme hot events, with a decrease in the frequency of extreme cold events and less severe cold events (Christensen et al., 2007; DeGaetano and Allen, 2002; Diffenbaugh et al., 2005). In addition, extreme precipitation events are predicted to increase in frequency and magnitude (Diffenbaugh et al., 2005; Kunkel et al., 2003). Increased rainfall amounts and decreased frequency of rainfall events indicate an increase in drought frequency, with more flooding possible when rainfall events occur. However, the current generation of available down-scaled climate guidance is not of sufficient spatial and temporal resolution to be useful for localized ecosystem process modeling such as those being developed for MCBCL as part of DCERP2. For example, a project of the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009) provides climate change guidance at 50-km horizontal spacing. Other guidance provides higher spatial resolutions (e.g., 10-km projections by Stefanova et al. [2012], 14-km projections by Maurer et al. [2007], 15-km projections by Hostetler et al. [2011]), but those projections only provide guidance for temperature and precipitation. These climate projection data sets use downscaling methods to relate changes in broader climate patterns produced by global climate models to more local spatial scales. However, there is no community standard method for downscaling, and none have been evaluated yet for application to ecosystem process models and decisions. In addition, historical climate data have not yet been fully leveraged to identify critical thresholds at which ecological impacts become significant or irreversible. Thresholds and climate factors that drive terrestrial and estuarine ecosystems must first be identified to assess the ability of current (and future) climate projection products and scenarios to give meaningful guidance for natural resource management.

9.2.2 Methods

During the first 2 years of Research Project CC-1, RTI DCERP2 Team researchers will identify the known climate sensitivities for their ecosystem of focus. The engagement process will include face-to-face meetings, when possible, and virtual meetings or conference calls when it is impossible to meet in person. These meetings will be used to determine the critical thresholds and climate variables that impact ecosystem processes at temporal and spatial scales relevant to the ecosystem process models included in each of the modules. Critical thresholds may include combined variables such as the number of consecutive days when maximum temperatures were greater than 93°F and when less than 0.10 inches of precipitation was observed. This example of combined variables may be associated with substantial increases in watershed eutrophication. These multidisciplinary discussions will serve to document the specific climate factors and

thresholds that drive change in the ecosystem and to integrate disciplinary scientists under the DCERP2 focus on climate change.

Using this input from ecosystem researchers, Year 2 of DCERP2 will focus on developing a set of historical climate variables at the needed ecosystem process scales for the targeted geography of MCBCL. Research Project CC-1 researchers will begin this process by compiling the critical variables for the RTI DCERP2 Team to review, and then breaking them down into general and ecosystem-specific thresholds and variables. General variables and thresholds are those that are critical regardless of species, habitat, or ecosystem in the domain of MCBCL. That is, these are critical to all ecosystem modeling efforts in DCERP2. Ecosystem-specific variables and thresholds are those that affect a specific species, habitat, or ecosystem and/or are critical to the ecosystem modeling efforts of another DCERP2 module. For example, some process models such as the LANDIS model (Research Project T-3) and the RCW DSS Tool (Research Project T-4) will need monthly climate data (e.g., monthly average temperature and rainfall data), whereas other models such as the ESM (Research Project TSP-2) are driven by daily temperature and rainfall data. By March 2015, both the critical climate variables and thresholds will be documented and made available to the RTI DCERP2 team members to review. For DCERP2, these critical values need to be derived from the same available historic climate data, but be processed at the temporal and spatial scales required by the respective process models. Research Project CC-1 researchers will use available data, including modeled estimates of historical climate (i.e., re-analysis), in situ observations of climate from MCBCL, and remotely sensed data to develop statistically based historical climatologies of relevant climatic variables and thresholds. The statistical techniques used to develop these climatologies will be based on available literature and guidance from NOAA, USGS, and DoD research efforts. Although we will attempt to use the same techniques among variables, we will consider different approaches for other variables if the scientific literature or alternate research efforts suggest that using alternate techniques will produce more meaningful results. In either case, we will evaluate the resulting climatologies for consistency prior to releasing them to the RTI DCERP2 Team.

Similarly, the CC-1 researchers will use the available guidance from NOAA, USGS, and DoD research efforts, as well as other SERDP–funded projects that anticipate results by 2015 to develop future scenarios of these critical climate variables and thresholds. The historical climatology developed will be perturbed based on scenario guidance from these other federal research efforts to produce consistent future scenarios of climate for input into other DCERP2 Team research efforts and their ecosystem process models. The techniques considered for producing these future scenarios will primarily be statistical techniques, given the time constraints of Research Project CC-1 and the potential number of variables that may be required for DCERP2 research projects. We will also use available literature and guidance from other research efforts when selecting the statistical downscaling techniques to be used. However, to simplify the process, we will statistically downscale only the most basic, required variables from the other data sets and will derive other required variables from these results. For example, if one DCERP2 ecosystem modeling effort requires daily temperature scenarios and other modules require monthly average temperatures, then we will statistically downscale the daily temperature and precipitation scenarios and will derive the monthly values from the daily temperature scenarios. We will store the resulting scenarios produced at a 4-km or finer resolution in MARDIS, provide a uniform and coordinated set of climate inputs for all research modules, and ensure that the results from scenario testing are comparable across all ecosystems.

For both the historical data and the future scenarios, there are several data sets that could be used to provide initial guidance for scaling historical data and future scenarios. There are also limitations to these data sets. For example, the historical climatologies used for the National Climate Assessment (NCA) cover the extent of the MCBCL domain, but do not have sufficient spatial or temporal resolution for the applications of the other DCERP2 research modules. In addition, some NCA climate products were created using 30 years of the observational record. This 30-year period does not capture the full extent of possible extreme events, which could be used by a statistical downscaling technique. Therefore, the production of scaled historical data will rely on other data sets, such as from PRISM (available from Oregon State University) and the U.S. Department of Agriculture, which has more than 30 years of data available. There are also several publicly available data sets (including NARCCAP) that have been created from the general circulation model data from Phase 3 of the Coupled Model Intercomparison Project (CMIP3). Given the timeline of this project, it is anticipated that the general circulation model data from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) and other down-scaled guidance created from CMIP5 will be available for use in DCERP2 by the time our data set production begins in 2015. Our initial focus will be on the use of NARCCAP products for initial conditions, which use A2 emissions scenario. If evaluation of CMIP5-based downscaled products suggests more valuable initial guidance for MCBCL, then we would focus on further scaling focused on the RCP8.5 scenario. Given the uncertainties in both NARCCAP and CMIP5 abilities over this geographical region, we will also evaluate possible methods to re-sample historically observed climate data and project these into the future as analogs. Use of historical analogs will likely not be reasonable for the late twenty-first century projections given the limited assumptions of climate stationarity, but we plan to consider how far into the future such analogs might be useful. However, the statistical techniques used will be based on available literature for scaling the metrics needed by the other RTI DCERP2 researchers.

Historical storm frequency will use guidance from Research Project RC-1702. Any future scenarios of storminess will be based on guidance from SERDP and the DCERP2 TAC, but Research Project CC-1 will serve as the DCERP2 focal point for this data and to ensure integration with all DCERP2 projects. Similarly, any sea level rise scenarios provided by SERDP will be coordinated through Research Project CC-1 for the DCERP2 team, but CC-1 will not develop any sea level rise scenarios.

The Research Project CC-1 Module Team will submit a modified Research Plan to SERDP in fall 2014. This modified plan will incorporate the guidance developed through the engagement process and provide detailed plans for generating the historical and future projections of climate for use by other RTI DCERP2 researchers.

9.2.3 Milestones

1.	Document critical climate variables and ecological process thresholds	3/2014
2.	Submit the revised Research Plan	9/2014
3.	Produce scaled historical climate data for relevant climate variables and thresholds	12/2015
4.	Produce scaled future climate scenarios for relevant climate variables and thresholds	12/2016

5. Prepare and deliver a final report on methods and data evaluations 10/2017

9.2.4 Deliverables

1. Upload scaled historical climate data to MARDIS 12/2015
2. Upload future climate scenarios to MARDIS 12/2016
3. Deliver Final Report on methods and data evaluation Draft 2016; final 9/2017

9.2.5 Planned Publications

Submit an article on the development and evaluation of techniques to produce consistent scaled future climate scenarios between independent data sets. The submission date is planned for December 2017.

Submit an article on the methods to scale future climate scenarios from CMIP5 data sets to the NRE. The submission date is planned for December 2017

Submit an article on the statistical relationships between near-shore sea surface temperatures and air temperatures in coastal North Carolina. The submission date is planned for December 2017.

9.3 Literature Cited

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton. 2007: Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press: Cambridge, United Kingdom, and New York, NY.

DeGaetano, A.T., and R.J. Allen. 2002. Trends in twentieth-century temperature extremes across the United States. *Journal of Climate 15*(22):3188–3205.

Diffenbaugh, N.S., J.S. Pal, R.J. Trapp, and F. Giorgi. 2005. Fine-scale processes regulate the response of extreme events to global climate change. In *Proceedings of the National Academy of Sciences USA 102*:15774–15778.

Hostetler, S.W., J.R. Alder, and A.M. Allan. 2011. *Dynamically Downscaled Climate Simulations over North America: Methods, Evaluation, and Supporting Documentation for Users*. U.S. Geological Survey Open-File Report 2011–1238. 64 pages. Available at http://pubs.usgs.gov/of/2011/1238.

Kunkel, K.E., D.R. Easterling, K. Redmond, and K. Hubbard. 2003. Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical Research Letters 30*:1900.

Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy. 2007. Fine-resolution climate projections enhance regional climate change impact studies. *EOS, Transactions, American Geophysical Union 88*(47):504.

Mearns, L.O., W.J. Gutowski, R. Jones, L.-Y. Leung, S. McGinnis, A.M.B. Nunes, and Y. Qian. 2009. A regional climate change assessment program for North America. *EOS, Transactions, American Geophysical Union 90*(36):311–312.

Stefanova, L., V. Misra, S.C. Chan, M. Griffin, J.J. O'Brien, and T.J. Smith III. 2012. A proxy for high-resolution regional reanalysis for the Southeast United States: Assessment of precipitation variability in dynamically downscaled reanalyses. *Climate Dynamics 38*(11–12):2449–2466.

10.0 Translating Science into Practice

10.1 Introduction

As discussed in Section 3.3.3, the third thematic area to be addressed by DCERP2 involves translating the scientific findings of DCERP's integrated research, modeling, and adaptive management activities into practice for installation managers, federal, state, regional, and local natural resources managers, and other interested stakeholders. The goal of the TSP Module is to ensure that the scientific knowledge generated in each of the DCERP2 ecosystem modules is translated into practical models and tools that are easy to understand and easily accessible so they can be broadly applied in making informed management decisions. This is perhaps the most challenging of the three thematic areas because it affects each of the other thematic areas and will be a major focus of all research projects.

The TSP Module contains two research projects with different objectives that are designed to assist in the overall integration and goals of this module. First, Research Project TSP-1 focuses on expanding on the tools and functionality of the Web-based prototype SDSS framework developed as part of DCERP1 and fully implementing and integrating it with the DCERP DIMS (**Figure 10-1;** see Section 11.0 for more information on DIMS). The SDSS framework will provide a one-stop-shop portal to the various tools and models developed by DCERP researchers and will allow accessibility to these products by MCBCL and other DoD installation staff. Research Project TSP-1 also provides an overarching support function for the entire program in making data, decision-support tools, and models available to a variety of user groups.

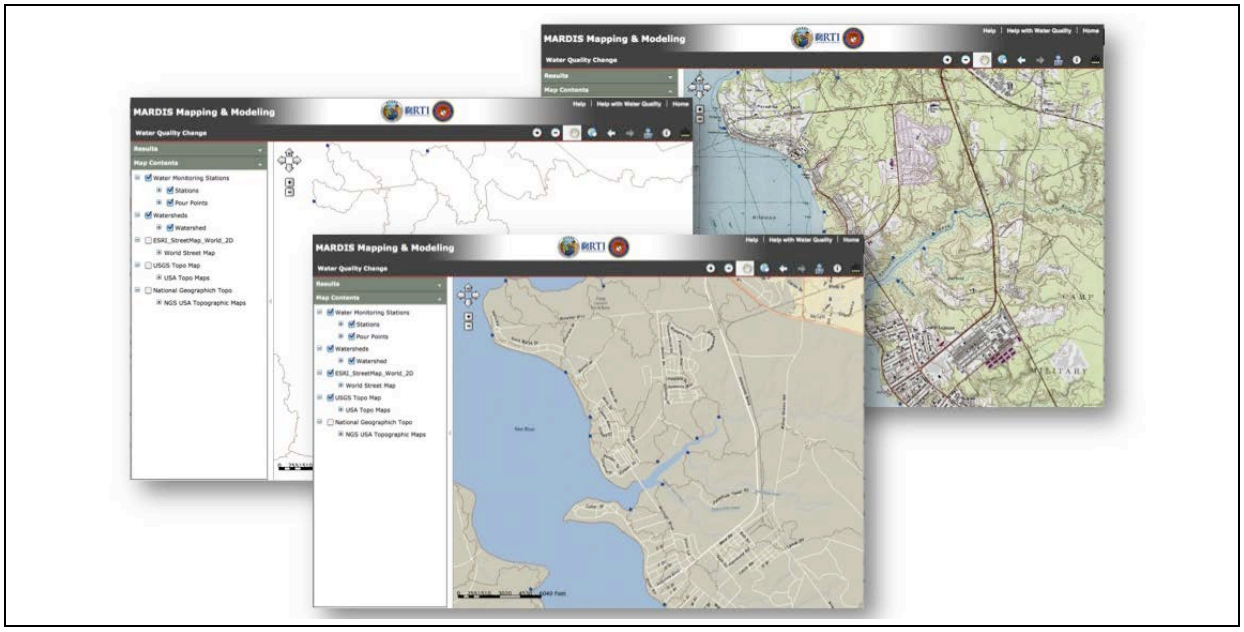

Figure 10-1. Prototype mapping and modeling system providing access to GIS and MARDIS data layers.

In contrast, Research Project TSP-2 focuses on refinement of the ESM developed during DCERP1 and creating a decision-support tool that can be accessed through the SDSS framework to address management issues associated with carbon flux and storage, nutrient cycling, and

water quality impairment based on current and future changed climate conditions. The ESM will play a pivotal role in integrating research and monitoring data from Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5 and interpreting current adaptive management strategies for carbon, nutrients, and sediments. In addition, we will use this model in scenario testing to assess the impacts on estuarine and coastal ecosystems under future climate conditions.

Table 10-1. TSP Module research projects, senior researchers, outcomes and benefits to MCBCL, and duration of the projects

Project	Research Project Title	Senior Researchers and Duration
TSP-1	*Development of a Common Spatial Decision-Support System (SDSS) Framework*	**Senior Researcher:** Dr. Patrick Halpin
	Outcomes and benefits: Implementation of a common SDSS Framework that provides a centralized location for accessing DCERP data, models and tools; improved access to DCERP and MCBCL data collections; a common Internet mapping framework; tools for viewing data synthesized over space and time; improved usability and understanding of the data; integration of certain models directly with DIMS and the DCERP data; and model outcomes in formats directly accessible by MCBCL and other DoD installation staff. Development of online tools, which make the GIS data, models, and research and monitoring results of the DCERP modules Web-accessible, include the following: (1) climate-change scenarios interface: access to down-scaled local data provided by Research Project CC-1; (2) landscape change image analysis and terrestrial carbon accounting; (3) spatial interface for querying MARDIS data and (4) enhanced access, visualization, and reporting features, allowing for overlay and side-by-side comparison of the results of multiple modules.	**Duration:** 3/2013–10/2017
TSP-2	*Coupled Ecosystem Modeling of the NRE for Research, Synthesis, and Management*	**Senior Researcher:** Dr. Mark Brush
	Outcomes and benefits: Research Project TSP-2 will result in a unique and expanded ESM focused on coupled climate and land-use scenario analyses. Results will provide an improved understanding of the impact of climate change, inter-annual hydrologic variability, episodic events, and MCBCL development on coastal carbon cycling, estuarine water quality and ecosystem services (e.g., carbon sequestration), and the potential tradeoffs between management for carbon versus nutrients. These results will be widely applicable to temperate estuaries well beyond the NRE. The model will produce specific recommendations for MCBCL managers to enhance NRE carbon storage in a changing climate, while maintaining water quality and estuarine ecosystem services. The project will produce an online decision-support tool for use by MCBCL, with the potential for implementation at other DoD installations. Application of the ESM at MCAS Cherry Point and Eglin AFB will demonstrate the broad applicability of the ESM.	**Duration:** 3/2013–10/2017

10.2 Research Project TSP-1: Development of a Common Spatial Decision-Support System (SDSS) Framework

Lead Investigator: Dr. Patrick N. Halpin (Duke University)

Supporting Researchers: Danette Boezio (RTI) and two Research Technicians

Technical Objectives/Goals: The goals of Research Project TSP-1 are to provide one-stop access to DCERP data, maps, models, and tools to facilitate use in planning and management decisions and to provide common mapping and data access functionality across the DCERP Team. The SDSS framework will provide a Web-based repository to document the scope of DCERP research and will provide accessibility to research models and tools by MCBCL and other DoD installations. To provide accessibility to models and tools, the framework will host or provide direct links to models developed by other DCERP Team researchers. We will directly integrate the LANDIS II model (Research Project T-3) and the RCW Decision-Support Tool (Research Project T-4) into the mapping environment. We will integrate other models, such as the ESM (Research Project TSP-2), into the framework as much as the underlying software allows, with spatially aware referrals to external hosting, if necessary. We will also directly integrate the ongoing greenness/vegetative change model as a test bed for the broader aggregation of research projects.

10.2.1 Background

MCBCL has undergone and is completing expansion in housing, infrastructure, and military training facilities that will continue into the immediate future. In addition to changes on MCBCL, land use and demographics of the surrounding Onslow County region also are changing. Decisions facing MCBCL and the surrounding region are also potentially influenced by global trends of climate change and sea level rise. Aspects of climate change (direct climate effects and sea level rise impacts) and emerging needs to manage changing ecosystem services and carbon sequestration will bring new demands on installation natural resource management. Management of existing landscape features and future development may bring direct environmental impacts and cumulative changes that may limit future capacity of the installation to support its military training mission.

The full value of data and analysis from DCERP research is revealed when it directly informs decisions made by installation planners. Practical application of DCERP information involves bridging the gap between expert reporting, in which researchers have comprehensive knowledge of a domain, and installation planners, who may interface with the data only infrequently. Making research results relevant to non-experts will require synthesizing and, in some cases, simplifying results. Summarizing data and giving it context is vital to incorporating research results into installation operations.

10.2.2 Methods

The common SDSS framework is intended to support multiple levels of end-user objectives. There are three primary levels of system development:

1. Interactive access
2. Environmental assessment and planning
3. Spatial decision-support and planning tools.

10.2.2.1 Interactive Access

The SDSS framework will provide interactive access to DCERP and MCBCL data in MARDIS using an intuitive geographic query system to improve the ease of user access and mapping capabilities to MARDIS, MCBCL, and other relevant external data sources. We developed an initial SDSS framework, an Internet mapping system, and a prototype water quality decision tool (**Figure 10-2**) as a supplemental research project in the DCERP1 effort. Under DCERP2, we will expand the Internet mapping tools using the ArcGIS Server Internet mapping environment and production-quality development of customized mapping and data query tools. We will implement these Internet mapping tools and will closely integrate them within MARDIS. We will create geospatial map services to make the DCERP and MCBCL spatial data in MARDIS available to the expanded Internet mapping tools. This will give users the ability to overlay and query DCERP and MCBCL data layers together in an interactive and intuitive manner **(Figure 10-2**). Links to regional and national information systems using Web services will also be exposed at this level of the SDSS.

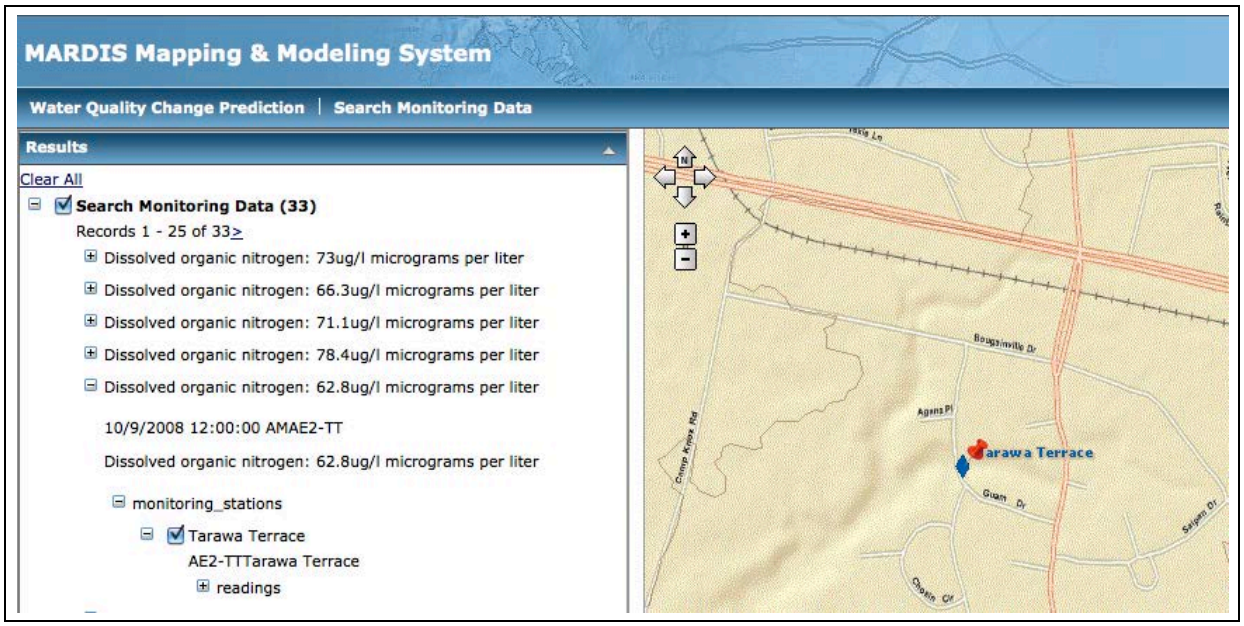

Figure 10-2. Prototype query tool for MARDIS monitoring data.

10.2.2.2 Environmental Assessment and Planning

We will develop an enhanced query interface and data summary and analysis tools to provide access to DCERP data and to link DCERP data products into MCBCL monitoring, planning, and assessment processes. According to MCBCL staff, assessment and planning requirements comprise a significant portion of the workload for end users at MCBCL. Building a direct connection between DCERP data acquisition and analysis tools with environmental assessment and planning needs of MCBCL is a direct way to increase the use and relevance of DCERP investments.

In some cases, there may be the need to provide simplified models, subsets of the complete research, or summarized data within the SDSS. The system strength will be in presenting

multiple tools, so that they can be compared and overlaid in a uniform way. The Framework Development Team will work with the remainder of the DCERP Team to determine the best way to adapt research results to the common framework, balancing intuitive tool design with completeness. Depending upon the complexity of a module's products, presence in the framework could be as minimal as a link that would redirect end users to an external Web site or as rich as complete presentation of the projects data and methods in the SDSS.

10.2.2.3 Spatial Decision-Support and Planning Tools

The primary goal of Research Project TSP-1 is to provide spatial decision-support and planning tools within a common, centralized SDSS framework. Some of the common SDSS tools required to meet the goals of the DCERP2 will be best implemented by the SDSS Framework Team directly, such as the water quality model and the greenness change analysis. Other specific models and tools will be best developed by individual research teams, such as the RCW decision-support tool (Research Project T-4), LANDIS II model (Research Project T-3), and the ESM (Research Project TSP-1). As part of the SDSS framework, all models and tools will be accessed through a single Web portal within the DCERP DIMS to provide a common interface for end users (**Figure 10-3**). The framework Web portal provides an intuitive interface for planning and a discovery method to guide users to other projects.

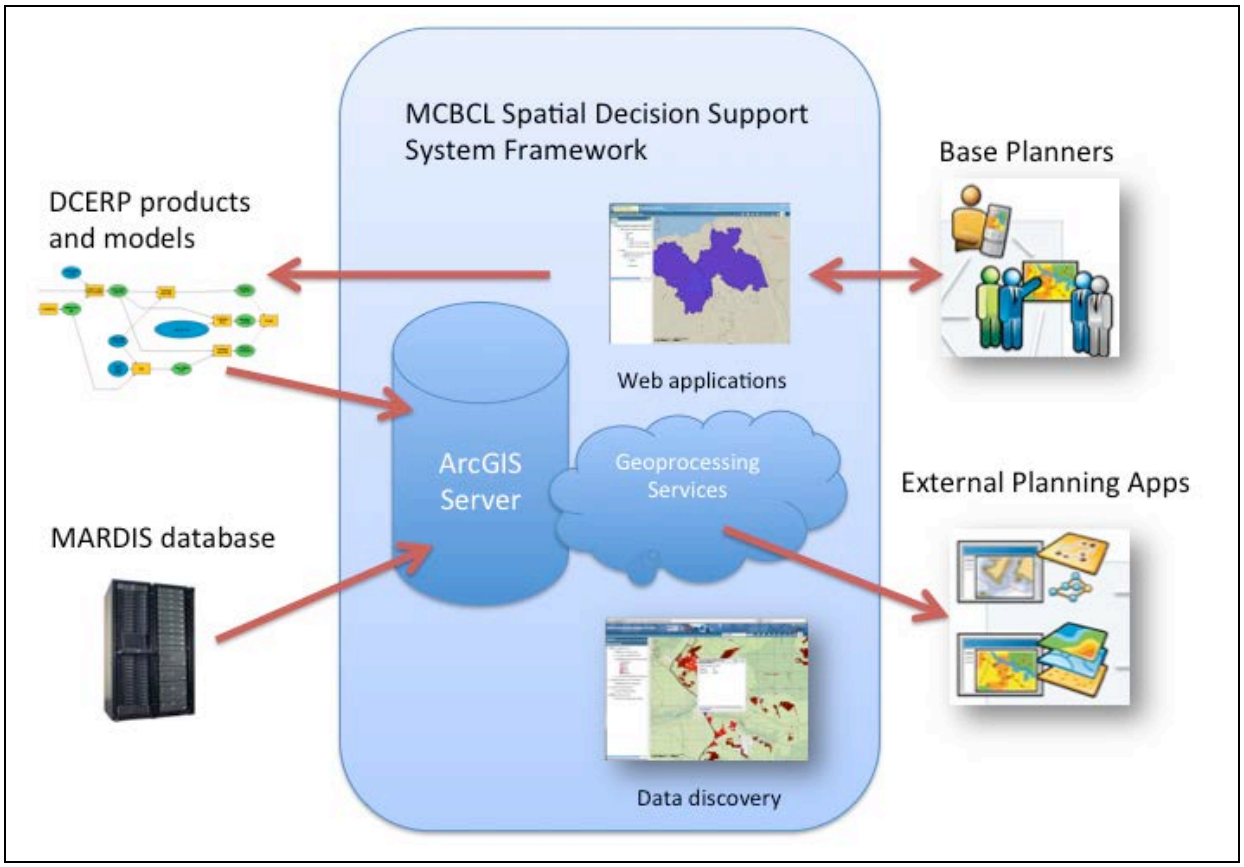

Figure 10-3. Relationship between the SDSS framework, other DCERP modules, MCBCL end users and external uses.

Water Quality Model

DCERP1 provided an opportunity for developing and testing a prototype SDSS. During the prototype exploration, a water-quality model that passed data through multiple scientific software packages (ArcGIS and the R statistical package) was adapted into an online geoprocessing service. This online service accepts input polygons that fall within the MCBCL boundaries, representing areas of proposed construction. Soil, water quality and watershed data relevant to the selected area is automatically put through a modeling algorithm and the resulting spatial and numeric data is displayed on the map (**Figure 10-4**). The service providing the analysis can also be used by other models and tools independent of this user interface.

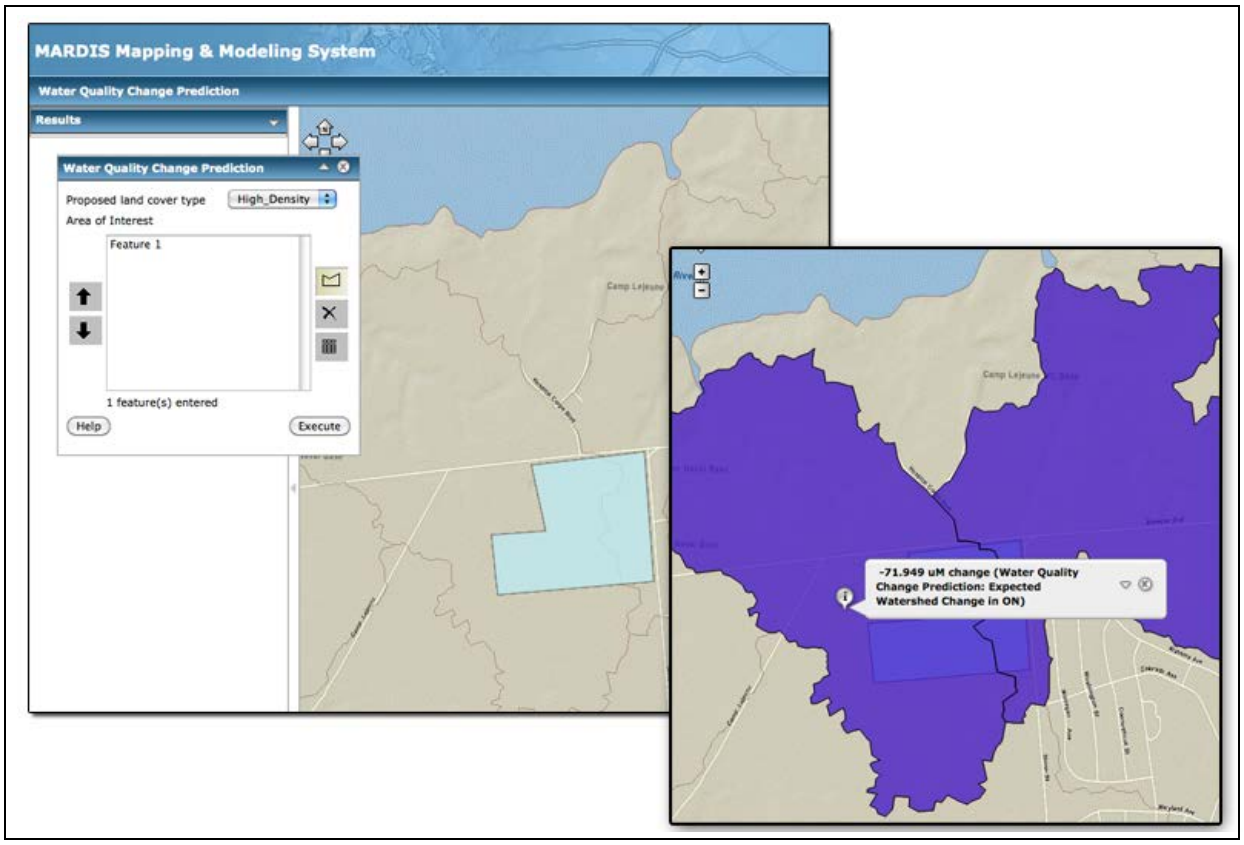

Figure 10-4. Web interface for the prototype planning application.

Implementing DCERP analytical models as geoprocessing services achieves the following project goals:

1. This allows research products to be used in a practical way by MCBCL planners
2. This frees end users from having to acquire licenses for the advanced scientific software packages used in DCERP research
3. Algorithms behind the models are moved to the Web relatively intact, without the need to rewrite them in a new programming environment.
4. Geoprocessing tools can be made available over the Web to other DoD installations.

RCW DSS Tool

The RCW DSS tool to be developed by Research Project T-4 for MCBCL and Fort Bragg (also in North Carolina) determines how RCW population dynamics are likely to be altered by climate change and improves ability to integrate carbon sequestration goals and RCW recovery goals despite climate change. In addition to the desktop tool created under Research Project T-4, the SDSS Framework Team will work with the Research Project T-4 to create a Web-based version of the tool integrated directly into the SDSS framework. The Web-based version of the tool will include user interfaces accessible from within the SDSS framework and will be connected directly to data contained in MARDIS. With the RCW RASP underway at MCBCL, there is an opportunity to integrate complementary data from both a DCERP scientific module and the Base Managers. The TSP-1 Team will work with both groups to identify connections useful to both teams and to package the tool for general consumption in the Web application.

LANDIS II Model

The LANDIS II model to be applied by Research Project T-3 simulates forest change and carbon flux and storage in the context of MCBCL forestry management practices, including harvest (clear-cutting), overstory and midstory thinning, and prescribed fire and wildfire regimes at the stand level and across the MCBCL landscape. Similar to the RCW tool, the SDSS Framework Team will work with the Research Project T-3 to adapt the LANDIS II desktop tool into a Web-based version that will be integrated directly into the SDSS framework and will have direct access to data in MARDIS.

Estuarine Simulation Model

The ESM developed under DCERP1 provides an example of how complex simulation models might fit into the framework. The ESM is an online application that provides a powerful stand-alone tool, allowing users to control multiple parameters of estuary management, such as controlling nutrient inputs, restocking oysters, and managing shoreline areas.

It may be possible to provide an intuitive user interface for each of these parameters, directly controlled from within the SDSS. If the underlying software used to produce the model, STELLA, is not portable to the framework, it could still be spatially “discovered” by users. When framework users identify an area that overlaps with the MCBCL estuary, the reporting feature will guide users to the VIMS site hosting the ESM model.

An intermediate case might be a model in which some aspects are suited to the ArcGIS spatial framework, and simplified results are incorporated in the planning tool, along with guidance on how to proceed with a more complete analysis.

Greenness Change Analysis—An examination of above-ground biomass/carbon sequestration using remote sensing data at MCBCL

Greenness change analysis from DCERP1 will continue on under Research Project TSP-1, providing a pilot case for tight integration of DCERP research within the framework. During DCERP1, Peter Harrell examined vegetation change patterns at MCBCL, in terms of both gain and loss of vegetation. During DCERP2, these efforts will continue under Research Project TSP-1. A historical pattern of change prior to the start of DCERP1 in 2007 was established using

Landsat imagery for 1984, 1990, 1998 and 2005. Beginning with 2007, we then added imagery every 2 years to capture the changes happening currently at the MCBCL—2007, 2009, and 2011. This provides change information for six individual time periods for both vegetation gain and loss. We also used this data to create a time sequence "change code." This allowed us to map the change trajectory for every location at MCBCL from 1984 to 2011.

During DCERP2, we will continue this greenness change analysis, documenting the impacts of MCBCL activities and allowing for better management of these impacts. This will be critical to continue to provide a suitable environment to train the U.S. Marines while maintaining sustainable ecosystems—two goals with difficult and often conflicting sets of requirements. We will aim to collect Landsat data every 2 years—2013, 2015, and 2017—provided quality imagery are available. This will provide a change history from 1984 to 2017 at regular time steps, a 33-year history of vegetation change at MCBCL. To our knowledge, such a change history has never been assembled before. This change information can then be used in SDSS tools to directly aid in management decisions.

We will also use remote sensing data to examine the standing biomass and carbon sequestration of the forest environment at MCBCL. This work will begin with the use the NCSU LiDAR data collected in 2001 and the 2007 LiDAR data collected over MCBCL. These data will allow estimates of canopy height, an important variable for many forest management activities and models of ecosystem processes. Initial work will focus on the development of methodology and sensitivity testing to effectively measure canopy height. The next step will be to use height data and algorithms linking height to biomass and carbon to develop biomass and standing carbon estimates for forested areas of MCBCL. With the two dates of LiDAR data, 2001 and 2007, we can compare estimates from both and may be able to look at change in height and biomass in the intervening 6 years. The final step is to include the greenness change products and the LiDAR height and biomass estimates in SDSS tools under development to aid in forestry and carbon management decisions by MCBCL personnel.

We will also use LiDAR data from the 2001–2007 period to establish a baseline of natural grass and canopy height prior to changes in off-road training maneuvers that are expected in the coming years. As this change in training is implemented, LiDAR should be able to detect greenness impacts, possibly down to the scale of tank tracks and tire ruts. MCBCL LiDAR data from early 2013 will provide the baseline for comparison and will be shown in the earliest phases of the DCERP2 Web applications.

10.2.3 Milestones

1.	Conduct SDSS planning phase and user needs assessment	11/2012–ongoing
2.	Integrate new Landsat images for greenness change temporal sequence	2013, 2015, 2017
3.	Expand Internet Mapper functionality and integrate with MARDIS	6/2014
4.	Finalize SDSS framework and water quality tool	6/2014
5.	Analyze LiDAR data for height measurement and integration of greenness data in framework	2014, 2016
6.	Integrate the RCW model into the SDSS framework	6/2015

7. Integrate the LANDIS II model into the SDSS framework 3/2016
8. Update/expand Internet Mapper with new data layers and queries as needed 6/2016
9. Assess other research projects for integration into the framework 2014–2016
10. Integrate other tools or models, such as climate change tools and those module efforts near completion 6/2017
11. Prepare and deliver the final Research Report 10/2017

10.2.4 Deliverables

1. Expand Internet Mapper functionality and integrate with MARDIS 6/2014
2. Finalize SDSS framework and water quality tool 6/2014
3. Integrate the RCW model into the SDSS framework 6/2015
4. Integrate the TCAT into the SDSS framework 3/2016
5. Prepare and deliver final Research Report Draft 3/2017; final 10/2017

10.2.5 Planned Publications

Harrell, P., and P.N. Halpin. 2013. Coastal landscape change detection and above ground carbon monitoring. To be submitted to *Remote Sensing of Environment.*

Donnelly, B., P.N. Halpin, and P. Harrell. 2013. Development of a spatial decision support system for coastal environmental management. To be submitted to *International Journal of Geographical Information Science*.

10.3 Research Project TSP-2: Coupled Ecosystem Modeling of the NRE for Research, Synthesis, and Management

Lead Investigator: Dr. Mark J. Brush (VIMS)

Supporting Researchers: One Postdoctoral Research Associate and one Ph.D. student

Technical Objectives/Goals: Research Project TSP-2 synthesizes DCERP data into an ecosystem modeling platform for analysis of the NRE carbon budget, predicting NRE response to changes in both climate and land use, and development of a decision-support tool for translating scientific information into practice through the following objectives:

1. Expand the utility of the DCERP1 ESM through the addition of more ecosystem state variables and the CO_2–pH system
2. Synthesize DCERP2 data from the Aquatic/Estuarine, Coastal Wetlands, and Coastal Barrier Modules into a carbon budget for the estuarine and coastal region of MCBCL and compare to the modeled budget
3. Simulate NRE response to climate and land-use changes, particularly with respect to carbon cycling, the role of the estuary as a carbon source or sink, water quality, and ecosystem services
4. Quantify potential tradeoffs between management to increase carbon storage and reduce nutrient-fueled eutrophication
5. Develop and deliver a readily transferable, online decision-support version of the ESM to facilitate MCBCL management
6. Demonstrate the broad applicability of the ESM by applying the model to the Neuse River in North Carolina (MCAS Cherry Point) and Pensacola, Escambia, and Choctawhatchee Bays in Florida (Eglin AFB).

Research Questions:

1. Are the NRE and its associated marshes currently net sources or sinks for carbon?
2. Are the major sources and sinks of carbon in the NRE and its associated marshes or allochthonous? If autochthonous, what components of the system contribute most to production and respiration?
3. How will elevated water temperature and increased freshwater loading due to climate change affect the metabolic balance of the NRE? Specifically, will the system shift from net autotrophy (net carbon sequestration) towards net heterotrophy (net carbon release).
4. How will changes in watershed material loading interact with changing climate to affect NRE water quality, net metabolic balance, and capacity for carbon storage? Specifically, what are the combined effects of changes in nutrient loading, organic carbon loading, and increased water temperature and freshwater input?
5. Are there tradeoffs between management for estuarine carbon sequestration versus nutrient load reduction? How are these tradeoffs affected by inter-annual hydrologic variability and long-term climate change?

10.3.1 Background

Dynamic simulation models have a long history as heuristic and synthetic research tools in the study of coastal marine ecosystems (Brush and Harris, 2010; Canham et al., 2003; Kremer and Nixon, 1978; Riley et al., 1949; Steele, 1974). These models have been increasingly applied to guide management, particularly related to the effects of nutrient loading on cultural eutrophication (Giblin and Vallino, 2003; Harris et al., 2003; NRC, 2000; U.S. EPA, 1999). In the United States, large investments over many years have been made in the development of high-resolution, biogeochemically complex ecosystem models of major estuarine and coastal systems, including the Chesapeake Bay (Cerco and Noel, 2004), the Long Island Sound (HydroQual, 1991), and the Massachusetts Bay/Boston Harbor (Chen et al., 2010; Jiang and Zhou, 2008).

Although these models typically focus on biogeochemical cycling of carbon and nutrients and the effects of changing nutrient loads on estuarine water quality, using models to predict coastal ecosystem response to climate change is just beginning (Brito et al., 2012; Carr et al., 2012; Justić et al., 2005; Neumann, 2010). Many estuaries are currently undergoing a "natural experiment" in which nutrient loads are being reduced with concurrent climate change (Nixon, 2009). In other cases, estuarine dynamics are changing primarily due to climatic influences without concurrent changes in nutrient loads (Nixon et al., 2009). As climate continues to change, with increases or decreases in nutrient loading, predictive tools are required for determining the synergistic effects of these changes on estuarine water quality, ecosystem function, and the ability of estuaries to process, sequester, and remove carbon and nutrients.

With the increasing demand for models to inform management decisions across a wide range of estuarine and coastal systems (e.g., total maximum daily loads for all impaired waterbodies in the United States; U.S. EPA, 1999), managers need readily applied, generally transferable modeling tools that can be applied quickly to a variety of systems with limited resources. During the past two decades, a growing body of research has been conducted that examined the role of complexity and spatial resolution in models (Baird et al., 2003; Denman et al., 2003; Friedrichs et al., 2006; Fulton et al., 2003 and 2004; Ménesguen et al., 2007; Raick et al., 2006). In addition, multiple calls have been made for the development of simpler, "intermediate complexity" models for use in management (Duarte et al., 2003; NRC, 2000; Pace, 2001; Rigler and Peters, 1995). Such intermediate complexity modeling tools have the potential for rapid application in the myriad of smaller coastal systems around the nation, including those with adjacent DoD installations, which do not often have the resources to support long-term development of more complex models. These simpler models also typically offer fast run times, enabling the efficient use of the models, either on desktop computers or over the Internet (see Section 9.4.2), by managers.

During DCERP1, we developed an intermediate complexity ESM for a heuristic study of the NRE and its response to natural and anthropogenic stressors (primarily nutrient loading). The ESM will ultimately be used as a decision-support tool for MCBCL. The current ESM (**Figure 10-5** and **Figure 10-6**) is a mechanistic, process-based model that runs for the period 1998–2010. This model simulates daily concentrations of phytoplankton (PHYTO) and BMA biomass (as chlorophyll *a* [chl *a*], carbon, nitrogen, and phosphorus); biomass of eelgrass (*Zostera marina*; as carbon, nitrogen, and phosphorus); and concentrations of DIN and DIP, dissolved oxygen (DO), TSS, and water column and sediment pools of labile organic carbon (C_{WC} and C_{SED}, respectively) and their associated nitrogen and phosphorus. The ESM aggregates key state variables and formulates selected rate processes using robust, cross-system empirical linkages to avoid use of multiple loosely constrained parameters and enable direct comparison of model predictions to observations (Brush and Nixon, 2010; Brush et al., 2002). The ESM is in line with recent calls for models of intermediate complexity for use in management (Duarte et al., 2003; NRC, 2000).

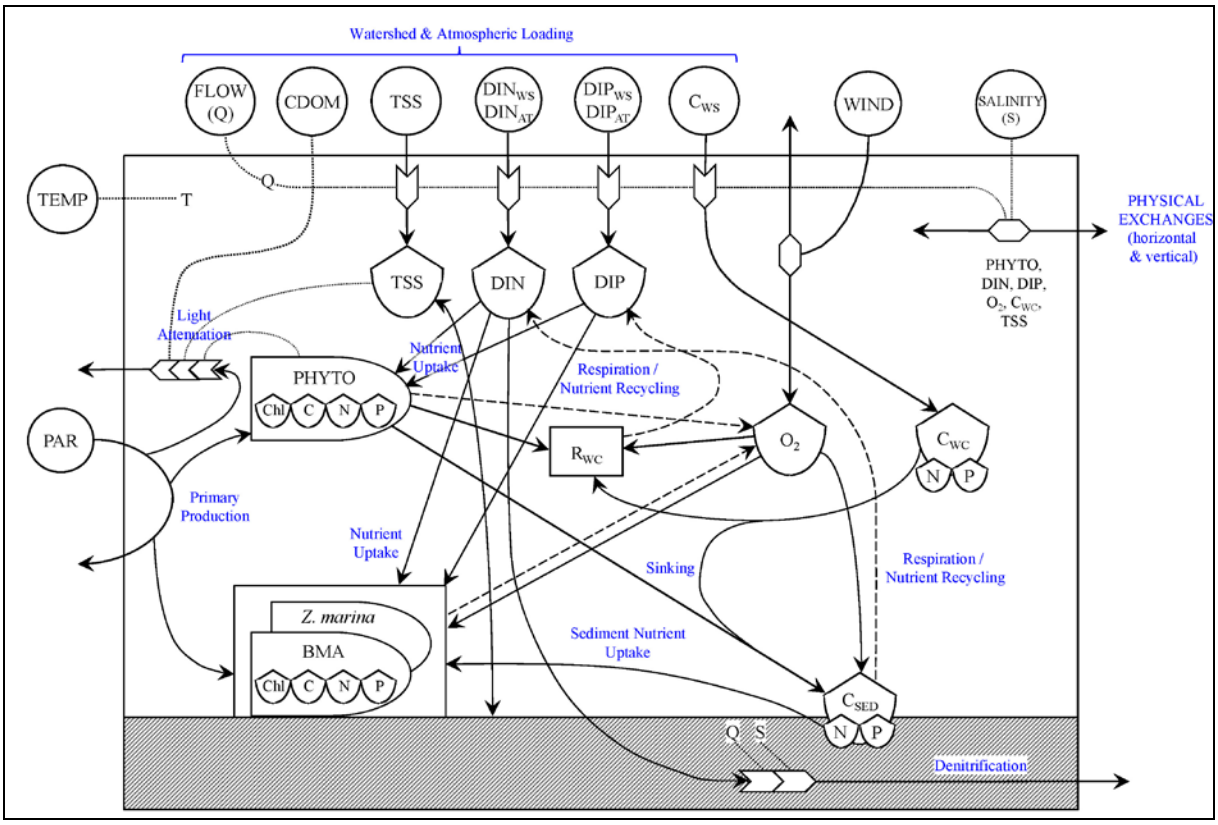

Figure 10-5. A schematic of the DCERP ESM.

Note: Subscript WS = watershed; subscript AT = atmospheric deposition; R_{WC} = integrated water column respiration. All other terms are defined in the text.

The ESM is forced with measured water temperature and salinity, meteorological time series, atmospheric nutrient deposition, and watershed loads of freshwater and nutrients (**Table 10-2**). The model runs in a series of coarse spatial elements, each with surface and bottom layers (**Figure 10-6**). Although boxed schemes lose spatial resolution, they capture the major down-estuary and surface-to-bottom gradients in water quality, facilitate rapid implementation in new study systems, and make multiple fast runs (seconds to minutes) possible during model testing and subsequent use as a decision-support tool. Recent work has confirmed the utility of boxed approaches (Kremer et al., 2010; Ménesguen et al., 2007; Testa and Kemp, 2008).

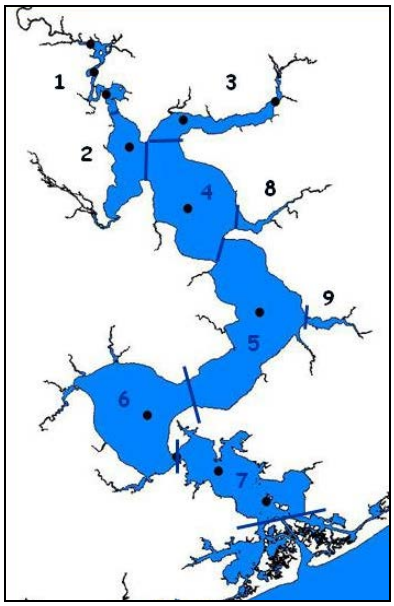

Figure 10-6. The spatial elements of the DCERP ESM.

Each element has surface and bottom layers separated by the pycnocline.

Table 10-2. Current forcing functions and state variables of the DCERP ESM[a]

Forcing Functions	
Water temperature	Photosynthetically active radiation (PAR)
Salinity	Watershed loading (water, N, P, and TSS)
Precipitation	Atmospheric N deposition (wet and dry)
Evaporation[b]	Onslow Bay concentrations of Chl, N, P, and oxygen (O_2)
Wind speed	CDOM (Chromophoric Dissolved Organic Matter)
Turbidity (Nephelometric Turbidity Unit [NTU])[c]	
State Variables	
Phytoplankton[d]	Dissolved inorganic nitrogen (DIN)
Benthic microalgae (BMA)[d]	Dissolved inorganic phosphate (DIP)
Eelgrass shoots[d, e]	Dissolved oxygen (DO)
Eelgrass roots and rhizomes[d, e]	Total suspended solids (TSS)[c]
Water column organic carbon[d, f]	Sediment organic carbon[d, f]

[a] C = carbon; N = nitrogen; P = phosphorus; Chl = chlorophyll a
[b] Evaporation can be forced directly or computed if air and dew point temperature are forced.
[c] Users can either force measured turbidity or simulate TSS.
[d] State variables are computed in carbon units; N, P, and chl a (phytoplankton and BMA only) are computed stoichiometrically.
[e] Eelgrass is *Zostera marina* L.
[f] Water column and sediment organic carbon pools represent freshly produced, labile material in both dissolved and particulate forms.

During DCERP1, the ESM was calibrated to MCBCL monitoring data (1998–2007) and DCERP1 monitoring and research data (2007–2010). The model was primarily used to determine (1) the characteristics of the NRE ecosystem that control its response to anthropogenic nutrient loading and (2) the NRE response to these loads under inter-annual hydrologic variability in terms of water quality and ecosystem function. The modeling work in Research Project TSP-2 as part of DCERP2 will expand the ESM developed during DCERP1 to include more components and management endpoints (e.g., two new seagrass species, marsh dynamics, phytoplankton groups, and the CO_2–pH system). The planned modeling work also extends the ESM's focus, which was primarily on nutrient response and management to carbon cycling and management, as well as NRE response to climate change. Additionally, the planned work will deliver the ESM to MCBCL via an online interface and demonstrate the utility of the ESM in two more coastal systems adjacent to DoD installations (MCAS Cherry Point and Eglin AFB).

10.3.2 Methods

The ESM will first be expanded with additional components to increase the model's utility to DCERP2 research on carbon and climate change and its ultimate use as a decision-support tool for MCBCL. During DCERP1, a range of Watershed Simulation Models (WSMs) were applied to MCBCL; the most successful were the simple Nitrogen Loading Model (Giordano et al., 2012; Valiela et al., 1997) and the intermediate complexity Regional Nutrient Management (ReNuMa) model (for more information, see http://www.eeb.cornell.edu/biogeo/nanc/usda/renuma.htm). We also developed a series of multiple regression models for predicting loads. In DCERP2, we will couple one or more of these models directly to the ESM to enable scenarios in which users can change land-use distributions on the Base. Second, we will experiment with the incorporation of multiple phytoplankton functional groups using DCERP1 pigment data and adding sub-models for salt marsh production and biogeochemistry and shoreline erosion based on results from DCERP1. The original ESM contains eelgrass (*Z. marina*), one of three species

of submerged aquatic vegetation in the NRE. We will add sub-models for the other two species, *Ruppia maritima* and *Halodule wrightii*. Finally, because carbon cycling is a major focus of DCERP2, we will add a sub-model for the CO_2–pH system.

The expanded ESM will be updated with DCERP2 monitoring and research data to extend the calibration through at least 2015. The focus of the calibration will continue to include basic water quality data (e.g., chl *a* biomass of phytoplankton and BMA, nutrient and oxygen (O_2) concentrations from monitoring activities AEM-1, AEM-3, and CWM-1) and key rate process data related to carbon cycling (e.g., phytoplankton, BMA, and marsh primary production; water column, sediment, and marsh respiration; air-sea CO_2 fluxes from Research Projects AE-4, AE-6, CW-4, and CW-5). The calibrated model will then be used to generate a system-wide carbon budget for the NRE and its associated marshes over multiple years. Model uncertainty will be assessed through the use of simulations with stochastically varying parameters, which propagates error through model calculations to account for imprecisely known and temporally variable parameter values (Kremer, 1983). We will compare this modeled budget to an empirical budget constructed from data collected across multiple projects in the Aquatic/Estuarine, Coastal Wetlands, and Coastal Barrier Modules, coordinated by Research Project TSP-2 (**Figure 10-7**). Sufficient data are being collected on all major pathways in the estuarine/coastal carbon budget as part of DCERP2 to provide a meaningful validation of the ESM–based carbon budget. This comparison will primarily be used to validate the modeled carbon budget with the empirical measurements and identify major routes of carbon cycling in the estuarine-coastal system, but it can also be used to identify areas in which the two budgets agree and areas in which they diverge that require further consideration.

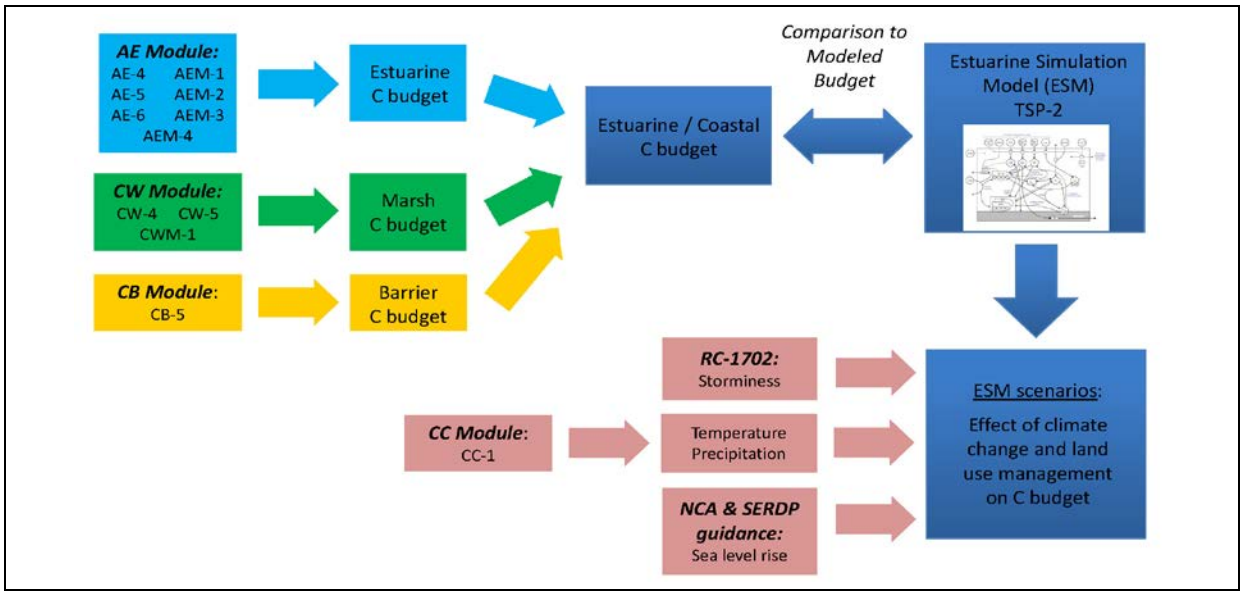

Figure 10-7. (Left) A conceptual flow diagram for the synthesis of DCERP2 research and monitoring data into an estuarine and coastal carbon budget (coordinated by Research Project TSP-2). (Top right) A comparison with the modeled carbon budget. (Bottom right) The use of projections from Research Project CC-1 and related efforts to conduct ESM scenarios on the effect of concurrent climate change and land-use management on the NRE and its carbon budget.

After validating the ESM–predicted carbon budget, the model will be run across the full period of input data (1998–2015) to assess the effect of inter-annual hydrologic variability and episodic events (i.e., storms) on the NRE carbon budget and its role as a carbon source or sink. We will also use the model to conduct a series of simulation analyses to understand the response of the NRE (and changes in its carbon budget) to combined changes in climate and land use (**Figure 10-7**). Projections of likely changes in local climate (e.g., air temperature, precipitation, storminess, sea level rise, and atmospheric CO_2 concentration alone and in combination) from Research Projects CC-1, RC-1702, and the pending National Climate Assessment (as adapted locally by the DCERP2 Team) will be used to drive climate change scenarios. We will also apply a continuum of land-use conversions from forest to impervious surfaces in the watershed. Modeled response of the NRE will be characterized in terms of key management endpoints, primarily water quality (phytoplankton chl *a*, nutrient concentrations, degree of hypoxia or anoxia), net autotrophy versus heterotrophy of the NRE, and ecosystem services (primarily the role of the NRE as a carbon source or sink and efficiency of nitrogen removal). We will use the model scenarios to address the our research questions.

To transfer the ESM to MCBCL management staff and to facilitate its use as a management tool, we will create an online decision-support version of the model. We have recently developed this capability using a version of the ESM to guide restoration planning in a tributary system of the Chesapeake Bay (e.g., www3.vims.edu/netsim/netsims/brush/wrr_model_apr_2011/index.html; **Figure 10-8**). The intermediate complexity, boxed approach used in the ESM makes fast run times (minutes on a desktop computer) possible, thereby enabling efficient use of the model over the Internet. The online interface will contain a user-friendly, graphical user interface (GUI) with documentation, user instructions for running simulations, and user-defined inputs for key parameters. These parameters include watershed land-use distributions, nutrient loading, and the magnitude and direction of changes in temperature, precipitation, storminess, and sea level rise. The interface will provide ready access to model output for the key management endpoints previously listed. This approach enables use of the model without the need for extensive modeling expertise or costly software, with support provided by VIMS' Ecosystem Modeling Program. We will develop the interface in collaboration with MCBCL managers to ensure that it meets their needs and then will demonstrate it to MCBCL through workshops. The online model will be linked from the SDSS framework developed by Research Project TSP-1. We provided an initial beta version of the online ESM to MCBCL, MCAS Cherry Point, and Eglin AFB staff at the April 2013 TAC meeting and invited feedback and testing. We propose presenting installation staff with annual updates on the tool at each TAC meeting. Review and testing of the beta version by the installation staff and feedback at each TAC meeting will guide revisions, refinements, and inclusion of additional capabilities and functionalities during the remainder of DCERP2. The final online tool will be delivered to MCBCL via a training workshop in 2017, with versions (including training) for MCAS Cherry Point and Eglin AFB provided upon request.

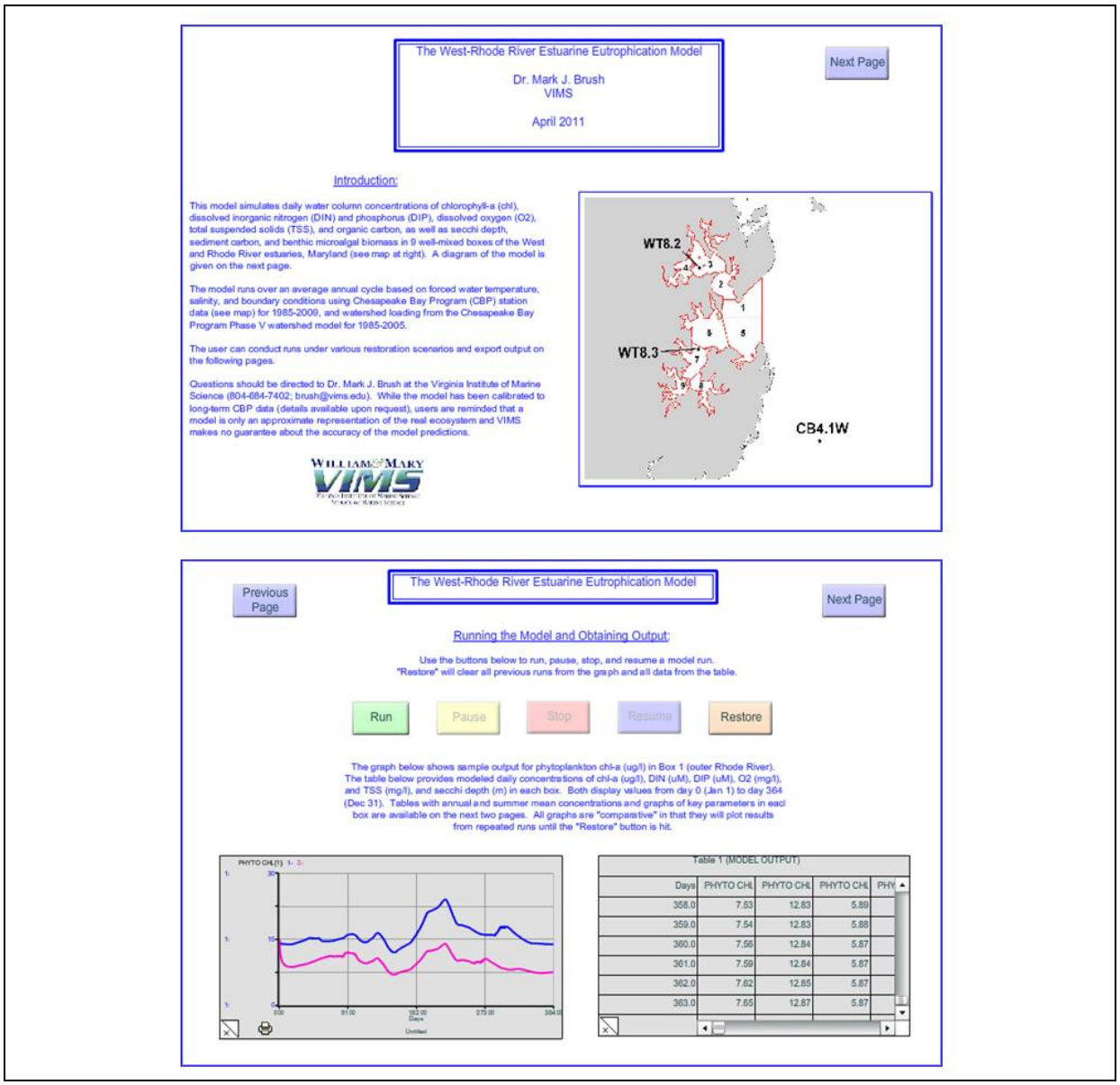

Figure 10-8. An example of an online interface for the DCERP ESM, taken from a recent project using a related model in the West-Rhode River Estuaries, MD.

(Top panel) The opening screen. (Bottom panel) The screen contains buttons for running the model and options for viewing output. The online interface contains additional pages (not shown here) describing the model, explaining how to conduct scenarios, providing options that users can manipulate (e.g., nutrient loading), and viewing complete model output.

Finally, we will demonstrate a wider utility of the ESM by applying it to estuaries at other coastal DoD installations from which monitoring data are available for calibration. We have selected the nearby Neuse River Estuary in North Carolina (MCAS Cherry Point) and Pensacola, Escambia, and Choctawhatchee Bays in Florida (Eglin AFB) as study sites (**Figure 10-9**). The ESM will be set up at these locations and used to simulate either the mean annual cycles of key water quality parameters (chl *a*, nutrients, and O_2) or time series of these parameters over selected periods. These applications of the model, combined with applications of the ESM in

systems along the U.S. East Coast (from Cape Cod to the Chesapeake Bay) as part of other funded projects, will demonstrate the wide applicability of the ESM in estuaries from New England to the Gulf of Mexico (**Figure 10-10**). This portion of Research Project TSP-2 will also result in operational models at two additional installations and a generally transferable model that can be rapidly adapted to other DoD installations.

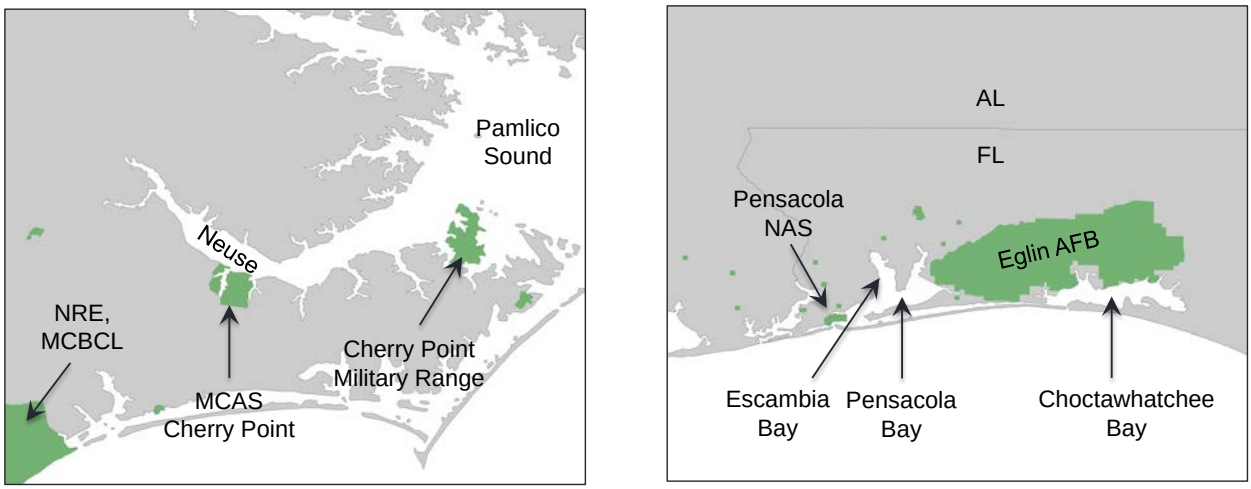

Figure 10-9. The new sites selected for ESM application in DCERP2 and adjacent DoD facilities.

The RTI DCERP2 Team will apply the ESM in the Neuse River Estuary in North Carolina (left panel) and Escambia, Pensacola, and Choctawhatchee Bays in Florida (right panel).

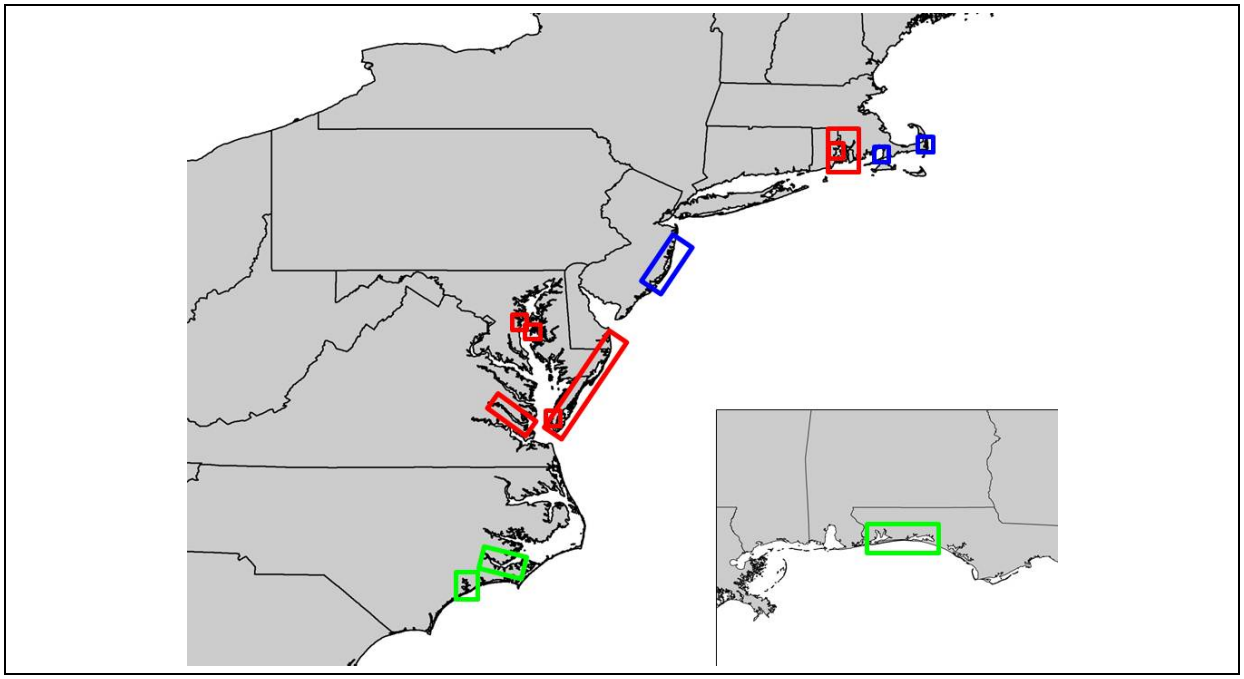

Figure 10-10. Estuarine and coastal systems in which the ESM is currently being applied or has been recently applied via DCERP1 and DCERP2 (green polygons), other funded projects (red polygons), and a pending project (blue polygons).

10.3.3 Assessment of Climate Change Impacts

Research Project TSP-2 will produce a simulated carbon budget via the ESM for each year of DCERP2, thus capturing the effects of inter-annual climatic and hydrologic variabilities on the role of the NRE system as a carbon source or sink. Once validated using data collected by the Aquatic/Estuarine, Coastal Wetlands, and Coastal Barrier Modules, the DCERP2 team will use the ESM to run a series of climate change scenarios to predict response of the NRE to climate change in terms of water quality, ecosystem services, net autotrophy versus heterotrophy, and the role of the estuary and coastal marshes as a carbon source or sink.

10.3.4 Intended Study Areas

ESM expansion and application will be focused on the NRE at MCBCL and will apply the ESM to the Neuse River Estuary in North Carolina (MCAS Cherry Point) and to Pensacola, Escambia, and Choctawhatchee Bays in Florida (Eglin AFB).

10.3.5 Milestones

1.	Expand the utility of the ESM with addition and testing of new submodels	3/2013–2/2015
2.	Apply the ESM to the Neuse River Estuary, NC	3/2013–8/2014
3.	Apply the ESM to Escambia, Pensacola, and Choctawhatchee Bays in Florida	8/2014–2/2016
4.	Conduct model simulation analyses (carbon budget and climate- and land-use change scenarios)	2/2014–2/2017
5.	Develop an estuarine carbon budget (presented annually at the TAC meeting)	Annually
6.	Present updated ESM and online tool to installation personnel (annually at the TAC meeting pending installation interest)	Annually
7.	Refine and deliver an online decision-support version of the ESM with a user's guide to MCBCL (and MCAS Cherry Point and Eglin AFB as requested)	2/2016–5/2017
8.	Conduct a workshop for training MCBCL (and MCAS Cherry Point and Eglin AFB as requested) staff on use of ESM tool	8/2017
9.	Prepare and deliver the final Research Report	10/2017

10.3.6 Deliverables

1.	Provide an online decision-support version of the ESM with a user's guide	5/2017
2.	Present a training workshop with MCBCL (and MCAS Cherry Point and Eglin AFB as requested) staff on using the ESM tool	8/2017
3.	Prepare and deliver the final Research Report	Draft 3/2017; final 10/2017

10.3.7 Planned Publications

Unless specified, papers will be written for publication in one of the following mainstream estuarine science journals: *Estuaries and Coasts, Marine Ecology Progress Series, Estuarine, Coastal and Shelf Science,* or *Limnology and Oceanography.*

Brush, M. Modeling the effect of inter-annual hydrologic variability and nutrient loading on NRE net metabolism and role as a carbon source or sink (results of Year 1 simulations using existing ESM, but focused on carbon and metabolism). Submission is planned for spring 2014.

Student (to be determined), and M. Brush. Modeling multiple phytoplankton functional groups and their responses to nutrient loading and climate change. Submission is planned for winter 2014–2015.

Brush, M., and S. Lake: Broad applicability of the ESM (paper reporting results from ESM application from southern New England to the Gulf Coast). Submission is planned for spring 2016 to *Ecological Applications.*

Brush, M., S. Lake, et al. Modeling the NRE carbon budget and potential changes due to climate and land use change. Submission is planned for spring 2017.

Brush, M., and S. Lake. A reduced complexity, online decision-support modeling tool for estuarine nutrient and carbon management. Submission is planned for fall 2017 to *Ecological Applications.*

Brush, M., S. Lake, et al. Modeling the tradeoffs between management for nutrient loading vs. carbon sequestration (including the effects of climate change and inter-annual hydrologic variability). Submission is planned for fall 2017.

10.4 DCERP2 Stakeholder Engagement

The DCERP2 Team will use an iterative process to engage installation users. At the first TAC meeting in April 2013, the RTI Team invited installation staff from MCBCL, Eglin AFB, MCAS Cherry Point, and Fort Bragg to participate in a tool development workshop session. The team will hold an annual workshop to provide a venue to encourage greater interaction between tool developers and installation staff (throughout the tool development process). The purpose of this workshop will be to determine their management needs and explain each tool that the team has proposed for development. This workshop will also provide training on the newly developed tools and obtain feedback that will be incorporated into the tool development and refinement processes by having the installation staff beta test the decision-support tools and models.

The TSP Module will start this process by incorporating the existing DCERP1 products into the SDSS. June 2014 is the milestone for the first mapping tool, integrating the greenness change model into the MARDIS database. In addition, it will be possible to incorporate non-DCERP spatial data relevant to planning and climate change scenarios. This Web application will be stable enough that it can be demonstrated to installation planners and environmental assessment users and be left accessible to installation staff as other analysis capabilities are incorporated into the SDSS.

An introductory training session will be held for MCBCL staff members in summer 2014 to present this early version of the SDSS framework. Modifications will be made based on suggestions from this session. This training meeting should include MCBCL Web administrators to identify the appropriate areas in the installation's Web site to connect to the framework. The challenge with the greenness change model is that it is only practical to a subset of the planning and assessment users, so the training session will also need to communicate potential uses. Existing MCBCL GIS data sets (e.g., streams, wetlands, land use, buildings, training ranges, roads, future facilities) will be integrated in the SDSS at regular intervals during 2014 to draw potential users back to the Web application after the in-person session. Follow-up e-mails will be used to announce expansion of the SDSS. Static spatial data, in contrast to dynamic model outputs, from the DCERP researcher projects are significantly easier to incorporate into a Web-based GIS. Regular contact, more frequent than annual training sessions, is necessary to keep users engaged in a Web site, and small-scale improvements announced by e-mail and at DCERP meetings can be used to promote these changes.

Delivery of the online, decision-support version of the ESM (Research Project TSP-2) will take place in coordination with MCBCL, MCAS Cherry Point, and Eglin AFB staff. Dr. Brush presented a pilot version of this tool to installation staff during the 2013 TAC meeting. These interactions will continue throughout the course of DCERP2 via TAC meetings, conference calls, responses to specific inquiries, and workshops as requested. Decision-support tools such as the RCW DSS tool will be completed in July 2014 for MCBCL and March 2015 for Fort Bragg. The TCAT will be completed in November 2016. The Geospatial Marsh Model will be completed in December 2016. The Research Plan for Research Project TSP-2 specifically calls for a workshop to train MCBCL users on utilizing the ESM tool and delivery of the final online version of the ESM and user's guide in May 2017.

10.5 Literature Cited

Baird, M.E., S.J. Walker, B.B. Wallace, I.T. Webster, and J.S. Parslow. 2003. The use of mechanistic descriptions of algal growth and zooplankton grazing in an estuarine eutrophication model. *Estuarine, Coastal and Shelf Science 56*(3–4):685–695.

Brito, A.C., A. Newton, P. Tett, and T.F. Fernandese. 2012. How will shallow coastal lagoons respond to climate change? A modeling investigation. *Estuarine, Coastal and Shelf Science 112*:98–104.

Brush, M.J., and L.A. Harris. 2010. Introduction to the special issue of Ecological Modelling: Advances in Modeling Estuarine and Coastal Ecosystems: Approaches, Validation, and Applications. *Ecological Modelling 221*:965–968.

Brush, M.J., and S.W. Nixon. 2010. Modeling the role of macroalgae in a shallow sub-estuary of Narragansett Nay, RI (USA). *Ecological Modelling 221*(7):1065–1079.

Brush, M.J., J.W. Brawley, S.W. Nixon, and J.N. Kremer. 2002. Modeling phytoplankton production: problems with the Eppley curve and an empirical alternative. *Marine Ecology Progress Series 238*:31–45.

Canham, C.D., J.J. Cole, and W.K. Lauenroth (Eds.). 2003. *Models in Ecosystem Science*. Princeton University Press: Princeton, NJ.

Carr, J.A., P. D'Odorico, K.J. McGlathery, and P.L. Wiberg. 2012. Modeling the effects of climate change on eelgrass stability and resilience: Future scenarios and leading indicators of collapse. *Marine Ecology Progress Series 448*:289–301.

Cerco, C.F., and M.R. Noel. 2004. *The 2002 Chesapeake Bay Eutrophication Model*. Report 903-R-04-004. Chesapeake Bay Program Office, U.S. Environmental Protection Agency, Annapolis, MD. 349 pages.

Chen, C., R. Tian, R.C. Beardsley, J. Qi, and Q. Xu. 2010. *Modeling 2008 in Massachusetts Bay Using an Upgraded Unstructured-Grid Bays Eutrophication Model*. Report 2010-15. Massachusetts Water Resources Authority, Boston, MA. 118 pages.

Denman, K.L. 2003. Modelling planktonic ecosystems: parameterizing complexity. *Progress in Oceanography 57*(3–4):429–452.

Duarte, C.M., J.S. Amthor, D.L. DeAngelis, L.A. Joyce, R.J. Maranger, M.L. Pace, J. Pastor, and S.W. Running. 2003. The limits to models in ecology. Pp. 437–451 in *Models in Ecosystem Science*. Edited by C.D. Canham, J.J. Cole, and W.K. Lauenroth. Princeton University Press: Princeton, NJ.

Friedrichs, M.A.M., R.R. Hood, and J.D. Wiggert. 2006. Ecosystem model complexity versus physical forcing: Quantification of their relative impact with assimilated Arabian Sea data. *Deep-Sea Research Part II 53*:576–600.

Fulton, E.A., A.D.M. Smith, and C.R. Johnson. 2004. Effects of spatial resolution on the performance and interpretation of marine ecosystem models. *Ecological Modelling 176*(1–2):27–42.

Fulton, E.A., A.D.M. Smith, and C.R. Johnson. 2003. Effect of complexity on marine ecosystem models. *Marine Ecology Progress Series 253*:1–16.

Giblin, A.E., and J.J. Vallino. 2003. The role of models in addressing coastal eutrophication. Pp. 327–343 in *Models in Ecosystem Science*. Edited by C.D. Canham, J.J. Cole, and W.K. Lauenroth. Princeton University Press: Princeton, NJ.

Giordano, J.C.P., M.J. Brush, and I.C. Anderson. 2012. Quantifying annual nitrogen loads to Virginia's coastal lagoons: Sources and water quality response. *Estuaries and Coasts 34*:297–309.

Harris, G.P., S.W. Bigelow, J.J. Cole, H. Cyr, L.L. Janus, A.P. Kinzig, J.F. Kitchell, G.E. Likens, K.H. Reckhow, D. Scavia, D. Soto, L.M. Talbot, and P.H. Templer. 2003. The role of models in ecosystem management. Pp. 299–307 in *Models in Ecosystem Science*. Edited

by C.D. Canham, J.J. Cole, and W.K. Lauenroth. Princeton University Press: Princeton, NJ.

HydroQual. 1991. *Water Quality Modeling Analysis of Hypoxia in Long Island Sound*. Report to the Management Committee of the Long Island Sound Estuary Study and the New England Interstate Water Pollution Control Commission, HydroQual, Inc., Mahwah, NJ. 280 pages.

Jiang, M.S., and M. Zhou. 2008. *Massachusetts Bay Eutrophication Model: 2005 Simulation*. Report 2008-13. Massachusetts Water Resources Authority, Boston, MA. 85 pages.

Justić, D., N.N. Rabalais, and R.E. Turner. 2005. Coupling between climate variability and coastal eutrophication: Evidence and outlook for the northern Gulf of Mexico. *Journal of Sea Research 54*:25–35.

Kremer, J.N., and S.W. Nixon. 1978. *A Coastal Marine Ecosystem: Simulation and Analysis*. Springer-Verlag: New York, NY.

Kremer, J.N., J. Vaudrey, D. Ullman, D. Bergondo, N. LaSota, C. Kincaid, D. Codiga, and M.J. Brush. 2010. Simulating property exchange in estuarine ecosystem models at ecologically appropriate scales. *Ecological Modelling 221*(7):1080–1088.

Kremer, J.N. 1983. Ecological implications of parameter uncertainty in stochastic simulation. *Ecological Modelling* 18:187-207.

Ménesguen, A., P. Cugier, S. Loyer, A. Vanhoutte-Brunier, T. Hoch, J-F. Guillaud, and F. Gohin. 2007. Two- or three-layered box-models versus fine 3-D models for coastal ecological modelling? A comparative study in the English Channel (Western Europe). *Journal of Marine Systems 64*(1–4):47–65.

Neumann, T. 2010. Climate-change effects on the Baltic Sea ecosystem: A model study. *Journal of Marine Systems 81*:213–224.

Nixon, S.W. 2009. Eutrophication and the macroscope. *Hydrobiologia 629*: 5–19.

Nixon, S.W., R.W. Fulweiler, B.A. Buckley, S.L. Granger, B.L. Nowicki, and K.M. Henry. 2009. The impact of changing climate on phenology, productivity, and benthic-pelagic coupling in Narragansett Bay. *Estuarine, Coastal and Shelf Science 82*:1–18.

NRC (National Research Council). 2000. Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution. National Academy Press: Washington, DC.

Pace, M.L. 2001. Prediction and the aquatic sciences. *Canadian Journal of Fisheries and Aquatic Sciences 58*(1):63–72.

Raick, C., K. Soetaert, and M. Gregoire. 2006. Model complexity and performance: How far can we simplify? *Progress in Oceanography 70*(1):27–57.

Rigler, F.H., and R.H. Peters. 1995. Science and limnology. Book 6 in *Excellence in Ecology*. Edited by O. Kinne. International Ecology Institute, Oldendorf/Luhe. 239 pages.

Riley, G.A., H. Stommel, and D.F. Bumpus. 1949. Quantitative ecology of the plankton of the Western North Atlantic. *Bulletin of the Bingham Oceanographic Collection 12*:1–169.

Steele, J.H. 1974. *The Structure of Marine Ecosystems*. Harvard University Press: Cambridge, MA.

Testa, J.M., and W.M. Kemp. 2008. Regional, seasonal, and inter-annual variability of biogeochemical processes and physical transport in a partially stratified estuary: A box-modeling analysis. *Marine Ecology Progress Series 356*:63–79.

U.S. EPA (Environmental Protection Agency). 1999. Protocol for developing nutrient TMDLs. U.S. EPA report 841-B-99-007. EPA Office of Water, Washington, DC.

Valiela, I., G. Collins, J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawly, and C. Sham. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: New method and application. *Ecological Applications* 7:358–280.

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11.0 Data Management

Environmental data collected throughout the duration of the program are critical to DCERP research and modeling activities and to the development of decision-support management tools. The types and volumes of data that were created during DCERP1 were extensive and consisted of multimedia data collected across more than 350 sampling locations in a variety of formats and structures. The DCERP1 data include 37 data sets and more than 23 million records.

During DCERP2, the RTI DCERP2 Team will continue to collect monitoring and research data. The research data to be collected are described in Sections 5.0 through 9.0 of this Research Plan. The monitoring data are described in the separate *DCERP2 Final Monitoring Plan* (December, 2012). As part of DCERP2, several new monitoring data sets and parameters and more than 20 new research data sets are expected to be added.

11.1 Data Management System

In support of DCERP1, the Data Management Module developed the Data and Information Management System (DIMS) and procedures to manage the data and to enable efficient, secure, and accurate input, analysis, integration, display, and sharing of data. Data integration, sharing, and management are key functions of the DIMS that will continue into DCERP2.

Web-based access and interfaces allow the RTI DCERP researchers, MCBCL staff, and other users to access DCERP data from MARDIS. The DIMS also makes DCERP information available to the general public via the DCERP public Web site, provides a secure password-protected Web site for team collaboration, and supports the data management needs of DCERP, including data archiving, searching, and retrieval. The DIMS consists of several distinct systems as shown in **Figure 11-1**.

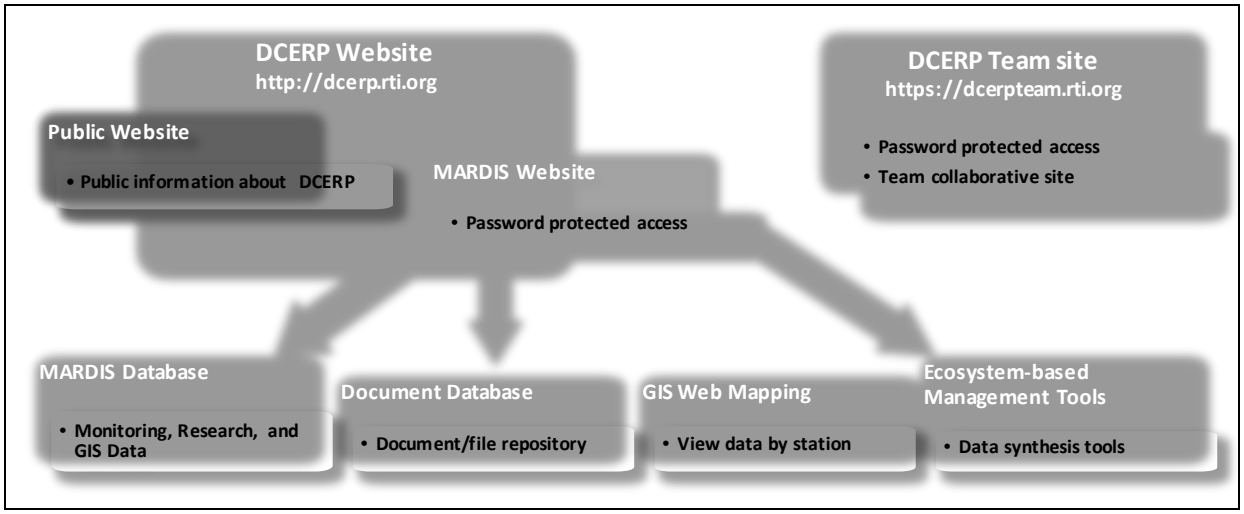

Figure 11-1. DCERP Data and Information Management System.

11.1.1 DCERP Web sites

The DCERP Team Web site is a password-protected site that is only for the RTI DCERP2 team. At this site, team members can share administrative planning documents, reports of activities, and other information of interest to facilitate communication and provide a forum for discussing the results and implications for management. At the start of DCERP2, the team will perform minor organization and archiving tasks, but no major enhancements are planned for the DCERP Team Web site.

The DCERP Public Web site (see http://dcerp.rti.org) provides the general public with information about the program, including the mission statement for DCERP, the background, objectives, approach, the benefits to military installations, and descriptions of the Research and Monitoring Plans. This site also contains contact information for SERDP staff, the SERDP Program Manager, the DCERP OSC, the DCERP PI, and all DCERP Module Team members, as well as links to affiliated organizations. The RTI DCERP2 Team will post technical reports, presentations, and other outreach materials to this site throughout the duration of the program. It is important to note that only documents that have been reviewed and approved by the researchers, MCBCL, and SERDP are posted on the public Web site. The team will update the content in the public Web site annually.

11.1.2 MARDIS Web site

MARDIS is part of the complete DCERP DIMS framework that has evolved into more than a simple data archive. In addition to the Relational Database Management System (RDBMS) serving as the back-end database, the team has used a framework application to serve as the front-end Web interface to the MARDIS database. Due to the robustness, security, and flexibility of this DIMS framework, MARDIS also hosts the Document Database, GIS Web Mapping and spatial data, and the Ecosystem-based Management Tools. MARDIS provides controlled access to all data and functions, and the MARDIS Web site provides access to the data described in Sections 11.1.2.1 through 11.1.2.4.

11.1.2.1 MARDIS Database for Structured Data

The MARDIS database serves as the long-term repository for all DCERP research and monitoring data. MARDIS contains tabular and geospatial environmental monitoring data from each ecosystem module that have defined content and structure and are managed in a standard RDBMS.

11.1.2.2 Document Database for Unstructured Data

The Document Database is used to store and manage non-spatial, unstructured, or derivative DCERP data such as maps, photographs, data files, reports, and other files and documents that cannot be stored as structured data in MARDIS. The Document Database serves as a searchable repository for all of the RTI DCERP Team’s finished products such as technical reports for the MCBCL, DCERP final reports for SERDP, and journal articles directly related to data collected as part of DCERP’s monitoring and research activities. Metadata associated with each document are searchable to facilitate document retrieval and help researchers understand the content of the documents and locate files that contain data of value to their research.

11.1.2.3 Web Mapping and Geospatial Data

Web Mapping

A simple interactive station map interface is provided as part of the MARDIS Web site to allow users to query stations by station name; data set name; geographical location, known as DCERP area; type of sampling station (land, ocean, estuarine, stream/river or wetland); or parameter group. In DCERP2 as part of Research Project TSP-1, the team will develop Web-based geospatial data services and a fully functional GIS Web mapping application, which will enable users to interact with, query, and visualize the spatial and non-spatial data in MARDIS. The team will integrate this Web mapping application into MARDIS as part of the SDSS framework from Research Project TSP-1 and will allow the design and development of decision-support systems that will run on the geospatial data in the spatial data repository.

Geospatial Data

The DCERP geospatial data structure follows the DoD Spatial Data Standards/Facilities, Infrastructure, and Environment (SDS/FIE) to the extent possible; in DCERP2, the geospatial data will be upgraded to the newest version of SDS/FIE. Geospatial data are archived, along with the standardized metadata that users can view via a Web page on the MARDIS Web site where they can request spatial data of interest. During DCERP2, access to geospatial data will be made easier through a new Map Gallery that will serve as a portal for DCERP–created maps and spatial data.

11.1.2.4 Ecosystem-Based Management Tools and Spatial-Decision Support System

Ecosystem-Based Management Tools are a set of statistical processes that provide a means of screening and highlighting data for further analysis. These advanced tools allow all MARDIS users to quickly and easily put DCERP data into practical use, such as allowing users to query data by data set, and then view various statistical results by parameter, including minimum/maximum, average, standard deviation, sum, count of records, and user-defined exceedances. In addition, MARDIS users can screen data further by viewing various statistical results by parameter and then by filtering a parameter further based on user-defined value limits.

An ultimate goal of DCERP is to develop decision-support tools to enable installation managers to identify adaptive, ecosystem-based management approaches, such as models for forecasting the impacts of military training activities or indicators for assessing healthy, transitional, or degraded conditions. To meet these goals, Research Project TSP-1 will implement an *SDSS* framework that will provide common mapping and data access functionality, integrated with MARDIS and within the DCERP DIMS. The team will create data services so that data in MARDIS can feed directly into modeling and decision-support tools both within and outside of the SDSS. Integrating the SDSS into MARDIS and DIMS will provide a centralized interface for access to data, maps, models, and tools developed during DCERP and will allow for cross-module access and integration of the DCERP data.

Full integration of the SDSS framework, integrated models, and decision-support tools into MARDIS will enable MCBCL managers to make informed decisions to support their long-term

goals of military training and preparedness. For more information on the SDSS framework, see the description for Research Project TSP-1 in Section 10.0 of this Research Plan.

11.2 DCERP2 Data Management Tasks

Data management for DCERP2 will continue to use the DCERP DIMS that was developed and implemented during DCERP1. The RTI data management tasks will focus on archiving data from DCERP2, improving and streamlining the existing DIMS, and expanding the system to assist with translating the data into useable information. The new data management effort will consist of leasing and maintaining servers, upgrading the current software applications, developing additional transpose tools for new data sets, and working closely with RTI DCERP Team researchers to assist in transposing data into the established Electronic Data Delivery (EDD) templates for loading into MARDIS. The RTI DCERP2 Team will also update the data structure to more easily and thoroughly capture additional metadata, provide updates to the public Web site, continue performance tuning as the amount of data grows, and provide support to MCBCL staff and other user groups.

During DCERP2, the team will also integrate the SDSS from Research Project TSP-1 into the DCERP DIMS. MARDIS will provide the underlying framework and data for the SDSS and the DCERP tools and models. For more information about the DCERP DIMS, see the *DCERP1 Data Management Report* (RTI, in preparation).

11.3 DCERP2 Data Management Plan Overview

The Data Management Plan for DCERP2 will remain relatively the same as that developed for DCERP1. Below is a brief overview of the Data Management Plan, including the changes planned for DCERP2.

11.3.1 Data Processing, Quality Assurance and Quality Control, Validation, and Upload

DCERP researchers are responsible for processing raw monitoring data results (e.g., laboratory and field results) into the EDD templates for loading into MARDIS. The researchers are also responsible for conducting the quality assurance (QA) and quality control (QC) procedures on data they have collected. The MARDIS upload mechanism provides basic validation checks to ensure that, where possible, data values that are invalid or out of range are detected prior to loading.

11.3.2 Data Storage

RTI's Information Technology Services (ITS) Department provides high-end management of RTI's Information Technology (IT) infrastructure, including experienced staff, facilities, and equipment (e.g., back-up generators, off-site data backup) necessary to handle DCERP's IT needs. RTI's ITS staff provide patch management, back-up management, routine maintenance, and call support 24 hours per day, 7 days per week.

The RTI DCERP2 Team will continue to use the DCERP1 hardware and software environment configuration, which allows users to interact with the MARDIS database through the Internet and includes a standard set of development, staging, and production database and Web application

servers. These servers will be upgraded to the latest server standards and software versions and will be used to handle the development, testing, and final production duties required in a complex database application environment. The server and software upgrades will consist of the following:

- One leased server to host the staging and production MARDIS databases
- One Web application server to host the DIMS Web interfaces, with costs shared by RTI
- Two servers used for development, provided by RTI
- The following five leased software applications will be updated to the most current versions:
  - Microsoft Windows Operating System
  - BackupAgent
  - Patch Management
  - McAfee security software
  - Microsoft SQL 2008 (standard license)
- Three Secure Sockets Layer (SSL) certificates (https) purchased (and renewed yearly) to handle encrypted communications between the data servers and client Web browsers
- One ArcGIS software program purchased (and renewed yearly)
- To constrain costs, the DCERP Collaborative Web site will continue to be hosted on a server provided by RTI for a nominal cost to cover the software license.

11.3.3 Data Access, Release, and Use Policies

The DCERP program developed and will continue to abide by the *DCERP Data Policy* (see **Appendix D).** DCERP data are made available to authorized users via access to MARDIS. In this way, all data are easily searched via the Web. When possible, DCERP monitoring data will be available in MARDIS within 6 months of collection, and research data will be available within 2 years of the data collection date. After these dates, the data will be available to the broader community for academic, research, educational, government, or other not-for-profit professional purposes. Varying levels of data access have been implemented in the DCERP DIMS via user groups and roles to prevent unauthorized access to sensitive information or compromising data quality.

Table 11-1 describes the different data users and the MARDIS user-access privileges for each user group based on the type of data (monitoring or research data) requested.

Table 11-1. Data and MARDIS user-access privileges for DCERP research and monitoring data

Data Users	MARDIS Access	Monitoring Data	Research Data
RTI DCERP2 Team	Yes	The DCERP Team has MARDIS view and download data privileges. Prior to downloading the data, users must agree to the Data Use Agreement. Before using the data, the user must also inform the respective DCERP researcher, discuss collaboration, and receive approval from that researcher.	The DCERP Team has MARDIS view and download data privileges. Prior to downloading the data, users must agree to the Data Use Agreement. Before using the data, the user must also inform the respective DCERP researcher, discuss collaboration, and receive approval from that researcher.
SERDP	Yes	SERDP has MARDIS view-data-only privileges.	SERDP has MARDIS view-data-only privileges.
MCBCL	Yes	MCBCL has MARDIS view and download data privileges. Prior to downloading the data, users must agree to the Data Use Agreement, which says that the data will only be used for MCBCL reports. Users will also be required to acknowledge in each report that DCERP is the data source.	MCBCL has MARDIS view-data-only privileges. MCBCL staff should contact the respective DCERP researcher who generated the data and consult with that researcher to request data and ensure appropriate interpretation of the data.
Non-DCERP SERDP and Environmental Security Technology Certification Program (ESTCP) researchers	Yes	Non-DCERP SERDP/ESTCP researchers have MARDIS view and download data privileges. Prior to downloading the data, users must agree to the Data Use Agreement. Before using the data, the user must inform the respective DCERP researcher, discuss collaboration, and receive approval from that researcher.	Non-DCERP SERDP/ESTCP researchers do not have access to data in MARDIS. The user must contact the respective DCERP researcher to request data, discuss collaboration and the specific use of the research data, and receive approval from that researcher before using the data.
RCC	No	Requests for data must be approved by the DCERP OSC, MCBCL, and the DCERP PI (in consultation with the DCERP researcher who collected the data). The DCERP Data Management Team will make the data available only to approved data requestors and will track all data releases.	RCC does not have access to data in MARDIS.

(continued)

Table 11-1. Data and MARDIS user-access privileges for DCERP research and monitoring data (continued)

Data Users	MARDIS Access	Monitoring Data	Research Data
General public	No	Requests for data must be approved by the DCERP OSC, MCBCL, and the DCERP PI (in consultation with the DCERP researcher who collected the data). The DCERP DMM will make data available only to approved data requestors and will track all data releases.	The general public does not have access to data in MARDIS.

11.4 Transitioning of DCERP2 Data

At the end of DCERP2, all the data and information collected and stored in MARDIS can be transitioned to end users in many different formats (e.g., SQL, geospatial, Microsoft Access or Excel) depending upon the user's needs. The RTI DCERP Team will investigate long-term Web-accessible databases that may be appropriate for DCERP data. For the most part, the MARDIS, SDSS framework, and model front-end Web-based interfaces have been or will be developed using technologies in line with current MCBCL–accepted technologies, and these interfaces can be distributed to MCBCL or other DoD installations if desired. However, it may be necessary to install, modify, configure, and customize these Web-based application tools; the respective DoD installation requesting the data would be responsible for working in their specific Web application environments.

As an alternative, MARDIS and the SDSS framework could continue to be hosted at RTI at a maintenance level after the end of the DCERP2 contract period**.** The DCERP Team will need to assess and determine the requirements of the end users, desires of SERDP, and the available resources throughout DCERP2 to select the preferred options and appropriately design and develop the SDSS framework and tools to ensure the most efficient use of resources. The team will reassess end user needs throughout DCERP2 to appropriately focus efforts and allow adjustments as needed as the program progresses.

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12.0 Measures of Success

The successful implementation of DCERP2 will foster a greater understanding of the basic science behind aquatic/estuarine, coastal wetlands, coastal barrier, and terrestrial ecosystems of MCBCL and of the interactions of these ecosystems within a military training environment as well as foster the development and practical application of decision-support tools and products. This scientific knowledge gained and the practical application of decision-support tools will aid in the long-term management and sustainability of coastal ecosystems, which will enhance and sustain DoD's military training mission.

Measurement of DCERP2's success will come from assessing whether the scientific outcomes and decision-support products are: (1) produced in a timely manner, (2) distributed widely to both the scientific community and natural resource managers, and (3) achieve their desired objectives by either being used by other researchers to build on and expand a scientific area of study or by being implemented by DoD installations to make installation management decisions. The major outcomes and products of DCERP2 can be grouped into two main categories and their completion dates for both the major programmatic and project-specific outcomes are summarized in **Tables 12-1** and **12-2**:

- Programmatic—These outcomes and products include administrative requirements such as delivering required documents on schedule and on budget, ensuring that the DCERP2 Web site is serving its design functions and is fully operational, meeting SERDP monthly, quarterly, and annual reporting requirements, and providing timely and effective feedback to MCBCL and other DoD installations, as well as outreach to state, regional, and local stakeholders.
- Project specific—These technical outcomes and products include those resulting from advancing the scientific knowledge or methods as a result of the research effort and through the development of decision-support tools and models for practical application at DoD installations. In some cases, these outcomes will provide information to address environmental issues that are currently impacting installation operations or that may impact installation operations under projected climate change scenarios. In addition, the majority of the DCERP2 research activities will provide the information necessary to gain a comprehensive understanding of ecosystem functions, including carbon cycling, nutrient cycling, and sediment transport, which will better prepare DoD to address future environmental issues under changed climate conditions. Key outcomes and products that are anticipated to result from each of the research projects are described in Chapters 5.0 through 10.0 of this Research Plan. We have also established several DCERP Team goals related to the development of project-specific science information and decision support tools that are highlighted in **Table 12-2**.

In addition, the DCERP2 Team has also set goals for several major technical outcomes at the program level, including:

1. Publication of 10 peer-reviewed articles per year of which two articles per year will be published in high-impact journals

2. Delivery of a minimum of 20 presentations per year at national or international scientific conferences
3. Support for a minimum of eight graduate students and have two master's and six doctoral dissertations published over the course of the 5-year program.

Table 12-1. Time line for programmatic and project-specific outcomes

Product/Activity/Outcome	Due Date
Final Monitoring Plan—Document activities included in the monitoring program for the Aquatic Estuarine and Coastal Wetlands Modules	May 2013
Final Research Project Plan—Describe the 13 research projects that will be conducted during the DCERP2 implementation period	May 2013
Annual meetings with MCBCL and other installation managers as appropriate—Ensure ongoing awareness of DCERP2 research activities and facilitate dissemination of information to installation management	Beginning March 2013 and ongoing
Annual Report—Provide official summaries of annual findings and activities that provide opportunities for outreach and collaboration with other researchers	March of each year (2014, 2015, and 2016)
Final DCERP2 Research and Monitoring Report—Summarizes significant research and monitoring findings of the 5-year DCERP2 program	November 2017
Functional Data and Information Management System—Supports the data management needs of DCERP2 and ultimately supports those of MCBCL's long-term, ecosystem-based data management	February 2013 and ongoing
Program Web sites—Maintain a secure password protected site to facilitate information sharing among DCERP2 Team members and MCBCL and other installations, as well as a public site to provide information to other federal, state, and local stakeholders and the general public	February 2013 and ongoing

Table 12-2. Time line for major project-specific outcomes

Product/Activity/Outcome	Due Date
Methodology for real-time through the hull continuous pCO_2 monitoring system (Research Project AE-4)	June 2013
GIS maps linking land use and land cover with carbon, nutrient, and sediment loadings from tributary streams (Research Project AE-5)	March 2015
GIS maps linking forestry and stormwater management to carbon, nutrient, and sediment loadings from tributary streams (Research Project AE-5)	June 2017
GIS maps of pCO_2 and water quality in the NRE from data flow (Research Project AE-6)	December 2016
Advance scientific methods or knowledge relating to the measurement of carbon sources, flux, and sinks in estuarine/coastal systems (Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5)	November 2017
Carbon budget for the estuarine/ coastal area of MCBCL (a summary product of Research Projects AE-4, AE-5, AE-6, CW-4, CW-5, and CB-5)	March 2015 (draft) March 2017 (final)
GIS data files and maps showing predicted fate of MCBCL marshes under different sea level rise scenarios (Research Project CW-4)	June 2017

(continued)

Table 12-2. Time line for major project-specific outcomes (continued)

Product/Activity/Outcome	Due Date
Carbon budget for the coastal marshes (Research Project CW-5)	June 2016
Maps of shoreline position, beach slope, width, dunes under various climatic and sea level rise scenarios (Research Project CB-4)	September 2017
Carbon budget for the barrier island (Research Project CB-5)	January 2017
Maps of barrier island morphological changes (Research Project CB-5)	September 2013, 2014, and 2015
Terrestrial Carbon Assessment Tool for estimating carbon storage associated with different forestry management practices (Research Project T-3)	November 2016
RCW DSS Tool for MCBCL with user's guide (Research Project T-4)	July 2014
RCW DSS Tool for Fort Bragg with user's guide (Research Project T-4)	March 2015
Presentation materials to conduct longleaf pine restoration workshop for installations in the Southeast United States (Research Project T-1)	October 2016
Final scaled historical climate data for archiving in MARDIS (Research Project CC-1)	December 2015
Final scaled future climate data for archiving in MARDIS (Research Project CC-1)	December 2016
Functional and easily accessible SDSS framework installed in MARDIS (Research Project TSP-1)	June 2014
Expanded and enhanced online version of ESM and user's guide (Research Project TSP-2)	May 2017
Decision-support tools and models ready for deployment to MCBCL and other DoD installations (Research Projects T-3, T-4, TSP-2, CB-4, and CW-4)	Beginning in 2014

The three previously listed metrics of timeliness of the products, distribution of products to target audiences, and application of the products can be used to measure the program's overall success and the success of individual research project-specific products. The easiest of the three metrics to measure is the timeliness of the products based on whether the projected dates of completion have been achieved. Distribution of the scientific information can be gaged by the number of articles published or presentations made to the scientific community, whereas distribution of the decision-support tools will be gaged by the number of installation users of the products. Finally, the measure of the successful application of the scientific knowledge can be gaged by the number of citations of the journal article in subsequent publications and, for the decision-support tool, by the degree of implementation of the tool at DoD installations based on the number of installations that adopt the tool.

The DCERP2 Team has defined decision-support tools as models, GIS data layers, maps, final installation reports, or other reports that can be helpful in making management decisions. An advantage to developing the SDSS as a Web application is that access and use of these decision-support tools can be quantified with Web site analytic—tracking not just visits to the site, but also the actual quantification of the frequency of tool use. Web analytics can be used between in-person meetings to improve engagement and inform mid-project training sessions. By maintaining a standing prototype Web application, as well as parallel development instances, we will know exactly how much we are engaging MCBCL users and DCERP researchers and will refine the standing application accordingly. In addition, for all of the decision-support tools

produced, the DCERP Team will obtain input on the usefulness and effectiveness of each product by providing a questionnaire to be completed by users of the decision-support item (**Appendix E**). This type of questionnaire can be customized to the type of product delivered and be distributed to users of the product at training sessions for each decision-support tool or circulated with the user's guide for the models and tools. MCBCL staff may want to fill out these questionnaires after they have conducted initial beta testing of a draft product and again after changes have been made to the final decision-support tool. Responses to the questionnaire will help the product developers improve later versions of the tool and determine the distribution and utility of the product. DCERP TSP Module staff will also be able to track the number of users accessing specific tools on the decision-support tool framework, once it becomes functional. In addition, a questionnaire will be used to determine how many individuals are interested in the tool and also how many of these users found the tool to be useful in making management decisions.