Annual Report for Period: 12/2009 - 11/2010
Submitted on: 10/01/2010
Principal Investigator: McGlathery, Karen .
Award ID: 0621014
Organization: University of Virginia
Submitted By:
Porter, John - Co-Principal Investigator

Title:
Long-Term Drivers, State Change and Disturbance on the Virginia Coast Reserve: LTER V

Project Participants

Senior Personnel

Name: McGlathery, Karen
Worked for more than 160 Hours: Yes
Contribution to Project:
Lead PI; research focuses on lagoon biogeochemistry and metabolism, seagrass restoration, and changes in marsh coverage in response to climate change (sea-level rise, storms)

Name: Wiberg, Patricia
Worked for more than 160 Hours: Yes
Contribution to Project:
Signatory PI; research focuses on lagoon hydrodynamics, sediment suspension and transport, and changes in marsh coverage in response to climate change (sea-level rise, storms)

Name: Porter, John
Worked for more than 160 Hours: Yes
Contribution to Project:
Signatory PI and Information Manager, research focuses on mammal population dynamics on barrier islands and GIS analysis.

Name: Anderson, Iris
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-PI, Subcontract to Virginia Institute of Marine Sciences; research focuses on lagoon biogeochemistry and metabolism

Name: Bachmann, Charles
Worked for more than 160 Hours: No
Contribution to Project:
Co-PI, Naval Research Laboratory; research focuses on hyperspectral remote sensing of mainland, barrier island, marsh and lagoon systems

Name: Berg, Peter
Worked for more than 160 Hours: No
Contribution to Project:
Co-PI, University of Virginia; research focuses on application of novel eddy correlation technique to subtidal systems to investigate benthic metabolism and groundwater fluxes

Name: Blum, Linda
Worked for more than 160 Hours: No
Contribution to Project:
Co-PI, University of Virginia; research focuses on the effects of sea-level rise on marsh accretion, and bacterial community structure and intertidal and subtidal systems

Name: Brinson, Mark
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-PI - Subcontract to East Carolina University; research focuses on state change in marsh ecosystems in response to sea-level rise

and disturbance

Name: Christian, Robert

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI - Subcontract to East Carolina University; research focuses on state change in marsh ecosystems in response to sea-level rise and disturbance

Name: D'Odorico, Paolo

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on modeling of alternate stable states in coastal lagoons

Name: Day, Frank

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to Old Dominion University; research focuses on plant community dynamics on barrier islands

Name: Dueser, Raymond

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to Utah State University; research focuses on small mammal genetics, population dynamics and predator-prey interactions on barrier islands

Name: Erwin, Russell

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia and U.S. Geological Survey, Biological Resources Division; research focuses on population dynamics of waterbirds

Name: Fagherazzi, Sergio

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to Boston University; research focuses on model lagoon hydrodynamics, coastal geomorphology, and marsh accretion/erosion in response to climate change (sea-level rise, storms)

Name: Fuentes, Jose

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on land-atmosphere carbon dioxide fluxes in marshes using tower-based eddy covariance technique

Name: Galloway, James

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on atmospheric nitrogen deposition, and nitrogen cycling between land, water, and atmosphere

Name: Macko, Stephen

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on using isotope geochemistry to understand trophic dynamics in subtidal systems, specifically in relation to state change to seagrass system. On leave working at NSF 2008-2009.

Name: Mills, Aaron

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on groundwater hydrology and nutrient fluxes via tidal streams into lagoons, in particular on importance of denitrification in the riparian zone and stream sediments

Name: Moncrief, Nancy

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, Virginia Museum of Natural History, collaborates with Co-PI Dueser; research focuses on small mammal genetics, population dynamics and predator-prey interactions on barrier islands

Name: Oertel, George

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to Old Dominion University; coastal oceanographer whose research focuses on reconstructing antecedent landscape of the VCR, hypsometry, and water residence times of lagoons

Name: Reyes, Enrique

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to East Carolina University; research involves creating a landscape model of state change for the VCR marsh-lagoon-barrier island system in response to climate and land-use change

Name: Scanlon, Todd

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; uses eddy covariance and laser techniques to study nitrous oxide and carbon dioxide fluxes from at the marsh-upland interface

Name: Shugart, Herman

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; terrestrial ecosystem modeling of the barrier islands

Name: Smith, David

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; leads SLTER program with Arthur Schwarzschild, research focuses on invertebrate and fish communities in the coastal lagoons

Name: Young, Donald

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-PI, Subcontract to Virginia Commonwealth University; research focuses on plan community dynamics on barrier islands, specifically on shrub expansion, invasive species and birds as agents of seed dispersal among islands

Name: Zieman, Joseph

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on salt marsh chronosequence on barrier island and on nitrogen dynamics in salt marshes

Name: Schwarzschild, Arthur

Worked for more than 160 Hours: Yes

Contribution to Project:

Research Site Manager, Co-PI, University of Virginia; leads SLTER program with David Smith

Name: Reidenbach, Matthew

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research focuses on sediment movements in the lagoon. Started 2008.

Name: Moore, Laura

Worked for more than 160 Hours: No

Contribution to Project:

Co-PI, University of Virginia; research on coastal geology and ecology using remote sensing. Started 2008.

Name: Challard, Margaret

Worked for more than 160 Hours: No

Contribution to Project:

Ph.D student working 2010-2015 with PI Mills on stream nitrogen loading and denitrification. Supported by a UVA fellowship 2010.

Post-doc

Name: Safak, Ilgar

Worked for more than 160 Hours: No

Contribution to Project:

2010-2012. Post-Doc for PI Wiberg, working on sedimentary geology in Hog Island Bay. Supported by UVA funding.

Graduate Student

Name: Battistelli, Joseph

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2004-2009). Advisor: Mills; working on the effects of physical arrangement of nitrifiers in spaces at the scale of the organism on nitrificaiton rates.

Name: Bissett, Spencer

Worked for more than 160 Hours: Yes

Contribution to Project:

MS & Ph.D Student (2005-2009). MS thesis (2005-2009): Avian dispersal of Frankia for successful nodulation of Myrica seedlings. Ph.D student (2009-2014); Working with PI Young, focusing on the physiological ecology of Myrica shrub expansion in coastal environments.

Name: Blecha, Staci

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student. (2006-2010) Advisor: Day; Thesis: Interisland variability in above and belowground plant biomass in interior marshes on the Virginia barrier islands

Name: Brantley, Steven

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2005-2009). Advisor: Young. Dissertation: Consequences of shrub encroachment: linking changes in canopy structure to shifts in the resource environment.

Name: Cole, Luke

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. Student (2005-2010), Advisor: McGlathery; working on the effects of seagrass restoration on nitrogen cycling and retention in coastal lagoons

Name: Conroy, Patrick

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student (2005-2007), Advisor: D. Smith; worked on the effects of macrophytes on invetebrate density and diversity in coastal lagoons

Name: Fennell, Jeremy

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student (2005-2007). Advisor: Young; Thesis: Phragmites australis patch characteristics in relation to watershed landcover patterns on the Eastern Shore of Virginia

Name: Flewelling, Samuel

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2003-2008), Advisor: Mills; Dissertation: The hydrological control of nitrate fluxes from groundwater to streams on the Eastern Shore of Virginia.

Name: Harbeson, Stephanie

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D Student (2003-2010). Advisor: Macko; Ph.D Dissertation: An investigation of nutrient transfer in a restored eelgrass, Zostera marina, meadow

Name: Hardison, Amber

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. Student (2004-2009). Advisor: Anderson; working on the influence of macroalgal blooms on biogeochemical processes in coastal lagoons using a dual isotope tracer and biomarker approach

Name: Haywood, John

Worked for more than 160 Hours: Yes

Contribution to Project:

MS Student; (2007-2009) working with Mark Brinson on effects of disturbance and stressors on ecological state change in tidal marshes at the VCR.

Name: Hume, Andrew

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2004-2007). Advisors: Berg & McGlathery; Thesis: Dissolved oxygen fluxes and ecosystem metabolism in an eelgrass (Zostera marina) meadow measured with the novel eddy correlation technique

Name: Kathilankal, James

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2004-2008). Advisor: Fuentes. Dissertation: Carbon and Energy Flow Dynamics in a Coastal Salt Marsh.

Name: Koopmans, Dirk

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2006-2011). Advisor: Berg; working on using the eddy correlation technique to measure groundwater fluxes into coastal waters

Name: Kunz, David

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2006-2008). Advisor:Brinson. Examining shorezone concept with respect to rising sea level. Includes comparisons of NC and Virginia.

Name: Lawson, Sarah

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2002-2008), Advisor: McGlathery & Wiberg; Dissertation: Physical and biological controls on sediment and nutrient fluxes in a temperate lagoon

Name: Marsh, Amanda

Worked for more than 160 Hours: Yes

Contribution to Project:

M. S. Student (2005 ? 2007), Advisor: Christian. Thesis: Effects on a salt marsh ecosystem following a brown marsh event

Name: McMillan, Brett

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2003-2008), Advisor: Day. Dissertation: Plant assemblage structure on 'pimple' dunes at the Virginia Coast Reserve Long-Term Ecological Research site.

Name: Michaels, Rachel

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2003-2009). Advisor: Zieman; working on the effects of Uca pugnax on pore water biogeochemistry and salt marsh productivity and stability in the context of sea-level rise

Name: Mozdzer, Thomas

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2004-2009), Advisors: Zieman & McGlathery; Dissertation: Variation in the availability and utilization of dissolved organic nitrogen by the smooth cordgrass, Spartina alterniflora.

Name: Naumann, Julie

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2002-2008). Advisor: Young. Dissertation: Linking physiological responses, chlorophyll fluorescence and hyperspectral imagery to detect environmental stress in coastal plants.

Name: O'Connell, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. student (2003-2009), Advisor: Shugart; Dissertation: Ecohydrology of Delmarva Peninsula barrier island forests and the application of lidar to measure and monitor forest structure.

Name: Poleto, Juliette

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2007-2009). Advisor: Anderson; Thesis: Nutrient Loading and System Response in the Coastal Lagoons of the Delmarva Peninsula.

Name: Reynolds, Laura

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. student (2006-2011). Advisors: McGlathery & Zieman; working on genetic basis of seagrass restoration success in coastal lagoons

Name: Robertson, Travis

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student (2006-2009). Advisors: Blum, McGlathery & Wiberg; Spatial patterns of bacterial abundance in a seagrass restoration site on the Eastern Shore of Virginia (USA). MA thesis. University of Virginia, Charlottesville, VA.

Name: Sahu, Parameswar

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2005-2007). Advisor: Scanlon; worked on nitrous oxide fluxes from marsh-upland ecosystems

Name: Vick, Jackie

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2005-2007). Advisor: Young. Thesis: Corticular photosynthetic dynamics for a coastal evergreen shrub: Myrica cerifera.

Name: Voss, Christine

Worked for more than 160 Hours: No

Contribution to Project:

M.S. student (2005-2007). Advisor: Christian; worked on network analysis of nitrogen cycling in coastal lagoons

Name: Weinmann, Richard

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2003-2008). Advisor: Shugart; worked on water budgets of coastal watersheds.

Name: Shafer, Justin

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2006-2010). Advisor: Day; Thesis: Interisland variability of dune plant community structure on Virginia's barrier islands

Name: Shiflett, Sheri

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2006-2008). Advisor: Young. Thesis: Avian seed dispersal on Virginia barrier islands: potential influence on vegetation community structure and patch dynamics.

Name: Mcleod, George

Worked for more than 160 Hours: No

Contribution to Project:

M.S. student (2006-2009) Advisor: Oertel; working on data interpolation for DEM's and comparing lagoon hypsometry and repletion in Hog Island Bay, Chincoteague Bay and Magothy Bay

Name: Gomez, Loreto

Worked for more than 160 Hours: No

Contribution to Project:

M. S. student (2006-2008) Advisor: Oertel; Thesis: Spatial analyses and repletion of Gargathy coastal lagoon.

Name: Clarkson, Charles

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D Student (2007-2012). Advisor: Erwin; working on waterbird population dynamics

Name: Priestas, Anthony

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. student (2007-2011), Advisor: Fagherazzi; working on marsh erosion and modeling feedbacks with vegetation

Name: Harrington, Christine

Worked for more than 160 Hours: No

Contribution to Project:

M.S. student (2007-2009), Advisor: Fagherazzi; working on field measurements of marsh erosion

Name: Mariotti, Giulio

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D. student (2008-2012), Advisor: Fagherazzi; modeling tide and wave dynamics in the coastal lagoons

Name: McLoughlin, Sean

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student (2008-2010). Advisors:Wiberg/McGlathery; working on measuring plant feedbacks controlling marsh erosion

Name: Gulbransen, Dana

Worked for more than 160 Hours: Yes

Contribution to Project:

PhD student (2008-2013). Advisor: McGlathery; working on effects of invasive macroalga, Gracilaria vermiculophylla, in subtidal seagrass and intertidal marsh ecosystems

Name: Romanowich, Jennifer

Worked for more than 160 Hours: Yes

Contribution to Project:

PhD Student (2007-2012). Advisor: Reidenbach; working on hydrodynamics in seagrass beds and effects on sediment suspension

Name: Funk, Clara

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student (2008-2010). Advisor: Scanlon; working on nitrous oxide fluxes from marsh-upland interface to atmosphere

Name: Webster, Kirby

Worked for more than 160 Hours: Yes

Contribution to Project:

PhD student (2007-2012). Advisors: Berg & McGlathery; working on measuring benthic metabolism in lagoons using eddy correlation system, with specific focus on state change from benthic algal to seagrass dominance

Name: Robertson, Wendy

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2006-2009). Advisors: Mills & UVA colleague Janet Herman; Thesis: Diurnal Variations in Nitrate Concentrations in the Cobb Mill Creek, VA

Name: Probasco, Paul

Worked for more than 160 Hours: Yes

Contribution to Project:

PhD student (2006-2012). Advisors: Herman & Mills; working on dentrification in riparian zones and stream beds in coastal watersheds

Name: Serebryakova, Alexandra

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student (2007-2008). Advisor: R. Christian; working in Coastal Resource Management at ECU on a long-term data set of vegetation cover in a salt marshes to use in GIS analysis.

Name: Rafferty, Emmett

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student (2007-2009); working with G. Oertel on modeling field-generated depth data to create a DEM of Magothy Bay.

Name: Carr, Joel

Worked for more than 160 Hours: Yes

Contribution to Project:

Ph.D student working with Wiberg and D'odorico (2008-) Modeling, hydrology

Name: Wolner, Catherine

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. Student. University of Virginia. (2008-). Advisor: Moore. Working on remote sensing of barrier island-lagoon system.

Name: Willis, Patricia

Worked for more than 160 Hours: Yes

Contribution to Project:

M.A. Student 2007-2009; Advisor Blum. Thesis:The effect of hydroperiod on surface elevation and sediment accumulation in Philips Creek Salt Marsh, Virginia, USA

Name: Kost, Elizabeth

Worked for more than 160 Hours: Yes

Contribution to Project:

VCU Biology MS student working with Don Young on studies on the shrubs on Hog Island 2010-2013.

Name: Rubis, Kathryn

Worked for more than 160 Hours: Yes

Contribution to Project:

VCU Biology MS student working with Don Young on studies on the shrubs on Hog Island 2010-2013.

Name: Greener, Jill

Worked for more than 160 Hours: Yes

Contribution to Project:

M.S. student working 2010-2013 with PI McGlathery on carbon cycling in seagrass.

Name: Taube, Sara

Worked for more than 160 Hours: No

Contribution to Project:

MS student working 2010-2013 with PI Wiberg on sediment distribution in salt marshes. Supported by a UVA fellowship 2010.

Undergraduate Student

Name: Curtis, Ben

Worked for more than 160 Hours: No

Contribution to Project:

2007 worked with PI Zieman and graduate student Thomas Mozdzer on nitrogen cycling in salt marsh communities.

Name: Hippert, Rachel

Worked for more than 160 Hours: Yes

Contribution to Project:

2007 worked with PI McGlathery on seagrass restoration.

Name: Long, Bridget

Worked for more than 160 Hours: Yes

Contribution to Project:

2007-2008 worked with PI's Blum, Christian and Brinson on marsh productivity database. BA Thesis 2009: Belowground production of the mixed high marsh plant community Spartina patens and Distichlis spicata. University of Virginia, Charlottesville, VA.

Name: Wiles, Cory

Worked for more than 160 Hours: Yes

Contribution to Project:

2009-2010 ECU undergraduate student contributions to Haywood marsh study (faculty advisor, Christian)

Name: Ellis, Stuart

Worked for more than 160 Hours: Yes

Contribution to Project:

2009-2010 ECU undergraduate student contributions to Haywood marsh disturbance study and independent study project on below ground organic matter (faculty advisor, Christian)

Technician, Programmer

Name: Overman, Kathleen

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician, Laboratory Manager, assists with long-term monitoring

Name: Boyd, David

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician, responsible for boat logistics and assists with long-term monitoring

Name: Buck, Christopher

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician, assists with long-term monitoring

Name: Fauber, Donna

Worked for more than 160 Hours: Yes

Contribution to Project:

Fiscal Technician

Other Participant

Research Experience for Undergraduates

Name: Richards, Joshua

Worked for more than 160 Hours: Yes

Contribution to Project:

Worked with graduate student Andrew Hume and PIs Berg and McGlathery on benthic metabolism in lagoons during 2007.

Years of schooling completed: Sophomore

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2007

REU Funding: REU supplement

Name: Smith, Chris

Worked for more than 160 Hours: Yes

Contribution to Project:

2007 Worked with Iris Anderson on lagoon nitrogen studies.

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other: Virginia Institute of Marine Sciences/ William & Mary

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2007

REU Funding: REU supplement

Name: Hondula, Kelly

Worked for more than 160 Hours: Yes

Contribution to Project:

2008 worked with PI McGlathery and graduate student Laura Reynolds on seagrass demographics

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2008

REU Funding: REU supplement

Name: Barry, Savannah

Worked for more than 160 Hours: Yes

Contribution to Project:

2008 REU worked with PI Reidenbach and graduate student Jenny Romanowich
on clam filtration and seagrass studies

Years of schooling completed: Sophomore

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2008

REU Funding: REU supplement

Name: Pendergrass, Jessica

Worked for more than 160 Hours: Yes

Contribution to Project:

2008 REU, worked with PIs Christian & Blum on genetics of salt marsh cordgrass, Spartina alerniflora

Years of schooling completed: Junior

Home Institution: Other than Research Site

Home Institution if Other: East Carolina University

Home Institution Highest Degree Granted(in fields supported by NSF): Master's Degree

Fiscal year(s) REU Participant supported: 2008

REU Funding: REU supplement

Name: Deemy, James

Worked for more than 160 Hours: Yes

Contribution to Project:

VCU undergraduate, worked with Don Young on shrub-related projects in 2010.

Name: Austin, Jared

Worked for more than 160 Hours: Yes

Contribution to Project:

VCU undergraduate, worked with Don Young on shrub-related projects in 2010.

Years of schooling completed: Freshman

Home Institution: Other than Research Site

Home Institution if Other: Virginia Commonwealth University

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2010

REU Funding: REU supplement

Name: Hoffman, Ava

Worked for more than 160 Hours: Yes

Contribution to Project:

UVA undergraduate, worked with Don Young on shrub-related projects in 2010.

Name: Mische, Paige

Worked for more than 160 Hours: Yes

Contribution to Project:

In 2010 worked with PI McGlathery and graduate student Dana Gulbransen on a project studying the ecological impacts of the invasive macroalage Gracillaria

Name: Olcott, Chris

Worked for more than 160 Hours: Yes

Contribution to Project:

In 2010 worked with PI Linda Blum in studies of the effects of fertilizer additions to below ground growth in saltmarshes

Name: Weakley, Meredith

Worked for more than 160 Hours: Yes

Contribution to Project:

In 2010 worked with PI Wiberg and graduate student Wolner on a sediment survey of Hog Island

Organizational Partners

USGS Biological Resources Division

Co-PI R. Michael Erwin is supported by USGS/BRD.

Department of Navy Naval Research Laboratory

Co-PI Charles Bachmann is supported by, and works at, NRL.

The Nature Conservancy

The Virginia Coast Reserve of the Virginia Chapter of The Nature Conservancy provides access to study sites and field research facilities. They are frequent collaborators on research projects. In 2010 they provided $75K to assist us in a joint purchase of LiDAR data for the Eastern Shore of Virginia.

NOAA National Environmental Satellite Data Information Service

NOAA installed an operates a Climate Reference Network station at our laboratory in Oyster, VA. The resulting data provides a valuable adjunct to LTER meteorological data.

Coastal Zone Management - Virginia

In 2007 a monthly public seminar series on environmental issues and research activities at the VCR-LTER was established with support by the Coastal Zone Management and Seaside Heritage Program of the Commonwealth of Virginia.

Virginia Museum of Natural History

Collaboration on GIS databases of predator locations involving PI's Dueser (USU), Moncrief (VMNH) and Porter (UVA)

Other Collaborators or Contacts

Dr. Robert Orth of the Virginia Institute of Marine Sciences has collaborated with us extensively on the seeding of seagrass beds at our research sites.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
See attached PDF file

Findings: (See PDF version submitted by PI at the end of the report)
See attached PDF file

Training and Development:
EDUCATION AND OUTREACH ACTIVITIES

The Virginia County (Northampton) that houses the VCR program is one of poorest counties in the Commonwealth. It has been our experience that the majority of primary and secondary school students on Virginia's Eastern Shore have never spent significant time on the water, and few have ever ventured into the marshes or mudflats. Consequently, our involvement with this audience is very important. We involve about 200 students each year in our Schoolyard LTER program, more than half of whom are representative of women and minority groups. The VCR Program has helped outfit the science faculty at the county high school with badly needed computers, specialized software (e.g., GIS software), portable GPS units, supplies, reference material, etc.

EDUCATION

The goals of our education program are to: 1) involve and excite local school kids and teachers in marine science in general, and specifically about their local coastal barrier island system; 2) reach a broader audience of students through web-based resources; and 3) train undergraduate and graduate students through VCR research and involvement in national and internal collaborations. Our site director, A. Schwarzschild, is our current Education and Outreach Coordinator and works closely with local teachers and students. He also has forged new education collaborations with our partners at The Nature Conservancy and colleagues at Chesapeake Experience. Schoolyard LTER ? Our Schoolyard LTER program is focused on local high schools in Northampton County and contains 3 main components: 1) curriculum development, 2) teacher training, and 3) high school student summer research internships.

1) Curriculum - We continue to work with science faculty at Northampton High School with the successful and popular Environmental Science II class. This class is built around water quality monitoring at 23 locations along the VCR, analogous to the water quality monitoring done as part of the VCR LTER data collection. Students learn basic laboratory techniques and are engaged in local environmental issues including: land use change and coastal eutrophication, sediment runoff, climate change and sea-level rise. SLTER support was used to purchase and maintain secchi tubes, thermometers, DO probes, refractometers, conductivity meters, and Smart Colorimeters used by the students to measure water quality parameters including: turbidity, temperature (water and air), dissolved oxygen, salinity, nitrate/nitrite, ammonia and dissolved phosphorus. Using digital cameras and hand held gps units, also purchased for the school with SLTER support, the students take pictures of the area surrounding their monitoring sites and collect latitude and longitude positional data. They use this information along with GIS software and computers supplied with SLTER funding to create GIS maps of their study sites in order to characterize the potential impacts of varying land use patterns (i.e. agriculture, development, nature preserve, etc.) on the water quality parameters being monitored. After quality control screening of the student data, it is entered into a long-term database so that the students can see how the data they collected compares to data collected by previous students. Students use these data to analyze long-term trends in water quality criteria along the VCR. At the end of each semester the students describe their methods and results in a PowerPoint presentation.

LTER staff and science faculty at Northampton High School also have developed a new high school science class on Coastal Ecology. This class is focused on the locally relevant human activities impacting the health, productivity and sustainability of coastal ecosystems along the VCR. We also make routine visits to Northampton High School to present guest lectures and assist in classroom instruction on such topics as gps technology, seagrass ecology and water quality in Earth Science, Chemistry and Marine Biology classes. Finally, we host field trips for a variety of visiting middle and high school classes and science groups ranging in size from 10-60 students. On average, 10 school groups visit the VCR each year from the VA Eastern Shore, Virginia Beach, Norfolk, Richmond and Charlottesville.

2) Teacher training our partnership with Chesapeake Experience continued during the Spring of 2010, with the completion of another teacher training/ professional development program, entitled Coastal Bay Ecology. This three day, short course provided instruction in ecology and environmental science topics centered around the Eastern Shore Barrier islands, but applicable to other VA ecosystems. Nine teachers from the Hampton Roads area participated in the program, held at the ABCRC facilities. A. Schwarzschild was the main instructor, with assistance from Jill Bieri from Chesapeake Experience. Instruction was provided through a variety of formal lectures, discussion groups, kayak excursions and two walking trips, one on the mainland and one across Hog Island. During these experiences, the participants were introduced to the varied ecosystems found on the VA Eastern Shore, the ecosystem services they provide, and the impacts of climate change, sea-level rise and human activities on these ecosystems. Another three-day workshop focused on ecology of migratory birds is scheduled for October.

3) Research internships ? Over the last 4 years we have involved 15 high school students in 8-week summer research internships. The program partners qualified high school students with graduate students conducting summer fieldwork at the VCR-LTER, and was initially motivated by a REHS (Research Experience for High School Students) supplement in 2007. Participation in this program is merit based and determined through a competitive application process. A. Schwarzschild provides program oversight and project coordination on site. Graduate students wishing to participate in the program are required to submit a proposal detailing their summer research objectives and indicating the role a high school intern would fill as a research assistant, along with a letter of support from their faculty advisor. All high school students wishing to apply are required to attend an orientation meeting in which they are introduced to the graduate students selected as mentors and presented brief summaries of the available research positions. The high school students then submit applications including: a prioritized list of the projects they would like to work on, a copy of their high school transcript, a letter of recommendation from at least one science teacher, and a an essay detailing why they wish to participate in the REHS program and what they hope to gain from the experience. They work under the direct supervision of their graduate student advisor on assigned tasks, and are also expected to conduct a related project of their own design. All participants gather for informal dinner meetings several times throughout the summer to discuss the progress of their projects. At the end of the summer each intern is required to make a public presentation of the results of their activities.

Six REHS interns were supported in 2007, 2 in 2008, 4 in 2009 and 3 in 2010. This summer The Nature Conservancy and Volgenau Foundation have again provided funding for 2 of the internships. Student projects this summer included an investigation of the ecological impacts of the invasive macroalgae G. vermiculophylla, assisting with our annual survey of seagrass restoration sites that examines the ecological implications of restoring eelgrass to the VA coastal bays, and a continuation of the SLTER water quality monitoring program to obtain summer time values to supplement academic year data taken by the Environmental Science II classes. The quality of the student involvement has been very high ? 2 students from last year were very motivated by their experiences, applied to and were accepted to UVA, joining a student from the summer of 2008 who is now a major in Environmental Sciences at UVA.

Undergraduate Research ? Each year the VCR LTER supports at least 2 undergraduate students with supplemental funding from the NSF Research Experience for Undergraduates (REU) program. Each student is partnered with a PI and graduate student as mentors for a 10- week field season. Students are based at the VCR site and assist with the ongoing research activities of their mentors, plus conduct a research project of their own. We expect students to present their work as a poster at the annual VCR LTER All Scientists meeting; UVA undergraduate students also typically make poster presentations at the annual Department of Environmental Sciences annual Graduate Student Symposium.

In addition to REU interns, we provide some support for undergraduate assistants in PI laboratories during the academic year. This allows students to continue their involvement in the LTER program and to get more deeply involved in research projects than a single summer allows. Undergraduate students have also been successful in obtaining their own funding for LTER research. For example, two students in McGlathery's lab applied with their graduate student mentors and received $5000 research grants from UVA to continue their LTER work. One of these students is now a graduate student in Pace's lab.

The VCR site serves as a platform for field classes that have been run by LTER PIs at the field site. Table 5 below includes a list of undergraduate and graduate courses that are taught everyone 1-2 years at the LTER site.

Table: Undergraduate and graduate level courses currently run by LTER PIs at the VCR

COURSE	INSTITUTION	ENROLLMENT
Methods in Aquatic Ecology	University of Virginia	15
Estuarine Ecology	University of Virginia	15
Aquatic Ecology	University of Virginia	15
Marine Invertebrates	University of Virginia	15
Marsh Ecology	East Carolina University	15
Barrier Island Ecology	Old Dominion University	15
Coast Geomorphology	Randolph Macon University	25
Biological and Ecological		

Conservation in
Chesapeake Bay   University of Virginia   20

Graduate Training - Graduate student training is an important part of our education mission. Each year we provide support for approximately 20 students who conduct their research at the VCR LTER site; about half of these students work with UVA PIs and the other half work with VCR PIs at partnering institutions. All completed M.S. and Ph.D. theses are uploaded on our website: http://www.vcrlter.virginia.edu/thesis/thesis.html. Thus far during this funding cycling, 18 M.S. and Ph.D. theses have been completed.

Outreach Activities:

The LTER has developed links with conservation organizations, and local, state, and federal agencies through outreach efforts. The LTER has a strong partnership with The Nature Conservancy (TNC), and through this we address the important management and conservation problems that face the region. This puts us in an excellent position to provide a solid, scientific foundation for making decisions related to planning, management, and ecosystem restoration. A good example of this is our collaboration with The Nature Conservancy (and VIMS) on the seagrass restoration in the VCR coastal lagoons. We provide key data (e.g., lagoon bathymetry) that facilitates the restoration program, and we also provide logistical support for the volunteer-driven TNC efforts on seagrass and oyster restoration.

An important part of outreach to the local community is a public seminar series hosted by the LTER and ABCRC, with monthly presentations by scientists working on the coastal barrier system. A. Schwarzschild runs this series, which began in Fall 2007 supported by a partnership between the NOAA Coastal Zone Management Program/Seaside Heritage Program, the Department of Environmental Sciences and the VCR-LTER. The purpose of the seminar series is to educate the local public about environmental research, management and restoration projects being conducted on the Eastern Shore of Virginia. Past seminar topics covered have included, seagrass ecology, barrier island history, the seaside heritage program, oyster catcher ecology, sea turtle ecology, habitat restoration in support of migratory song birds, the VA natural heritage program, salt marshes and sea level rise, oyster restoration, seagrass restoration, hypoxia and dead zones in the Chesapeake Bay, impacts of climate change on the Eastern Shore, stream and catchment hydrology, and the ecology of barrier island upland communities.

In addition to school classes we have also hosted groups of the UVA Ecology Club, the VA Aquarium Mentoring Young Scientists program, the Eastern Shore chapter of the VA Mater Gardeners and Master Naturalists programs, and the Virginia Association of Biological

Information Management

We continue to fully participate in LTER Network activities, such as Ecotrends, ClimDB, SiteDB, all-site bibliography and personnel directory. All metadata are available as high-quality Ecological Metadata Language documents that are available from the LTERNET Metacat server. Our web server has provided over 5 Terabytes of information and responded positively to formal 630 data requests (See the 'Contributions to Resources for Research and Education' section for detailed statistics on data access and use.).

In addition to formal datasets, the VCR/LTER provides near real-time data in graphical and tabular forms to the scientific and local community. During 2009 and 2010 we upgraded our tide station in Oyster VA to use a more reliable tide sensor using radar to detect changes in tide levels. In August 2007 we completed installation of a network of ten water-level monitoring stations on Hog Island, Virginia. The new stations use 900 MHz serial wireless communications to connect to the Wi-Fi network installed on the island in previous years. This upgrade replaces a mix of mechanical well monitors (using paper chart recorders) and electronic recorders (that required manual monthly dumps). The upgrade has dramatically cut data outages, because problems are identified at UVA, using graphs that are produced three times per day, and fixed before they become serious. Additionally, we have added an additional tide station and a flux tower to our wireless network.

We have begun a move towards Linux from the proprietary UNIX (SunOS) we use for servers. In this context, we worked on the implementation of virtual machines on a variety of low and high-end hardware. On the high end, in spring 2008 we purchased an eight-processor Linux server that has begun to replace the VCR/LTER web server (currently running on a Sun workstation). Currently the main web page and MYSQL database have been moved to the new server, but specialized functions are still provided by the old server. On the low-end, we have used PCs that were discarded due to low speed or lack of memory required to run new versions of Windows to install Linux variants which are much less consumptive of resources. These machines have been used to take over primary electronic data collection tasks using the wireless network at the ABCRC. By using VNC (Virtual Network Console) all the machines can be administered using graphical tools from any place in the world. Graphs and tables, along with updated data from these systems are placed on the public web several times each day.

International Outreach

The VCR/LTER has been active in international outreach, particularly in the East-Asia Pacific region in the area of Information Management and in Italy, focusing on comparisons of coastal systems.

We have continued our work with Taiwan Ecological Research Network (TERN) and participated in an East-Asia Pacific ILTER Urban Forestry and Information Management Workshop in Seoul Korea in the fall of 2007. In 2009 and 2010 we helped lead two workshops aimed at applying advanced ecoinformatics techniques to ecological data. Week-long workshops in Taiwan (2009) and Malaysia (2010) used Ecological Metadata Language and scientific workflow tools (e.g., Kepler) to analyze data from permanent plots at International LTER sites.

Three presentations were given in Italy in 2008 by Sergio Fagherazzi and Enrique Reyes to researchers working in the Venice lagoon and in the Po River delta, the two areas are part of the Alto Adriatico Italian/European LTER:
- Long-Term Environmental Change at the Virginia Coast Reserve, Department of Environmental Sciences, Parma University, Italy June 2008
- Long-Term Environmental Change at the Virginia Coast Reserve, ISMAR-CNR, Venice, Italy, June 2008 - Long-Term Environmental Change at the Virginia Coast Reserve, Department IMAGE, University of Padua, Italy, June 2008

One Ph.D. student from Boston University (Anthony Priestas) spent a month at the University of Padua in the summer 2008 funded by the LTER International Supplement. The student participated in field measurements in the salt marshes of the Venice Lagoon. Another Ph.D. student from Padua (Alberto Canestrelli) spent six months at Boston University working on modeling of intertidal hydrodynamics, and part of the dissertation of Mara Tonelli (PhD, University of Udine Italy) was based on the application of wave models to the VCR marshes.

Mark Brinson represented the VCR LTER at the Man and the Biosphere in the winter 2008. He presented a poster entitled 'Research and Education at the Virginia Coast Reserve Long-Term Ecological Research Project.'

Iris Anderson, Robert Christian and Karen McGlathery have begun a collaboration with Victor Camacho-Ibar on nitrogen cycling and ecosystem functions and hydrogeomorphology in San Quentin Bay, Mexico.

Network Activities

Bob Christian has collaborated with the LTER Network Office on a social network analysis project to evaluate the way the LTER network is coalescing as a network. They are using inter-site joint publications as the variable.

John Porter has collaborated with other information managers on the creation of a controlled vocabulary for LTER data sets that was accepted by the LTER Executive Board in 2010.

During 2010 the VCR/LTER participated in the MIRADA workshop, aimed at providing an environmental context for microbial genetics measurements, providing both microbial samples and associated environmental measurements.

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Web/Internet Site

URL(s):

http://www.vcrlter.virginia.edu

Description:

This is the main web site for the VCR/LTER project and serves as the "file cabinet" for all aspects of the project. The web site provides access to data, interactive maps, images, bibliographic listings and full-text of student theses and dissertations.

Other Specific Products

Product Type:

Data or databases

Product Description:

The VCR/LTER publishes over 120 datasets using standard Ecological Metadata Language metadata. In addition to the VCR/LTER web site they are available through the national LTERnet, KNB, NASA Mercury and the National Biological Information Infrastructure data catalogs.

Sharing Information:

Data is made available to all researchers online. Researchers fill out a data license indicating their agreement with LTER policies on proper acknowledgment and are immediately granted access to the requested data.

Details on this data use can be found in the "Contributions to Resources for Science and Technology" section of this report.

Product Type:

Audio or video products

Product Description:

The VCR/LTER has provided a variety of video products, including interviews of seagrass researchers, field trips, data collection procedures and formal presentations on educational and video sharing sites such as SciVee and COSEE.

Sharing Information:

A compilation of these can be viewed at:
http://amazon.evsc.virginia.edu/video/scivee.html .
Additionally, brief video clips for inclusion in presentations are available at: http://amazon.evsc.virginia.edu/video .

Contributions

Contributions within Discipline:

We have continued to contribute to the understanding of coastal systems through our efforts in studying the effects of sea level rise (which involves developing detailed understandings of the processes that effect accretion in marshes - both physical and biotic, and encroachment into uplands), storm disturbance, coastal eutrophication, seagrass restoration, controls on plant production, determinants of faunal biogeography in an island system, and prediction of future state change.

WATERSHEDS AND LAGOONS

Coastal eutrophication has been recognized as an increasing global problem. Symptoms of eutrophication include blooms of phytoplankton, which when they decompose may reduce available oxygen in the water; blooms of harmful algae that are toxic to fish, shellfish, and occasionally humans; blooms of macroalgae that cause die-backs of seagrasses which are vital to maintaining populations of many fish and crabs; and increasing anoxia. Eutrophication generally results from export of excess nutrients from land, in particular nitrogen. Sources of nitrogen include agriculture, septic tanks, waste-water treatment plants, industry, and atmospheric deposition of nitrogen derived from automobiles, power plants, and other industrial sources. Nitrogen from these sources is most often transported to coastal waters in shallow groundwater and in surface water
runoff.

Coastal lagoons are common features of the land margin, especially along the East and Gulf coasts. We have hypothesized that these lagoons play an important role in retarding and transforming nitrogen during transport from land to the sea. Our study of the Virginia Coast Reserve lagoonal system has been designed to: (1) measure groundwater sources of nutrients to the lagoon; (2) measure rates of biological processes that remove or transform nitrogen in the waters and sediments of the lagoon; (3) compare rates of nitrogen cycling processes to physical transport across and out of the lagoon in order to determine whether the nitrogen remains in the lagoon for a sufficient length of time to allow biological processing to occur.

Our modeling and process studies have indicated that the VCR lagoons receive relatively low inputs of nitrogen from the coastal watersheds compared to more eutrophic lagoons in the mid-Atlantic. This is true in part because population densities are relatively low in the VCR watersheds and there is little point-source agriculture (e.g., chicken farms). Much of the fertilizer nutrients that enter the groundwater is removed by an intact riparian zone and by stream sediments, both of which are active sites of denitrificaiton. Nitrogen that enters the lagoon is rapidly removed by both benthic macro- and microalgae. As a result, there is little flux of nutrients from the sediment to the water column and phytoplankton
concentrations are typically low. Blooms of macroalgae that occur in early summer typically crash during mid-summer, releasing much of the nitrogen as dissolved inorganic and organic nitrogen. The sediments act to rapidly remove the nitrogen released to the water column by a combination of mechanisms including immobilization by benthic microalgae and coupled nitrification - denitrification. We are currently attempting to determine how the nitrogen released during decomposition of the macroalgal bloom is partitioned between the various potential consumptive mechanisms. Our most recent research has shown that nitrogen is retained in the sediments for a longer time than would be expected by turnover of plant biomass because nitrogen 'shuttles' back and forth between bacterial and benthic microalgal pools.

Our conclusions regarding the importance of macroalgae in influencing the dynamics of nutrient movements within the lagoon helps to explain the role of the lagoon as an active mediator between mainland nutrient sources (e.g., agricultural fields) and the coastal ocean. The recent discovery that the dominant macroalga in the lagoon is an exotic (rather than its native congener), will be important to understanding long-term changes in the lagoon's characteristics.

Shallow bays in the VCR and elsewhere along the US Atlantic coast experienced a dramatic state change in the 1930's when a single storm decimated seagrass populations already decimated by disease. Until recently, VCR lagoons persisted in an alternate, algal-dominated state. Recent field work and modeling showed that high turbidity events in the VCR were episodic and wind driven and we estimated that average light availability over 65-87% of the lagoon bottom is suitable for seagrass recolonization (Lawson et al., 2007). Beginning in 2007, in collaboration with Robert Orth from the Virginia Institute of Marine Science, we began to restore seagrass in a 509 acre 'set aside' we have obtained from the Virginia Marine Resources Commission in our primary lagoon study site, Hog Island Bay. The set-aside was renewed in 2010. The restoration builds on our 10-year database on patterns and process in Hog Island Bay in the absence of seagrass, and gives us the opportunity to determine experimentally the ecosystem-level effects of a rapid state change back to the original seagrass-vegetated state.

The seagrass restoration project contributes to important theoretical and applied problems related to coastal ecosystems. On a more theoretical level, it directly addresses questions related to ways in which biotic feedbacks modify the response to of the systems to
external drivers by maintaining a stable state or facilitating a change to another state. In the lagoons, the biotic feedbacks that influence the success of seagrass establishment and growth include the vegetation effects on reducing sediment resuspension and the potential facilitation of seedling establishment by benthic fauna. In addition, a state change from algae to seagrass will have system-wide impacts because these benthic primary producers play key roles in determining rates and patterns of primary production and nutrient cycling and in trophic interactions. Variations in the rates and dominance of these processes as primary producer communities change, will ultimately determine the fate and retention of watershed nutrients as they pass through the lagoon 'filter' to the open ocean. As the community shifts to seagrass dominance, we expect the retention time of watershed N in the lagoon to increase. In addition, there may be landscape-level
feedbacks where stabilization of the lagoon sediments by seagrass restoration may reduce the availability of sediments for marsh accretion. This may have implications for the ability of marshes to keep pace with increasing rates of sea-level rise.

On a more applied level, the experimental approach we are taking to establishing and monitoring the seagrass plots in Hog Island Bay, a relatively pristine system, will provide important baseline information for restoration projects undertaken in more highly impacted systems. To put our results on the new seagrass beds in context, we have established a chronosequence by augmenting the Hog Island Bay meadows with those recently seeded (1-7 yr old) using the same technique in South and Spider Crab Bays, just south of Hog Island Bay, and a natural meadow in South Bay, which is at least 10 years old.

We have begun measurements of productivity, nutrient cycling, algal density/diversity, faunal densities/diversity, flow conditions and sediment resuspension in the new seagrass beds; a subset of these measurements are being made at sites along the seagrass chronosequence. In addition, we are quantifying macroalgae epiphytes, benthic microalgae, benthic invertebrates and fish through the seagrass recolonization period to assess changes in faunal abundance and diversity.

Surface Elevation Tables (SETs) are used at numerous VCR/LTER research sites to quantify changes in sedimentation and subsidence that ultimately will determine the fate of marshes in the face of sea level rise. These baseline measurements at different marshes are then used in association with process-based studies focusing on the processes such as transport of material through tidal flooding, burial of organic matter and its decomposition, marsh plant production (both above and below ground) and the feedbacks on sedimentation rates, bioturbation by crabs, and even herbivory by insects to develop models aimed at predicting changes in marshes over the coming decades. Our results indicate that the on mainland marshes, the rate of accretion is generally keeping pace with sea level rise, and that specific rates are position dependent, with the upper marsh receiving less input. Results in the lagoon marshes suggest that sea-level rise may be exceeding the ability of the marshes to keep up.

Recent work on microbial communities in the marshes and tidal creeks at the VCR (as well as 9 other coastal systems as part of a cross-site comparison study) contribute to our understanding of what abiotic and biotic factors determine microbial community structure and the scales over which microbial communities vary. Linking information about variation in microbial community structure and microbially controlled processes (e.g., nitrogen-fixation), will allow prediction of how critical ecosystem processes will be affected by disturbance. (Blum)

BARRIER ISLANDS

The results our work to date have increased our understanding of dynamic vegetation changes and their causes in coastal barrier island ecosystems. We have established that landscape position is they key factor controlling the pattern of plant community development and production on the islands, with distance from the shore (and susceptibility to salt spray and overwash disturbance) and elevation (and distance to the groundwater) as the important factors defining landscape position. New cross site and cross species analyses are linking meteorological and climatological drivers to plant production. This analysis is revealing complex patterns showing that all species and sites do not respond similarly to meteorological drivers.

To date, one of our most significant contributions has been to demonstrate that biotic interactions are very important in the coastal environment of the VCR, which we often define as being dominated by physical parameters. We have demonstrated the importance of the presence of a soil actinomycete, Frankia, for the successful establishment of Myrica cerifera. Myrica usually is usually the first woody species to establish in these environments. Once established, Myrica rapidly forms extensive thickets in coastal environments. These thickets are excellent indicators of island stability and may be precursors to the establishment of maritime forest.

Twenty years of research in shrub thicket ecology has provided excellent background and experience for studying the potential for invasive species in coastal environments. This is especially true for the weedy grass, Phragmites australis. Populations of Phragmites are establishing and rapidly expanding throughout the VCR as well as in coastal environments of the mid-Atlantic region. Phragmites often establishes in habitats similar to those of shrub thickets. The detailed understanding of the ecology of P. australis with respect to nutrient uptake and competitive relationships provide a basis for predictions regarding its ultimate distribution.

Studies of island-dwelling organisms, such as those underway at VCR, have long played an important role in testing ecological and evolutionary theory about patterns and processes related to distribution and abundance of species and genetic variation within and among natural populations. The Virginia coast is a highly dynamic, frequently disturbed landscape, and the Virginia barrier islands are the only undeveloped barrier system on the Eastern seaboard. As such, this system affords a unique opportunity to study phenomena associated with island systems, including fragmentation of habitats and populations, local extinction, dispersal, and colonization, which are also important issues in conservation biology. The relative isolation of the islands also provides an excellent opportunity for assessing the roles of parasitism and disease in overall vertebrate population dynamics.

The role of mammals and predation on the large waterbird community has been chronicled, and continues to show annual changes. Managing foxes and raccoons at selected barrier islands has dramatically enhanced the reproductive success of a number of species of ground-nesting waterbirds, including the federally threatened piping plover. Nonetheless, fewer colonies (but larger) of nesting terns (4 species) and black skimmers have consolidated onto fewer islands over the past decade compared to the distribution pattern in the 1970-80s.

SYSTEM-WIDE INTEGRATION

One of the questions we have begun to address is what the composition and structure of the VCR landscape patterns will be in the future and what processes will drive ecological states changes in those landscapes. We are using two types of models to synthesize our long-term monitoring and experiments and shorter-term process studies to address the causes and consequences of state change on the VCR landscape. The goal of this modeling effort is to be able to predict the non-linear and threshold responses of the VCR ecosystems to long-term environmental change and short-term disturbance events.

Landscape modeling: Previous VCR efforts focused on developing various conceptual and mathematical models of limited parts of the landscape and demonstrated a need to integrate the diverse spatial and temporal information into a regional model for the VCR ecosystem. In response, we have begun developing a mechanistic, process-based ecological basin model to understand the coupling between hydrologic and geomorphic free surface changes and the ecological responses of state change on scales that vary from local to the entire coastal reserve. The model integrates physical and ecological processes over a grid of landscape cells. Each cell contains a unit ecosystem model that represents a certain habitat type and incorporates location-specific algorithms to quantify fluxes of materials between cells. Hydrodynamic, soil, and plant productivity modules are dynamically coupled via a unit ecosystem model (Reyes et al. 2000, 2004). The model also contains a habitat-switching module that tracks habitat characteristics for each land parcel within the model boundary, such that long-term processes and ecological responses can be examined.

An important asset to support landscape modeling is LiDAR data obtained during 2010 that provides a highly accurate (18 cm or better) elevation data for all of Northampton and Accomac Counties. This data was purchased by the VCR/LTER and The Nature Conservancy under the condition that all the data be made available to other researchers and to the general public.

We have used NOAA data to assess changes in land use/land cover in the VCR watersheds for the last 20 years. For all the VCR watersheds, we found that changes over time were typically very small, illustrating how little development pressure the VCR watersheds receive relative to other watersheds in the mid-Atlantic region. These watersheds can be compared with more developed watersheds in the mid-Atlantic region to compare the effects of different levels of development and eutrophication on coastal bay processes.

Our modeling of the evolution of barrier islands reveals that substrate composition, followed by sea-level rise rate, and sediment supply rate, is the most important factor in determining barrier island response to sea-level rise. These results suggest that although barrier island migration rates may increase significantly in the future, barrier islands with sufficiently thick and sandy substrates are likely to persist as long as landward migration is not impeded and shoreface erosion can occur quickly enough to liberate sand volumes necessary to maintain subaerial exposure. We are now building on this work to address the biotic feedbacks of island vegetation structure on the island geomorphodynamics.

Network modeling: Ecological network analysis is an effective tool for evaluating both the biogeochemical and trophic consequences of state We have used ecological network analysis at the VCR to evaluate nitrogen cycling within mainland marshes (Thomas and Christian 2001) and the lagoon (Voss et al. 2005) and also the food web structure of salt marsh ponds (Dame 2005). We are expanding this effort to include states across the entire VCR landscape to provide assessments of nitrogen cycling relative to the contributions of biomass storage, recycling, physical and biotic exchanges. In addition, co-PI Bob Christian has furthered the use of network analysis within the ecological community via publications and workshops sponsored by NSF biocomplexity and the LTER network. Several groups within and beyond the LTER network have begun using the tools.

Contributions to Other Disciplines:

The studies conducted by the VCR/LTER are inherently interdisciplinary or multidisciplinary. Our studies are being performed by an interdisciplinary team of ecologists, hydrologists, biologists, and physical oceanographers. When such collaborations take place, it is not unusual that each each group of scientists will gain greater insight into problems that may not be recognized within their own discipline.

Additionally, our workshops on network analysis have exposed a broad group of scientists to the field or network ecology. Social scientists have also used network analysis, and one of our accomplishments has been to bring awareness of the different approaches to the broader group.

Research on ecological information management has included computer scientists. The challenges posed by ecological data provide opportunities for innovation in computer science. Our work with development of wireless sensor networks, and processing of the massive data flows they can generate, contributes to better defining the cyberinfrastructure challenges that will confront us in coming decades. During 2006-2007 the VCR Information Manager participated in the Cyberinfrastructure-Core group and we hosted a modeling workshop that focused on the cyberinfrastructure needs of advanced ecological modleling. He has continued work as an elected member of the LTER Network Information System Advisory Committee.

Through our support and collaboration with resource economist Stephen Swallow at the University of Rhode Island, we have helped develop new understandings of the tradeoffs involved in environmental conservation. Some recent presentations include:
- 'Consumer Willingness-to-Pay for Coastal Restoration ? Ecosystem Services and Individualized Pricing' -- Presented at International Institute of Fisheries Economics and Trade Conference. Montpellier, France (2010)
-'Selling Ecosystem Services as Public Goods to Consumer-Beneficiaries: An Auction Experiment on Restoration of Seagrass and Bird Habitat in Virginia Coastal Reserve' --Presented at The Soil and Water Conservation Society Conference. St Louis, Missouri (2010)
-'Generating Revenues from WTP for Ecosystem Restoration: An Auction Experiment on Public Goods' Presented at The Agricultural & Applied Economics Association Conference. Denver, Colorado (2010)

Contributions to Human Resource Development:

As can be seen from the number of graduate and undergraduate students listed on our participant list, this project provides abundant opportunities for training. Moreover, the inter- and multi-disciplinary nature of the research teaches the students how to operate in a collaborative environment. Each year, the VCR LTER supports approximately 20 graduate students who conduct their M.S. and Ph.D. projects at the VCR site.

Our SLTER program, and related activities, have helped introduce scientific concepts to K-12 students. All high school students take an LTER-based course before they graduate, and some take more than one course.

Contributions to Resources for Research and Education:

The VCR/LTER web page is widely used. Between the start of the current grant cycle and late August 2010, over 5.1 terabytes of information have been downloaded by over 700,000 distinct clients (http://www.vcrlter.virginia.edu/analog/Nov2006toAug2010/). On a daily basis an average of over 3.7 gigabytes of information are transferred. However, such raw statistics can be misleading because search engines (e.g., Googlebot) make up a large number of the 'hits.' More telling is that users came from over 190 different countries or international organizations (as shown by network domains). Countries with over 100,000 requests included India, Switzerland, Netherlands, Czech Republic, Russia, Canada and China, and 32 additional countries each had over 10,000 requests. Similarly the large number of distinct hosts (550,000) reflects a wide user community.

A more important measure of impact is datasets that are formally downloaded. These formal data requests require users to fill out a data license form. During the current grant, we have had 638 formal data requests. Not surprisingly, roughly one half of the data requests came from faculty and students in some way associated with the project (47%), almost entirely for research purposes. However, researchers and students not associated with the VCR/LTER requested 335 datasets, most (59%)were for research use, with the remaining 41% for educational uses (class projects, etc.).

Through our Schoolyard LTER supplement, we have been able to provide equipment such as global positioning system, taxonomic guides and water chemistry analysis kits and equipment to the Northampton Co. VA Public Schools. This program now extends from grades K-12 through the Northampton Co. elementary, middle and high schools.

Work that we are currently doing at the VCR is of much interest to the Department of Environmental Quality of the State of Virginia, and in particular to the Water Conservation Districts located on the Eastern Shore. The major source of nitrogen to VCR coastal lagoons is agriculture. Proper management of agricultural activities and fertilization practices requires an improved understanding of nitrogen losses to the coastal lagoons via groundwater and surface water runoff.

PI Reidenbach and his students have developed new instrumentation to conduct underwater particle image velocimetry (commonly known as PIV). This system uses a laser and optics to create a laser light sheet. This light illuminates suspended particles in the flow and, using a digital camera, particle motion is recorded. With the recent development of laser diodes, powerful yet energy efficient lasers can be placed in water tight housings and submersed underwater. The system developed uses a 250 mW laser with a wavelength of 532 nm (green light). A waterproof housing has been designed to hold both the laser and optics used to spread the beam into a narrow, yet wide sheet. The housing is sealed and the laser is pulsed on and off using a magnetic switch controlled from outside the housing. Imaging of the illuminated particles is done using a high definition camcorder (Sony HDR-HC7) that can obtain images up to 60 frames per second. Both the laser and camera are attached to a rigid frame and can be deployed in the coastal ocean where suspended sediment particles are tracked.

PI Berg has developed a new instrument to measure sediment-water column fluxes in aquatic habitats, based on eddy correlation. The new technique measures fluxes under true in situ hydrodynamic and light conditions.

Contributions Beyond Science and Engineering:

We have engaged in studies designed aid the conservation of avian fauna and better understanding of the extent and change in exotic plant species in the coastal zone in conjunction with The Nature Conservancy.

Knowledge of the relationship between land use, nutrient contamination of groundwater, groundwater export of nutrients to coastal lagoons, and the fate of nutrients within lagoons will be of benefit to state and federal agencies charged with managing coastal resources. This knowledge will be especially important given the ongoing return of seagrasses to large areas of the coastal bays, from which they have been absent for over 70 years. The VCR lagoons are also a model system to understand the important role of plants in mediating nutrient export from coastal watersheds to the open ocean (McGlathery et al. 2007).

Linking information about variation in microbial and fungal community structure and fungal and microbially controlled processes (e.g., nitrogen-fixation, decomposition), will allow prediction of how critical ecosystem processes will be affected by disturbances due to human activities in the coastal zone.

Activities with the UN programs on observing global change along coastal ecosystems have significance for broad aspects of public welfare and environmental protection. One of the greatest potential contributions from PI Christian's work at the VCR LTER are to the global observing systems and the ability to detect and assess global change in coastal ecosystems. The Coastal Module of GTOS is being developed to complement the Coastal GOOS program and highlights terrestrial, wetland, freshwater, and transitional ecosystems. Further and importantly it explicitly includes socio-economic components of global change in the coastal zone. This is the first significant introduction of the human dimension into the global observing systems.

Finally, we continue the monthly public seminar series begun in the summer of 2007 on environmental issues and research activities at the ABCRC was established with support from the Coastal Zone Management and Seaside Heritage Program of the Commonwealth of Virginia. During the seminars, VCR/LTER researchers provide information on their research to the general public.

Conference Proceedings

Sundback, K;McGlathery, KJ;Anderson, IC, Lagoons and shallow bays as filters in the coastal ecosystem, "MAY 27-29, 2008", 2008 IEEE/OES US/EU-BALTIC INTERNATIONAL SYMPOSIUM, : 516-519 2008

Christian, RR;Brinson, MM;Dame, JK;Johnson, G;Peterson, CH;Baird, D, Ecological network analyses and their use for establishing reference domain in functional assessment of an estuary, "APR, 2008", ECOLOGICAL MODELLING, 220 (22): 3113-3122 Sp. Iss. SI NOV 24 2009

Franklin, RB;Mills, AL, Importance of spatially structured environmental heterogeneity in controlling microbial community composition at small spatial scales in an agricultural field, "AUG, 2007", SOIL BIOLOGY & BIOCHEMISTRY, 41 (9): 1833-1840 SEP 2009

Special Requirements

Special reporting requirements: None
Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

VCR-LTER ANNUAL REPORT 2009-2010 - ACTIVITIES

Long-term Data sets

We continue our collection of long-term data sets that constitute the core of our long-term monitoring. These are summarized in the table below:

Long-term data set	Core Area	Research Question
Groundwater levels	nutrients, disturbance	A, B
Meteorology	disturbance	A, B, C
Tides	disturbance	A, B, C
Lagoon water quality	organic matter, nutrients	A, B, C
Watershed stream nutrients/discharge	organic matter, nutrients	B
Marsh vegetation (EOYB)	primary production	A, C
Lagoon vegetation	primary production	A, C
Island vegetation	primary production	A, C
Sediment elevation tables	organic matter, disturbance	A, B
Mammals	trophic dynamics	A
Colonial waterbirds	trophic dynamics	A (data set maintained by VCAP)
Lagoon fish	trophic dynamics	A (initiated 2009)
Flux tower	nutrients, primary production	A, C (initiated in 2008)

Specific details about the location of sampling sites and the frequency of monitoring are listed below:

- *Water quality transects* in 2 focal lagoons, Hog Island Bay and South Bay, including analysis of light, dissolved oxygen, temperature, total suspended solids, inorganic and organic nutrients, and chlorophyll.
- *Stream water chemistry* is obtained quarterly from 4 tidal creeks.
- *Stream discharge* from 4 tidal creeks: Cobb Mill Creek, Bundick's Creek, Phillip's Creek, and Tommy's Ditch. These will be used to develop rating curves and estimates of nutrient discharge to coastal lagoons.
- *Meteorological stations* at Phillips Creek Marsh, Hog Island and Oyster, VA, for precipitation, temperature, wind and light data.
- *Tide stations* at Red Bank, Oyster and Hog Island.
- *Surface elevation tables (SET)* in Phillips Creek Marsh, and 5 lagoon/mainland marshes for detailed measures of marsh accretion or erosion.
- *Atmospheric chemistry* – wet-deposition fluxes of major ionic species including SO_4^{2-}, Cl^-, NO_3-, NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, and H^+, and also $HCOO^-$, CH_3COO^-, $CH_3SO_3^-$, $(COO)_2^{2-}$ and Br^-.
- *Marsh grass end-of-year biomass* sampling at 9 sites to estimate annual productivity.
- *Island vegetation biomass and percent cover* estimates along a chronosequence on Hog Island.
- *Seagrass biomass and productivity and sediment characteristics* in a seagrass chronosequence of restored meadows in Hog Island and South Bays, representing ages 0, (bare), 1, 2, 3, and 7 years, and a mature reference site.
- *Groundwater levels* at 10 stations on Hog Island in marsh and upland habitats, and 5 stations in Phillips Creek Marsh.

- *Creek flows and nutrient concentrations* in 3 tidal creeks draining mainland watersheds to estimate baseflow nitrogen loading related to watershed land use.
- *Fish and invertebrate populations* in restored seagrass beds and adjacent bare sediments.
- *Small mammal population surveys* in fall and spring on 3 transects on Hog Island.
- *Photographic records* – landscape changes and unusual events are monitored using web cameras that monitor over 150 locations on a daily basis.

Research activities conducted over the period October 2009 – October 2010 are detailed below.

Watersheds and Lagoons

Modeled watershed nutrient loading

A model for calculating nitrogen loading to the VCR coastal lagoons based on watershed land use – land cover continues to be developed by Ph.D. student Luke Cole, working with P.I. Karen McGlathery. The multiple watershed-lagoon systems within the VCR vary considerably with respect to watershed land use and nitrogen loading to the coastal lagoons. They adapted the Nitrogen Loading Model (NLM) that was developed and validated by Valiela et al. (1997, 2000) for a Massachusetts coastal bay system, and applied it to 8 watersheds within the VCR. The model was then compared with baseflow nutrient loading determined for 7 smaller sub-watersheds from stream discharge and streamwater dissolved nitrogen concentrations (Fig. A1). In the model, nitrogen enters the system via three inputs: atmospheric deposition, fertilizer application (agricultural and residential) and wastewater from septic systems. Inputs are then subject to a series of reductions as they travel through different land covers, the vadose zone, and the aquifer, eventually arriving at a total nitrogen load entering the receiving water body from the groundwater (Valiela et al. 1997). Land cover categories in the model that influence these reductions include agriculture, residential turf, natural vegetation and impervious surfaces. The model was modified to include crop specific fertilization rates, areal extent of crop, and calculations for crop nitrogen removal and attenuation for additional nitrogen (Cole 2005).

Fig. A1. Watersheds in the VCR used for the Nitrogen Loading Model estimates.

Watershed nutrient loading based on streamflow measurements

P.I. Aaron Mills and colleague Janet Herman have continued their work on a regional examination of the VCR coastal watersheds to quantify loading of nitrate to the coastal lagoons via stream discharge. Improved estimates are being obtained by making monthly surveys of discharge in a large number of streams (ca. 15) and simultaneously collecting water samples for NO_3^- analysis. By correlating the spot measurements with the annual discharge hydrographs obtained at 4 streams that are being continuously monitored, they should be able to make a much more accurate and precise estimation of annual discharge that includes storm flow as well as base flow to all streams.

Mills and Herman continue to maintain continuously recording stream gauges at Cobb Mill Creek, Bundick's Creek, Phillip's Creek, and Tommy's Ditch. We have been putting an annual set of hourly discharge data for Cobb Mill Creek into the LTER database. They now have nearly a full year's stage data for the other three streams, and discharge data will be developed and placed in the database as soon as a rating curve for each stream can be developed. The two P.Is. plan to work together to obtain a large number of stage/discharge measurements from each of the streams during the next year to provide those curves.

Diurnal patterns of groundwater discharge to streams - implications for nitrate removal

Mills and Herman are also determining if daily fluctuations in groundwater discharge to Cobb Mill Creek alter the retention time in the biologically active sediments there sufficiently to create a change in NO_3^- discharge that is manifested in diurnal changes in stream NO_3^- concentration. Others have seen such fluctuations, but in many cases they have been attributed to water-column processes such as photosynthetic production (Rusjan & Mikos 2010). Mills and Herman conducted a 10-day, 24 hr/day study this summer to gather data to help test the hypothesis that evapotranspiration in the riparian forest causes a periodic (diurnal) fluctuation in nitrate concentration in the stream water. They will conduct a shorter (3-day) campaign in September of 2010 to determine the flux of nitrate from the stream sediments on a diurnal basis to support the data collection of the earlier collection.

Submarine groundwater discharge

Submarine groundwater discharge (SGD) can have a significant effect on nearshore coastal water quality. The established methods for quantifying groundwater between aquifers and coastal bay waters, including tracers such as radium and radon, piezometers, and bag-equipped seepage meters, have high uncertainties. For example, tracers such as radium and radon can be highly enriched in aquifers relative to bay waters, but because of differences in solubility and reactivity of elements in their decay series, their concentrations within an aquifer may vary by orders of magnitude, making accurate quantification of discharge difficult (Charette et al., 2005). Detailed measurements of the aquifer hydraulic head at the saline-freshwater interface with piezometer installations have also

Fig. A2. Dye displacement seepage meters.

been used to quantify material exchanges between bay waters and aquifers (e.g., Tobias et al., 2001), but the installation effort required restricts their use to relatively few sites. Seepage meters (Lee, 1977) offer advantages over radioisotopic tracers and piezometer installations in the simplicity of deployment, and the direct method of measurement, but bag-equipped seepage meters do not provide reproducible measurements of low rates of groundwater discharge, or of the inflow of overlying water into submarine sediments. Furthermore, seepage meters isolate sediments from the hydrodynamic environment that drives much of pore water exchange (Shum and Sundby, 1996). Because of the difficulties in measuring exchanges between aquifers and bays, and their importance to coastal ecosystems, P.I. Peter Berg and Ph.D. student Dirk Koopmans have developed two tools to improve measurements of this exchange: dye displacement seepage meters and the eddy correlation technique. First, dye displacement avoids the errors associated with bag-equipped seepage meters diverting some SGD around the meter due to pressure differences (Fig. A2). They developed a model that quantified the SGD measurement error associated with this pressure. The model is a two dimensional finite difference model of Darcy flow in cylindrical coordinates (Fig. A3). Second, eddy correlation measurements are made under *in situ* hydrodynamic conditions, relying on turbulent mixing to spatially integrate the tracer of interest (Berg et al., 2003). Berg and Koopmans have adapted eddy correlation for measurement of SGD, and published measurements of SGD using the technique in a coastal channel on Cape Cod (Crusius et al., 2008). They have recently applied the eddy correlation method to the determination of groundwater discharge to a creek at the VCR-LTER.

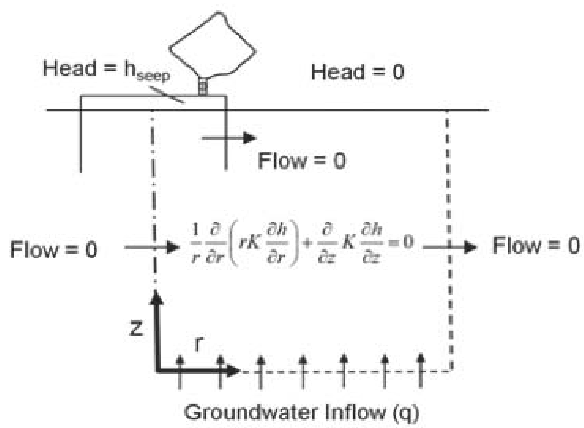


Fig. A3. Model of groundwater diversion around a seepage meter due to bag pressure.

Nitrous oxide fluxes

P.I. Todd Scanlon and his M.S. student Clara Funk are using a tunable diode laser trace gas analyzer as part of an eddy covariance system in the Cobb Mill Creek marsh to collect the first ecosystem-scale nitrous oxide fluxes to be measured in such a setting. The aim of this study is quantify the magnitudes of nitrous oxide (N_2O) emissions from the marsh and to determine the physical and biogeochemical drivers governing the spatial and temporal variability of these emissions. The system was installed in Cobb Mill Creek in summer 2006. Other instrumentation at this site includes an acoustic sensor at the outlet of the marsh, which measures bidirectional discharge in response to tidal fluctuations, and a stilling well and pressure transducer upstream of the marsh to measure inflow. Much of this instrumentation has been purchased through an NSF CAREER grant to Scanlon.

Ecosystem-scale fluxes of N_2O have been difficult to quantify using the eddy covariance method due to several factors. These include TGA instrument noise, the limited fetch available in the marsh, and the lower-than-expected intensity of the N_2O emissions. Scanlon and his student have shifted their attention to examining the spatial variability of these emissions. M.S. student Clara Funk is currently conducting a chamber study that takes advantage of the in-situ N_2O concentration measurements provided by the TGA.

Lagoon hydrodynamics

Hydrodynamic modeling provides a valuable tool for filling in the spatial and temporal picture of flow and estimating residence times. P.I.s Sergio Fagherazzi and Patricia Wiberg and their students are applying the 2D (depth-average) finite-element model IMAGE (also known as WWTM) to the system of lagoons at the VCR. The model solves the shallow water equations to compute tidal fluxes, and is equipped with a wave propagation module to calculate wave height during local wind events. The model was validated using measured water elevations, wave heights, and periods at five locations within the lagoon system. Scenarios with different wind conditions, storm surges, and relative sea level were simulated. The model is particularly suitable for the highly irregular bathymetry of the Eastern Shore tidal basins, characterized by deep channels, emergent salt marshes, and extensive tidal flats, similar to the morphology of Venice lagoon. Fagherazzi and Wiberg are collaborating with the Italian scientists who are developing the model to share model testing and new algorithms.

The IMAGE model couples a hydrodynamic finite element module based on the shallow water equations with a finite volume module that accounts for the generation and propagation of wind waves, solved on the same triangular mesh (D'Alpaos and Defina 2007). They have developed a preliminary grid for the VCR based on NOAA bathymetric charts and detailed bathymetric measurements in Hog Island Bay. Because of the shallow depths characterizing much of the VCR bays and the extensive salt marshes, calculated flow fields – and particularly wave fields – are sensitive to details of topography-bathymetry. One of the most significant steps forward we will take in the near future is the acquisition of LIDAR data for the VCR.

The application of IMAGE to the VCR was tested using field measurements of waves and tidal elevations. The model reproduces the water level at all sites as well as wave regime during storm events. In particular the model captures the wave dependency on wind speed, fetch, and water depth.

From the simulated distribution of bottom shear stresses, sediment resuspension and light attenuation can be calculated (Lawson et al. 2007). Wiberg et al. are applying this model to examine light attenuation and water residence times in two other lagoons in our new box transects – Gargathy Bay and Magothy Bay – that vary with respect to geomorphology and nutrient loading. We will use this model to assess habitat suitability for seagrass recolonization and survival based on water column turbidity.

Seagrass Restoration

Seagrass dominated the VCR lagoons prior to the disease and storm-driven seagrass extinction in the 1930's. We continue to work on a large-scale seagrass restoration effort studying the ecosystem-level consequences of the state change from a bare unvegetated state to one dominated by seagrass. The work is integrative and involves: 1) monitoring state variables related to nutrient cycling, primary production, and trophic relationships; 2) process studies on nitrogen cycling, net ecosystem metabolism, and sediment transport; 3) genetic studies relating genetic diversity to regional patterns and restoration success; and 4) modeling the dynamics of state transitions in the system. This is a large interdisciplinary effort involving a number of P.I.s (Karen McGlathery, Patricia Wiberg, Peter Berg, Matthew Reidenbach, Paolo D'Odorico, and Jay Zieman) and their students. Also, a number of undergraduate (REU) and high school students (REHS) are involved in the effort each year.

The work is a collaboration with Dr. Robert Orth of the Virginia Institute of Marine Sciences at the College of William and Mary and the Nature Conservancy. Orth has ~30 years of experience in seagrass restoration by seeding, and also has a large program in the Chesapeake Bay region. To the present, ~33 million seeds have been broadcast in 262 acres in the VCR coastal bays; now some 4500 acres have been colonized with productive seagrass meadows (Fig. A4). The VCR researchers focus on the return of ecosystem services as seagrass revegetate the lagoon bottoms, including enhancement of water quality, sediment stabilization, carbon and nutrient sequestration, and trophic dynamics. The experiment design includes both following initial establishment of seagrass meadows and development through time, and comparison of a chronosequence of meadows of different ages in the VCR bays.

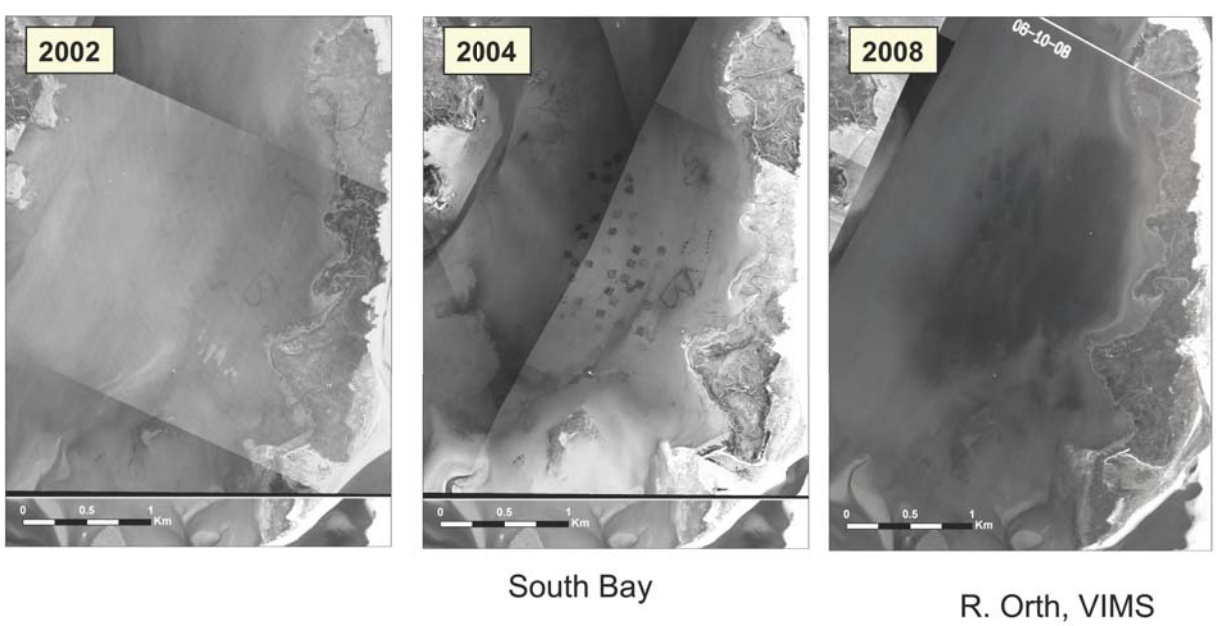


Fig. A4. Expansion of seagrass populations from 1.0 and 0.5 acre plots restored by seeding in 2002, which are most visible on the 2004 photo.

A number of students have their thesis projects focused on the seagrass state change:

• Ph.D. student Luke Cole is working with McGlathery on the consequences of the seagrass state change on nitrogen cycling. He is looking at specific processes of N fixation, denitrification, and N assimilation in the seagrass-vegetated sites in the chronosequence compared to nearby bare sediments colonized only by benthic algae.

• Ph.D. student Laura Reynolds is working with McGlathery and Zieman to understand both the genetic basis of successful seagrass restoration in the VCR lagoons, and the source of natural populations that have become established in one of the lagoons adjacent to the restored sites. She continues to sample the experiment she set up in 2007 to test whether increased genetic diversity of donor populations increases restoration success using the metrics of seagrass density, productivity, and also invertebrate density and nitrogen retention as proxies for ecosystem functions. This experiment was also designed to test for stresses associated with light limitation by blocking the plots along a depth gradient. She is also collaborating with a colleague in Australia, Michelle Waycott, who is one of the foremost experts on seagrass genetics.

• Ph.D. student Joel Carr is working with D'Odorico, Wiberg, and McGlathery to develop a state change model incorporating the dynamics of seagrass on modifying the fluid environment to investigate whether the seagrass system in Hog island bay exhibits unistable or bistable behavior. His research specifically investigates the strengths of positive feedbacks among seagrass cover, stabilization of bed sediments, turbidity of the water column, and the existence of a favorable light environment for continued growth of seagrasses. By assessing the strength of positive and negative feedbacks, he investigates whether shallow estuarine ecosystems are prone to catastrophic shifts to alternate "stable" states in response to gradual changes in environmental conditions and disturbance regime. In order to investigate the strength of the feedbacks a detailed hydrodynamic model of a within meadow environment was developed allowing for investigation of the presence or absence of bistability. This model has now been linked to a plant morphology growth model, to explore the how the temporal changes in the plant/meadow morphology affect the strength of the feedback. The model is also being used to explore the effects of grain size, shoot density and canopy height, water depth, water temperature, eutrophication, and relative storminess on the light necessary for seagrass growth/maintenance.

• Ph.D. student Jenny Romanowich is working with Matt Reidenbach to understand how seagrass beds affect boundary-layer flow dynamics and how this impacts the deposition and erosion of sediments within the lagoon. Dense seagrass beds create regions of reduced flow that promote sedimentation and the retention of particles, however little is known about the effects of shoot density on this process. Whether bulk flow is able to move through the seagrass bed or is diverted above and around it may be dependent on bed spatial heterogeneity. Work completed to date has focused on understanding the effects of turbulence and short-period/short-frequency waves on sediment dynamics, and how the presence of seagrass (*Zostera marina*) alters these dynamics. In particular, Romanowich and Reidenbach were interested in how meadow density and morphometrics alter shear and turbulence structure and modulate wave effects on sediment transport.

Flow and sediment dynamics were quantified three times during year (January, May and June

2010) using Nortek acoustic Doppler velocimeters (ADVs) and optical backscatter systems (OBSs) deployed in tandem for 72 hours. Water velocity, turbulence, and wave dynamics were correlated with *in situ* turbidity and therefore sediment transport mechanisms were explored. One ADV was placed with the sampling volume at 50 cm above the bed (cmab), above the seagrass meadow, and one with the sampling volume at 5 cmab, within the meadow. Additionally, bulk fluid currents throughout the water column were quantified via high resolution Nortek Acoustic Doppler Profilers (Aquadopps), which were placed in the seagrass meadow and at a bare site devoid of seagrass as a control site.

An additional focus of this work was the further development of an underwater laser-based velocity measuring system. Particle image velocimetry (PIV) has been used for a number of years in laboratories to measure velocity and turbulence over an area ranging from square millimeters to square meters. Essentially this system uses a laser and optics to create a laser light sheet which illuminates suspended sediment particles and, using a digital camera, sediment motion is recorded. A laboratory PIV system was modified and waterproofed, and was deployed within the seagrass bed, in natural flow conditions. The benefit of this system is that sediment motion directly adjacent to the seafloor and within the seagrasses can be quantified spatially over tens of cm simultaneously. Using software that tracks particle motions over time, a two dimensional map of sediment velocities was obtained and is being used in conjunction with longer-time series data obtained from the ADVs.

• Ph.D. student Dana Gulbransen is working with McGlathery on the impacts of the invasive seaweed, *Gracilaria vermiculophylla*, on seagrass and marsh ecosystems in the VCR. This 'super invader' is tolerant of a wide range of environmental conditions, and may impact seagrass restoration success. Gulbransen's research is addressing four specific questions: 1) How widespread is the *G. vermiculophylla* invasion? 2) Does *G. vermiculophylla* offer a nutrient and/or biomass subsidy to invaded regions? 3) How does the presence of *G. vermiculophylla* affect the abundance of invertebrates? 4) How does the presence of *G. vermiculophylla* affect seagrass seed germination survival and seedling recruitment? She conducted a large-scale synoptic survey of algal biomass at 40 sites during mid-summer and will continue to monitor 6 representative marshes 4 times/year for 3 years. Nearly 200 samples were sent to collaborator Carlos Fred Gurgel in Australia for genetic analysis and confirmation that on a regional basis, *G. vermiculophylla* has invaded both subtidal and intertidal habitats. In addition, she began a multi-year ^{15}N enrichment experiment on a number of intertidal marshes to test if the alga serves as a nutrient and/or biomass (habitat) subsidy between the subtidal mudflats and intertidal marshes. She hypothesized that *G. vermiculophylla* could enhance invertebrate biomass by increasing protection from predators as well as food availability. Increased numbers of invertebrate prey in algal mats could in turn affect shorebirds as well as an important tube building polychaete, *Diopatra cuprea*. In the summer of 2010 she collected cores on five VCR mudflats on bare sediment and in areas where *G. vermiculophylla* was present. Invertebrate species and abundance on the mudflats will be related to potential shorebird consumers. In fall 2010, she will begin an experiment to test the effect of *G. vermiculophylla* mat residence time on seagrass seed germination and seedling survival and growth. This data will be particularly important in the coastal bays where seeding is the primary method used for seagrass restoration.

Flow dynamics, larval settlement and metabolism of oyster reefs

Matt Reidenbach and his M.S. student Elizabeth Whitman are measuring flow, sediment uptake, and net metabolism by restored oyster reefs (*Crassostrea virginica*). The oysters were once prominent along the lagoonal land margin in the VCR and our partners at TNC are doing large-scale restoration of oyster reefs in the area. Filtration by oysters increases light availability to the benthos, and biodeposition of sediments is an effective bio-filter for nutrients. An oyster reef within the Hillcrest reef tract, which is adjacent to the harbor of Oyster, VA, where the LTER lab is located was instrumented with sensors to measure flow, sediment flux, and the uptake of oxygen by the oysters (Figs. A5, A6).

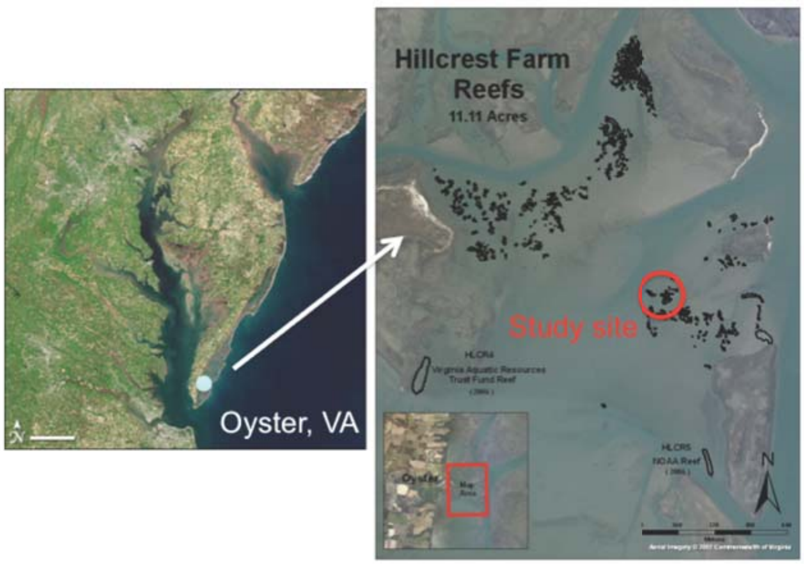


Fig. A5. Location of oyster reef sites instrumented with sensors to measure flow, sediment flux, and the uptake of oxygen by the oysters.

An additional objective of the work is to determine how the composition, topography, and benthic roughness of the ocean floor impacts settling success of oyster larvae. In particular, they want to understand both the large and small scale hydrodynamics involved in fluid transport and turbulent mixing over reefs, and how these dynamics impact larval transport and settlement on healthy and restoration reef areas. Larvae preferentially settle on existing oyster reefs due to a hard, stable substrate for firm attachment and topographic variability that prevents burial by sediments. Settlement success has been shown to be dependent upon their ability to quickly land, attach, and undergo metamorphosis before they are washed away by fluid stresses or transferred to areas where they can be buried by depositing sediments. Flow instruments and settling plates were deployed over an established oyster reef, a mud site, a restoration site made up of fossil shell from Sand Shoal Inlet, and a restoration site made up of whelk shell. At one site effect of elevation was tested by deploying 3 Acoustic Doppler Current Profilers (Nortek Aquadopps©) – one on the reef crest, one midway up the reef, and one in the mud at the base of the reef.

A detailed structure manipulation experiment is underway to determine how oyster spatfall and sedimentation differs among structures of different roughness at similar depths. Five replicates of three structures were created using slate tile as the settlement substrate (Fig. A6). Slate was set in 32 cm by 76 cm boot trays filled with Quikrete®. For the first structural set the slate tiles were laid horizontally flat along the base. For the second set, the tiles were cut into 30 cm by 8 cm pieces and set at angles to create an average spacing of 5 cm between 11 peaks. For the third set, tiles were cut into 30 cm by 8 cm pieces, but positioned 12 cm apart on average, with 5 peaks. In total, 15 structures were deployed in August 2010 between an established oyster reef and the restoration reef, and adjacent to the mud site. The spawning period for *C. Virginica* is June through September, and the structures will be retrieved in early September and a spatfall count will be conducted. Photo-monitoring is being used periodically during the deployment to document sedimentation.

Fig. A6. Structure manipulation experiment for oyster settlement. Tiles were composed of slate and arranged in 3 different geometries.

Clam beds and biogeochemical cycling

The VCR supports extensive bivalve populations that provide important ecosystem services through the provision of food and through regulation via their filter feeding activities. Some populations like the oyster (*Crassostrea virginica*) are being actively restored. Other populations such as the hard clam (*Mercenaria mercenaria*) are the subject of aquaculture. Hard clams are raised to harvestable size in pens throughout the VCR supporting a local industry valued at $24 million in 2004 (Murray and Kirkley 2005).

P.I. Michael Pace and M.S. student Kelly Hondula are examining to attributes of bivalves to characterize their functional role in the system. They have started two research activities focused on hard clams. Using stable isotopes of carbon (C-13), nitrogen (N-15), and hydrogen (H-2), they conducted a preliminary survey of the various sources of organic matter for clams in relation to the isotopic composition of clam tissues. They are testing if clams are supported primarily by resuspended organic matter. In addition, they are interested in whether they can detect any significant support via terrestrial organic matter where deuterium (H-2) is a useful indicator because of a distinct difference between in isotope ratios for aquatic versus terrestrial primary producers. They are also interested if the abundant macroalgal organic matter provides an important source for clams with the possibility that carbon, nitrogen, and/or hydrogen isotopes might be useful for distinguishing this source. Samples were collected, processed and sent to cooperating laboratories for analysis. They are awaiting return of data from the analytical labs to make further progress.

The second research activity is focused on clam beds and the specific question of whether these beds represent sites of enhanced biogeochemical activity. Filter feeding by clams results in the deposition of organic matter on sediments. In theory the local sediments should be enriched with organic matter and nutrients. They are testing this idea by comparing rates of oxygen consumption and denitrification in cores taken from sites within and outside of clam pens. This work is also in an early phase. They have developed methods for conducting core experiments and are nearly ready to conduct our first experiments. They will be measuring the consumption of oxygen and production of nitrogen in these experiments. The dissolved gases will be measured in a dissolved gas analyzer which employs a mass inlet mass spectrometer method allowing accurate measurement of changes in gas concentrations over short incubations (Kana et al. 1998). It is possible that clam beds facilitate nitrogen losses from the system and if so may provide another regulating ecosystem service through the enhanced denitrification of excessive nitrogen inputs.

Tidal Marshes

Marsh accretion relative to sea-level rise

P.I.s Linda Blum, Mark Brinson, and Bob Christian now have a 12-year database on salt marsh accretion in relation to sea-level rise at our core study site, Phillips Creek Marsh. Surface Elevetation Tables (SETs) and root-zone SETs have been monitored twice a year at low-, mid- and high-marsh sites. Surface accretion is measured using feldspar marker layers. They are particularly interested in the relationships between marsh elevation/accretion and plant biomass, groundwater elevations, patterns of tidal flooding, and rainfall. We also monitor SETs in several other lagoonal and mainland marshes in the VCR as part of studies on sea-level rise effects on colonial waterbird nesting (P.I. Michael Erwin) and climate change effects on marsh areal extent (P.I. Wiberg). At the Phillips Creek Marsh, hydrologic monitoring continues in tidal creeks, on the marsh platform, and in surrounding upland wells. Tidal creek and marsh recorders are programmed to capture frequency, duration, and flooding depths by semidiurnal tides, and summarized to correspond to the frequency of SET data

Fig. A7. Brown marsh syndrome at Upper Phillips Creek marsh. Extent of marsh die-off (red dashed line) in May 2004 is shown in the top panel. One of several transects (note yellow flag in the foreground) used to monitor recovery from the die-off is shown in the bottom panel.

collections. Surrounding upland wells are monitored monthly for water table and conductivity to capture longer-term effects of sea level influences beyond the marsh margin.

Marsh transgression and state change

Brinson, Christian and Blum are now in the second year of a field experiment to gain insight into the state change model of zonal migration in response to rising sea level and disturbance. This experiment is comprised of combinations of vegetation disturbance (clipping and killing vegetation) and stress relief (nutrient amendment) to examine resilience and resistance to state change. Two M.S. students are involved in this work – John Haywood and Brooke Costanza.

Their long-term experiment examines high marsh vegetation response to increased frequency of tidal flooding to mimic changes expected as sea level rises. The experiment has continued for 12 years with little evidence of an effect of increased inundation and significant plant resilience to changes in hydrology. As a result, Christian has decreased monitoring of standing stock biomass and elevation changes.

Patch dynamics of *Juncus* continues to be collected on an annual basis at the Phillips Creek Marsh by Brinson and Christian. They continue to harvest aboveground biomass at the annual peak with the intent of detecting climatic influences in this marine-dominated environment.

In 2010, a nutrient-dosing experiment was initiated to examine the response of above and below-ground net primary production of *Spartina alterniflora* by Blum and her undergraduate student Chris Olcott. This project will become Chris' Distinguished Majors Thesis in the Department of Environmental Sciences at UVA. In another undergraduate project (Bridget Long working with Blum), annual root and rhizome dynamics between a monoculture of short-form *S. alterniflora* in the low marsh and a mixed community of *Spartina patens* and *Distichlis spicata* were compared in the high marsh.

Christian and his graduate student Amanda Floyd continue to follow the interannual dynamics of brown marsh die-off, an effort initiated several years ago when an area of Phillips Creek Marsh was affected (Fig. A7).

Changes in marsh spatial coverage in response to climate change (sea-level rise, storms)

With supplemental funding from the DOE NICCR program, P.I.s Fagherazzi, Wiberg, and McGlathery and their students are investigating rates of erosion or accretion of the marsh-tidal flat boundary and the processes that control the evolution of that boundary. Extensive field measurements in Hog Island Bay are being coupled with modeling efforts at several scales to understand the physical and biological mechanisms responsible for marsh edge erosion and the coupled evolution of salt marshes and tidal flats in intertidal environments. The goal of the modeling is to predict changes in areal extent of marshes under different 100-yr climate change scenarios of increased sea level and storminess. The field component includes monitoring of 4 marsh boundaries with measurements of scarp erosion, vegetation and sediment characteristics, crab-burrow and bivalve density, and flow conditions (waves and tides) just lagoon-ward of the marsh edge. Three of the sites are erosional, reflecting the dominance of erosional sites in this system. One site, located behind a protective ridge of sand and oyster rock, appears to be accretional.

Numerical modeling - Fagherazzi and his students have developed a simple one-dimensional numerical model for the coupled long-term evolution of salt marshes and tidal flats. The model framework includes tidal currents, wind waves, sediment erosion and deposition, as well as the effect of vegetation on sediment dynamics. The model is used to explore the evolution of the marsh boundary under different scenarios of sediment supply and sea level rise. Wind wave attack is the fundamental cause of erosion of salt marsh boundaries. Tidal forcing acts as a proxy determining at which elevation waves pound against the marsh edge and conditioning the propagation and transformation of wave trains as they move towards these boundaries. Fagherazzi and students have also evaluated, through analysis of the results of a Boussinesq numerical model, the effect of wave action on marsh boundaries as a function of tidal elevation and wave height, for different edge configurations. In order to link numerical simulations to field conditions, the model inputs are based on topographical and hydrodynamical surveys conducted at study sites at the VCR.

Mechanisms of marsh edge erosion - An objective of the field work being carried out by M.S. student Sean McLoughlin, working with Wiberg and McGlathery, is to investigate the mechanisms of erosion occurring along edges of the study marshes and to determine which properties of the marsh may be influencing or driving these mechanisms. Previous studies have suggested that wave activity, aboveground and belowground vegetation structure, sediment characteristics, and infaunal burrowing activity may all play a role in the erosion of the marsh edge. To determine which factors may be important in controlling edge erosion, properties of the vegetation communities, sediment structure, and invertebrate communities have been measured at each of our four marsh sites. Sampling of the marsh sites was performed between June 2009 and July 2010. Measurements of vegetation properties include aboveground and belowground biomass, stem density, canopy height, and root and rhizome tensile strength. To evaluate sediment characteristics near the marsh edge, measurements of grain size, porosity, bulk density, organic content, shear strength, and sediment compaction were made. Because of the apparent importance of crab burrows to edge erosion at some of the sites, specific sampling focused on the geometry and spacing of these structures. Burrow densities, diameters, coverage (surface area), and volumes were recorded at each of the sites; crab counts and species identification were also performed. Though waves appear to be the drivers of marsh edge erosion, our results indicate that there may be specific properties of the marsh edge that play influential roles in the erosion process.

Flooding frequency and water table elevation - The relative positions of the water surface, land surface and groundwater table are important for understanding the morphodynamics and ecosystem dynamics in coastal environments. Fagherazzi and his students have been surveying the study sites regularly during this project. This summer Wiberg and McLoughlin have carried out one last survey using a survey-grade GPS system to place each site in an absolute reference frame. In addition, water-level recorders in wells sited near the marsh edge at each site provide tidal inundation depths that can be correlated with longer-term (10-

20 years) of water level measurements at tidal stations to characterize flood frequency and depth.

VCR Intra-site Coordination for Marsh Studies

As a result of the all-scientists meeting in January and in response to the midterm site review, two-day field excursions were organized for P.I.s and students working on different aspects of marsh vertical accretion and shore dynamics. The intent was to gain a better appreciation of the diversity of marsh types at the VCR megasite. One outcome is to use marsh age and geomorphic setting as an organizing framework for disparate marsh-related projects throughout the VCR. Funds were secured for isotopic sediment dating to determine marsh properties as a function of time since sea level intercepted the pre-Holocene surface.

Trophic interactions – environmental impacts on waterbirds

P.I. Michael Erwin continued to monitor the SETs at the Wachapreague and Mockhorn Island sites, as part of the LTER network of SETs. His work focuses the impact of geomorphic change of marshes and habitat loss on nesting waterbirds. In addition, Erwin continued to collect data on waterbird nesting at a number of Chincoteague Island colonies as part of a Virginia coastal bird partnership/collaboration including university, federal, state, and NGO (The Nature Conservancy) personnel.

Erwin's Ph.D. student Charlie Clarkson conducted the second year of fieldwork for his research at the VCR LTER and in New York on habitat effects on waterbird growth. His research includes an evaluation of growth rates, diet, and feather dynamics (termed "ptilochronology") of two nesting waterbird species, a generalist, the double-crested cormorant, and a specialist, the glossy ibis. The work is aimed at determining if feather growth of young birds can be used as a bioindicator of the quality of prey and hence, estuarine conditions, comparing a relatively pristine region (the VCR) with a highly disturbed and human-dominated landscape (the New York metro region). Early results support the hypothesis for the ibises; i.e. the width of the growth bars in young ibis is greater in VA than in NY. Also, the occurrence of "fault bars" (and indication of food stress or contaminant load such as mercury) was greater in NY than in VA. Research continues tying the feather growth with the food boluses collected, and with mercury analyses. Clarkson's work was recently featured by a news article on UVA Today (http://www.virginia.edu/uvatoday/newsRelease.php?id=12826).

Barrier Islands

Island vegetation

Our past work has shown that each island may respond in a unique fashion to sea level rise; however, sediment movement among islands and island position dictate that islands are affected by their neighbors. This is true of both physical processes (e.g sediment transport) and biological processes (e.g. movement of propagules, including organisms, seeds, and pollen). Our goal is to link the external drivers of storm disturbance (overwash, sand desposition, flooding, salt spray) that modify the land surface and water table to patterns of vegetation on the barrier islands. We are building on our long-term work on Hog Island, including permanent plots in the dune chronosequence, to include islands in the 2 new box transects. Our earlier work has shown that there is predictable spatial variation across the island landscape due to differences in microtopography and the decrease in disturbance magnitude and frequency with distance from the beach face, which result in different vegetation patterns across the islands (Fahrig et al. 1993). Thus storm-related effects should vary among islands as a function of island size and topography. We have now obtained LIDAR imagery for all islands, and this database will provide spatial variations in elevation distance to the shoreline for each island that can be related to vegetation communities and to predicted changes in island geomorphology.

P.I. Don Young and his students and post-docs continue to focus on landscape-level comparisons across the terrestrial portions of the VCR barrier islands. Their objectives are to understand and quantify important fluxes among the VCR landscape units, to remain inclusive of all barriers within the VCR system, and to place our results in the context of the knowledge base for other barrier systems and terrestrial ecosystems in general.

Using artificial perches on Smith, Hog, and Metompkin Islands, they determined that island woody communities are significantly influenced by avian dispersal of seeds. Species composition of the seeds collected did not closely reflect the surrounding mature community, and there was significant spatial variation in seed numbers and species composition relative to the surrounding community. Variations may be related to suitability of perches for passerines. In several instances, seed species identified were from relatively distant populations.

Shrub thickets provide important habitat for predators and are expanding on the islands, and they continue to add to our long-term data set on the expansion of *Morella* sp. thickets on the VCR islands. Most of their work continues to focus on island shrub thickets dominated by *Morella* (formerly *Myrica*) *cerifera* shrub thickets. Island thickets are an excellent model system for studying the mechanisms and consequences of woody encroachment into herbaceous dominated systems. In addition, island thickets represent an endpoint of high primary production, leaf area index and precipitation for comparisons among global woody encroachment studies. For example, they have quantified high C sequestration rates in barrier islands soils where shrub thickets are expanding which may also apply to relatively young coastal soils in general. Thus, the impact of woody encroachment of C cycling may be more complex than previously thought and soil history may be an important consideration. In addition, they have quantified seasonal variation in litterfall and litter N concentration in *M. cerifera* shrub thickets to assess changes in litterfall and associated N input after shrub expansion, and to estimate the proportion of litterfall N originating from symbiotic N fixation.

They continue to examine the suitability of remotely sensed hyperspectral data for extracting relevant data concerning ecological processes from the individual plant to the ecosystem level. Shrub thickets are very useful for testing indices because of the high LAI, monospecific uniform canopy, and documented soils and shrub ages as well as spatial variations in primary environmental stressors, e.g. salinity and drought.

P.I. Frank Day has completed the initial evaluation of inter-island variation in biomass and diversity of dune and inter-dunal marsh communities. Grassy dunes of young, intermediate and old age were sampled on Smith, Hog, and Parramore Islands. He also quantified plant biomass in interior marshes in inter-dunal swales on the same islands. Data were collected for depth to groundwater, salinity, soil organic matter, total soil nitrogen and total plant nitrogen to determine their possible effects on biomass and diversity. In addition, Day and co-workers completed a four-year study of Hog Island and Parramore Island "pimple" dunes.

Vegetation-predator-bird interactions

Nest predation by mesopredators has had a huge impact on breeding populations of ground-nesting birds on the Virginia barrier islands. Across the VCR landscape there is a relationship between vegetation structure and species composition, the presence of predators, and the abundance and nesting success of shore birds. Research by P.I.s Ray Dueser, Nancy Moncrief, John Porter, and student J. Martin have focused on four questions: (1) Which potential egg predators actually depredate eggs? (2) How important are mammalian predators relative to other egg predators? (3) Does mammalian predator removal reduce the overall predation rate on beach nests? (4) How long does the average nest survive on the beach? They use artificial nests stocked with surrogate eggs in conjunction with predator track analysis, clay eggs and/or camera traps to (1) identify the nest predators on an island and (2) compare the potential incidence of nest predation between islands. They observed 605 cases of egg predation during 1,600 egg exposure-days on two islands. Parramore Island (800 days) is well-stocked with both raccoons and red foxes; Metompkin Island (800 eggs) supports few mammalian predators and is subject to occasional predator removal.

They have previously documented the dynamic distributions of mesopredators (raccoons and red foxes) on the Virginia barrier islands, and documented the effects of these predators on ground-nesting birds once they reach an island. They are now using spatial least-cost path analysis to (1) determine the relative difficulty for mesopredators to reach individual islands from both mainland and islands sources, (2) assess the relative roles of mainland versus island populations of raccoons and red foxes as sources of immigrants to unoccupied (or depopulated) islands, and (3) identify transit hotspots where monitoring and removal efforts might be particularly effective in reducing predation impacts on ground-nesting birds.

They have completed the digitization and consolidation of all capture/removal information for mammalian predators on the islands. This included 1200+ captures or observations of raccoons (1200+) and red foxes (40+) 1999-2007 by several organizations. They have also characterized physical attributes such as surface area, isolation and habitat composition for each of 33 island and marsh surfaces, using Coastal Change Analysis Program (CCAP) data layers from 1984, 1988, 1996, 2001 and 2005.

Biogeomorphic controls on barrier island evolution in response to sea-level rise

Rising relative sea level and potentially increasing storm activity will cause barrier islands to overwash more frequently, thus altering their stability in the future. Changes in plant species composition, such as the prevalence and distribution of dune-building grasses, are also expected as climate warms. Underlying these changes in physical and biological forcing is the potential for non-linear feedbacks between geomorphic and biological processes, associated with overwash and dune-building, to reinforce and expand the presence of overwash zones. P.I.s Laura Moore and Don Young have funding from the DOE-NICCR program to investigate the existence of these biogeomorphic feedbacks in the VCR and to assess how they might respond to changes in physical and biological forcing thereby affecting future island stability. Specific questions they are addressing within VCR include: 1) How do morphological zones and plant species composition co-vary? 2) Are overwash and dune areas persistent through time and can this be tied to species composition? 3) What is the current status of barrier island vulnerability to storm impacts, how is this different from a decade ago and is there a relationship with changes in species composition? 4) How do changes in vulnerability compare to those we would expect given shifts in physical and biological forcing alone? and 5) Given current topography and species composition, potential feedbacks, and a range of anticipated changes in physical and biological forcing, what are likely barrier island responses in the future? These questions are being addressed using a combination of remote sensing, geophysical and numerical modeling methods including aerial photo analysis, ground-penetrating radar and sediment coring.

Field mapping and identification of focus areas - Identification of overwash zones on 2007 aerial photography was carried out in preparation for reconnaissance field mapping. Following the initial aerial photo examination, extensive field mapping of Hog and Metompkin Islands in the VCR was carried out on foot to determine the distribution and extent of relevant morphologic features (i.e., dunes and overwash), and to select sites for in-depth analysis. Overwash zones were classified into three categories: active (mostly bare of vegetation, very low topographic roughness, signs of recent wave activity), recovering/intermediate (low topographic roughness, but with noticeable recovery of vegetation and evidence of aeolian processes shaping the surface), and relict (low topographic roughness, but re-vegetated and cut off from wave action by high-relief seaward dunes). Drawing on evidence from field mapping, as well as preliminary examinations of historical aerial photographs and the literature, they have identified 4 focus areas (2 per island) that are morphologically representative of the northern and southern halves of Hog and Metompkin Islands, respectively.

Elevation/Vegetation Surveys - Preliminary vegetation surveys were conducted on Hog Island from August-October 2009 and Metompkin Island in October 2009. Sites surveyed in 2009 were selected from the three classifications of overwash identified by field mapping and from adjacent, undisturbed dune communities that served as reference sites. A June-July 2010 vegetation survey of Hog Island examined 2-3 sites within each of the focus areas (described above) that encompass and represent the range of morphologies in that area (e.g., active overwash, dunes, recovering overwash). For each site, vegetation community composition was determined by the quadrat method using a systematic sampling design.

Taxonomic composition and percent cover of living vegetation was determined in a 0.5 x 0.5 m quadrat every 5 m along each of three transects within each site. One cross-shore transect, starting on the seaside of the foredune, and two shore-parallel transects, arrayed across each cross shore transect, were established. Cross-shore transects varied in length, were based on the size and shape of the morphologic features being surveyed, and ranged from 30 m to >150 m. Shore-parallel transects were included to account for the variations in environmental conditions that occur between the beach and the stable upland or marsh, since these conditions strongly influence which species successfully colonize. One shore-parallel transect was established at the 5 m point of the cross-shore transect to represent variations in vegetation along the primary dune ridge, or the remnants thereof. The second shore-parallel transect was established at the mid-point of the cross-shore transect to represent variations in vegetation in the fan area of the overwash or interdunal swale in undisturbed sites. The alongshore transects were terminated 50 m in either direction from the cross-shore transect or, if the transect site was in an active overwash zone, 5 m into the stable, undisturbed adjacent vegetation (whichever came first). All taxonomic identifications follow Duncan and Duncan (1987). Vegetation sampling in 2010 was paired with high-resolution GPS elevation measurements. They have also measured parameters that may affect the likelihood of persistent overwash at each transect, including beach width (measured from the high-tide line to the start of the cross-shore transect), average grain size (determined from grab samples taken every 10 m along each transect), and average distance to laterally adjacent communities that include *Ammophila breviligulata* (determined from the alongshore transects). Surveys having the same design will be conducted on Metompkin Island in August - September 2010 after termination of bird nesting.

Ground Penetrating Radar (GPR) and coring - In addition to elevation/vegetation data, Moore and her students have collected ground-penetrating radar (GPR) surveys and sediment cores to examine stratigraphy in the focus areas, which allow them to evaluate overwash persistence on the scale of decades to centuries. They are using GPR to survey transect sites that include dunes, in search of stratigraphic evidence of buried (recovered) overwash. GPR surveys on Hog Island were completed in June-July 2010 and GPR surveys on Metompkin Island are planned for August-September 2010.

Coring efforts are centered on areas that are known to have experienced repeated overwash in the past, that have undergone minimal shoreline change (and thus are more likely to have a stratigraphic record of overlapping overwash on the decadal-centennial scale), and that are not accessible with GPR methods. In June-July 2010, they collected six cores in such areas on Hog Island, with penetration ranging from 1-2 m in sandy sites to nearly 7 m in high marsh areas. Select overwash deposits in cores will be dated using optically-stimulated luminescence (OSL) dating to improve evaluations of persistence. A similar coring effort on Metompkin Island is in the planning stages and will be carried out in August-September 2010.

LiDAR data analysis - To explore possible trends in island vulnerability to overwash and inundation during storms, analysis of a time series of LiDAR observations for the entire Virginia Eastern Shore are underway. A first year UVA graduate student has participated in Matlab training and visited the USGS Coastal Change Hazards group in Saint Petersburg, FL to receive training on previously established methods for assessing barrier island vulnerability via LiDAR observation. The USGS has provided algorithms that will be used to extract horizontal and vertical positions of the frontal dune crest (D_{HIGH}), frontal dune toe (D_{LOW}) and the shoreline as well as to calculate foreshore beach slope. These features have been extracted for 2005 and 2009 LiDAR data sets. The same process will be completed in Summer 2010 for the 1998 and 2010 data sets. Following feature extraction, each data set will be compared with local wave record statistics to assess changing vulnerability to storm generated waves ranging in severity from those generated by typical annual storms to those generated by more significant storms such as Hurricane Isabel and Nor'Ida.

Morphological-behavior modeling of barrier island vulnerability to increased rates of sea level rise

Morphological behavior modeling (e.g. Cowell et al., 1995; Stolper et al., 2005 and Moore et al., 2010) represents a significant improvement over the one-dimensional Brunn (1964) Rule approach to assessing the impact of sea-level rise on the potential future evolution of barrier island systems. Sediment transport models, driven by hydrodynamics, cannot yet address questions of large-scale coastal behavior such as the evolution of barrier islands over length scales of kilometers and time scales of decades to centuries and millennia. Morphological behavior models, which are driven by changes in sediment supply, sea-level rise, and shoreface geometry (e.g., Cowell et al., 1992; Stolper et al., 2005, Moore et al., 2007), without simulating the detailed physical processes of sediment transport, currently provide the best means for testing the geometric validity of hypotheses regarding barrier island evolution. Though these models do not simulate barrier island evolution at the scale of individual storm events, and therefore cannot directly simulate changes from one equilibrium state to another, they are a valuable tool for assessing the vulnerability of a landward migrating barrier to a change in state over longer time periods.

This approach, and a model called GEOMBEST (Geomorphic Model of Barrier, Estuarine and Shoreface Translations), have recently been applied by P.I. Moore to study areas in the North Carolina Outer Banks and the Chandeleur Islands of southeastern Louisiana yielding general insights in to the vulnerability of barrier islands to changes in state due to sea level rise (Moore et al., 2007; Moore et al., 2010; Moore et al., 2011). Sensitivity experiments presented by Moore et al. (2010) indicate that the quantity of sand-sized sediment available in the substrate underlying a barrier island system is the most important factor in determining whether or not a barrier island is likely to be maintained during increasing rates of sea level rise. Given the apparent finer-grained nature of offshore sediments, this may be an important factor for the Virginia barrier islands.

Their objective is to explore the potential geomorphic response of the Virginia barrier islands to sea level rise using GEOMBEST. Their investigation begins with the development of simulations exploring the late-Holocene and potential future evolution of Metompkin Island. An important aspect of this analysis will be to assess the importance of the presence (northern half of the island) and absence (southern half of the island) of subaerial lagoonal-marsh deposits in determining barrier island response. They hypothesize that the absence of subaerial marsh behind the southern portion of the island contributes to the relatively more rapid migrations rates compared to those found on the northern portion of the island. And, that differences in the area of marsh behind barriers will be critical in determining how the system evolves in the future.

Graduate student Owen Brenner has compiled NOAA bathymetry and USGS lidar data to create a representation of the modern bathymetry and topography (i.e., morphology) of north and south Metompkin Island. These two cross-shore profiles represent the average morphology of south and north Metompkin Island and the associated offshore out to water depths of approximately 35 m. Brenner and Moore then used stratigraphic information from the existing literature to develop an average representation of the stratigraphic layers underlying the morphology for north and south Metompkin, paying particular attention to the quantity of sand within these layers and degree to which they are erodible. By combining the modern morphology and stratigraphy with observations from the geologic literature that provide insight on the timing and location of barrier island formation, Brenner has developed an average morphology and stratigraphy that represents a plausible initial condition 4600 years before present. Additional initial conditions and parameters that must be specified in the development of late-Holocene and future simulations have also been compiled from existing literature. These include rates of relative sea-level rise over the last 4500 years, estimates for future relative sea level rise rates, sediment loss rate estimates, estuarine infilling rates and estimates of shoreface depth.

They are currently working to run the first simulations of barrier island evolution on the Virginia eastern shore using GEOMBEST. A comprehensive series of late-Holocene and future simulation experiments, including sensitivity analyses to determine which factors are most important in determining barrier island response to sea level rise in the Virginia barrier islands, will be carried out this fall, possibly extending into spring 2011. They will collect cores in Fall 2010 in concert with the project described above, which will provide us with a better measure of sand thickness on Metompkin Island. This information is critical to understanding likely future island behavior; modern and initial stratigraphies will be edited as necessary following core analysis.

Landscape Analysis

Landscape-scale models of ecosystem state change

Observed decadal trends in landscape change - We have assessed landscape change for all the VCR marine watersheds using published land cover data layers from the NOAA Coastal Change Analysis Program (CCAP). P.I. John Porter compiled data for five dates (1984, 1988, 1996, 2001 and 2005). The 1984-1988 data shared a common set of categories and methodologies, and the 1996-2005 data shared a different (but similar) set of categories and methods. Data layers were recoded to a common classification scheme that provided a coarse, but useful, categorization of land cover.

P.I. Enrique Reyes used the 1992, 1996, and 2005 data sets to compare changes in marsh area. The agreement between the two maps (1992 vs. 2005, and 1996 vs. 2005) was quantified with a goodness of fit spatial statistics routine comparing the spatial pattern of habitat cells at multiple resolutions (Costanza 1989), which returns a value out of a possible maximum of 100. The multiple resolution approach allows a more complete analysis of the way the spatial patterns match. The algorithm gradually degrades the resolution with which the fit is measured by gradually increasing the size of the sampling window in which the fit is calculated (Costanza et al. 1990). The total fit is a weighted average of the fit at all window sizes, with the smaller windows given the most weight.

Landscape modeling – Reyes continues to adapt his modeling framework for habitat change (Reyes et al. 2000, 2004) to the VCR landscape. The model (Virginia Landscape Model (VLM)) is a regional model that incorporates hydrodynamics, transport of water-borne particles (salt and sediments) and plant biomass over a grid of landscape cells, and focuses on intertidal marshes. Each cell contains a unit ecosystem model that represents a certain habitat type and incorporates location-specific algorithms to quantify fluxes of materials between cells (Boumans and Sklar 1990; Fitz et al. 1996). Feedback between the processes occurring within the cells and the landscape allows both the landscape and the processes affecting it to change over time. The VLM represents habitat changes at a 275 m^2 "pixel" for a total of 100,189 active cells, and produces daily values for water depth, salinity, sediment concentration and plant above- and below-ground biomass.

Most of Reyes' research efforts this year were committed to investigate and resolve issues with long-term water distribution and model stability. A more detailed examination of water transport and distribution indicated some problems along all of the inlets. The exchange of water between the islands and the open ocean has proven critical for model stability. A series of corrections on the bathymetry values appears to have solved the problem. Previous test runs were limited to 3 simulated years; they have completed runs for 10 years.

Remote sensing - A team led by P.I. Chip Bachmann of the Naval Research Laboratory (NRL) continues to work on analysis of data from their large-scale remote sensing campaign of the VCR LTER conducted in September 2007. The campaign took place across a 3-week period, and involved coordinate airborne remote sensing data collection from a multi-sensor (2 hyperspectral imagers and a thermal camera) suite and in situ cal/val activities on both land and water throughout the site. Initial focus of the effort of the land-based effort focused on remote retrieval and mapping of beach properties (composition, moisture, grain size, geotechnical meta-properties such as bearing strength/dynamic deflection modulus) and vegetation retrievals such as biomass from the airborne hyperspectral imagery flown during the experiment, primarily from the NRL CASI-1500 hyperspectral sensor. In the water, primary emphasis of the experiment was on shallow water bathymetry, although long-term goals include monitoring of SAV and water constituents.

Geomorphic model of landscape change

ROA M. Fenster and colleagues are developing an empirically-driven expert systems model (e.g., Bayesian) capable of predicting the landscape changes that will occur with predicted climate change scenarios. The work involves: 1) compilation of an empirical database of all factors (sediment supply, storms, tides, tidal inlets, waves, sea-level fluctuations (rise), and antecedent geology) that produce morphologic and geologic changes along the VCR; 2) geophysical work to provide a seismic facies analysis capable of analyzing the nearshore record of longer-term ($10^5 – 10^3$ yr) environmental changes; 3) an upgrade of the shoreline change GIS database for the entire VCR to include shoreline positions of all islands through 2009; 4) assessment of the impact of short-term disturbances (i.e., coastal storms) on the

Virginia barrier islands using a method that compares the shoreline position outliers to the magnitude and timing of the largest storm prior to a photo date; 5) use of a densely gridded wave refraction model developed by the Spanish Ministry of Environment and the University of Cantabria (González et al., 2007) to examine the role of both long-term wave climate and short-term wave (storm) disturbances on controlling the barrier-tidal inlet morphodynamics of the VCR; and 6) development of a sediment budget to enable determination of the sources that feed the Virginia barrier island sand prism and the sinks that remove sand from the system.

Shoreline changes along the VCR - Shoreline rates-of-change are used to monitor the movement of ocean-side, coastal geomorphic systems. Prior to this research, the shoreline change rates for the Virginia barrier islands came from Robert Dolan's (University of Virginia) COASTS database that contained between 6 to 9 shorelines (digitized high-water lines from aerial photographs) and vegetation lines (digitized ecotones), and spanned the period 1940 – 1989. Fenster and his colleagues have added to this long-term data base by: (1) upgrading the COASTS database from a DOS-Fortran-based data retrieval system to a modern ARC-ready Geographic Information Systems (GIS) platform; (2) updating the shoreline and vegetation line inventory by adding photographic and Global Positioning System (GPS) shoreline data from the 1990s and 2000s; and (3) analyzing these total data set using the USGS Digital Shoreline Analysis System (DSAS) to derive new linear trends at 50 m intervals along the shore. Ultimately, these data will be used for additional analyses to include regression modeling (see below) and outlier storm detection analyses.

They have now completed the new and updated GIS database integrating the COASTS data (1940-1989) – including scanned and rectified aerial imagery – with additional, more recent shorelines. The recent shoreline dates added to the newly developed GIS database include aerial orthophotography from March/April 1994 and 2002 and GPS shorelines from 2003 and 2006. The new data provide and updated trend analysis and decrease the uncertainty associated with trend delineation and prediction.

Sub-bottom geology and barrier island antecedent geological framework - Geophysical surveys consisting of 274 km of seismic reflection profiles and side-scan sonar were taken off the coast of Virginia's Delmarva Peninsula in order to answer the following questions: 1) Does a source of sediment exist that can supply Virginia's barrier islands with sand? 2) What are the characteristics of those sediment sources and in what volumes do they occur? Finally, 3) How does the nearshore subsurface geologic framework influence present-day barrier island morphodynamics?

The impact of sea-level rise: A field experiment to test the runaway barrier island transgression model - Research has shown that tidal inlets strongly control barrier island morphodynamics at various spatial and time scales. For the Virginia barrier islands, the ebb-tidal delta at Wachapreague Inlet has emerged as a potential major player in the evolutionary history and future of the islands. Fenster and colleagues have deployed three bottom-mounted, upward-looking acoustic Doppler current profilers (ACDPs) in three inlets (Figure 2; Metompkin, Wachapreague, and Quinby) and surveyed each inlet for more than a half tidal cycle (13 hr) with a downward-looking ADCP to obtain cross-sectional areas and tidal discharges. They will use these data to test a new barrier island fragmentation model postulated by FitzGerald et al. (2004, 2006, 2007). This model predicts the response of mixed-energy barrier islands to a regime of accelerated sea-level rise. In short, the model suggests that sediment that is deposited on ebb- and flood-tidal deltas and other shoals within the back-barrier comes from sand in the littoral system that enters the tidal inlet from the adjacent barrier islands. This sequestration process may prevent or greatly diminish sand bypassing around the tidal inlet, thereby depleting the sand reservoirs from the adjacent barriers, which may ultimately lead to their fragmentation and onshore migration. Ultimately, the inlet cross-sectional areas and tidal prisms for the three, surveyed inlets will be compared to historical data to identify morphological and sediment transport trends.

Social Science Research

Using supplement funding, we have developed a collaboration with Stephen Swallow, a natural resource economist at the University of Rhode Island, and his Ph.D. student Elizabeth Smith, to study the public valuation of seagrass, oyster, and bird habitat restoration. Increased demands on our coastal ecosystems, due to increased development and population growth, are threatening many environmental goods and the amenities associated with well-functioning ecosystems. While few to no markets exist for ecosystem services that provide public goods and are not traditional commodities, such as habitat services provided by healthy sea grass beds or water quality benefits associated with clam habitats, consumer preferences can provide insight to managers and policymakers on how to prioritize limited funding and make trade-offs between coastal restoration priorities. Swallow's ongoing research focuses on ecosystem valuation and markets that have potential to provide for public goods, specifically examining ways to generate revenues for public goods from consumers. While willingness-to-pay techniques have been used to estimate preferences on many environmental goods, this study goes a step further to explore real money auctions that generate revenues sufficient to pay for restoration activities. Our individualized pricing approach examines the willingness-to-pay on increments of restoration, grounded in Lindahl's marginal benefit theory for public goods.

Empirical analysis focused on public valuation for three specific types of ecosystem activities (bird habitat, sea grass restoration and shellfish restoration) in coastal Virginia. Pilot data were collected in 2008 and a full field experiment was executed in 2009, employing an experimental auction approach and mechanisms to reduce free riding often seen in the experimental economics literature. These incentive mechanisms were applied to individual restoration activities and willingness to pay estimates are compared to a baseline choice experiment that employs an incentive compatible, majority vote mechanism and actual (not hypothetical) money payments. A conditional logit model, rooted in McFadden's choice theory, was used to examine the trade-offs between ecosystem restoration activities to estimate willingness to pay. Linear and non-linear models were estimated to check for validity and sensitivity to scope.

Additional information was collected for each restoration activity using an individualized price experimental auction. Fields experiments involved approximately 90 residents of

Virginia's Eastern Shore. This portion of the experiment examines a practical method to attempt to implement an individualized-pricing approach. Participants faced a series of questions about how much they would be willing to pay to support a given level of a restoration activity, incrementally. In other words, they were asked how much they would offer for a single unit of restoration activity, then for two units of the same activity and so on. In all cases, the participant was provided $100-$150 with which to make decisions. Any money not offered towards incremental restoration activities was designated as cash to be taken home. In this way, if a participant decided to offer, for example, $90 for a single unit of restoration, they would be able to take $10 home if this was the highest amount of restoration provided by the group.

Rules for provision drew on established methods in experimental economics, notably methods for threshold public goods that involve a provision point or target of funds that must be raised to enable provision of the good. Participants were instructed that incremental provision for each good would happen only if the group offered enough funds to pay for the restoration activity. If enough funds were offered to pay for a single unit, then the auctioneer determined if enough funds were available to pay for two units based on each participant's incremental decision, and so on. The actual levels of ecosystem restoration provided are based on aggregate willingness to pay reaching a pre-determined (but unknown to the participants) provision point, or cost of implementing the project. This aggregate determination is done for each infra-marginal unit of restoration, based on the rules of the incentive mechanism, and no level of restoration can be implemented if the aggregate offers did not reach the provision point. In this way we are simulating an auction-like experience where participants willingness to pay (offers) on a given level of restoration is matched with the amount they have to pay for any level of restoration.

This work will contribute to understanding economic incentive mechanisms as an alternative to government action or voluntary fundraising by non-profit organizations as a viable approach to conservation (broader impacts) and private provision of public goods (basic science)**.** The scope of this work has implications for the private provision of public goods, impacting government, non-profits, opportunity for private organizations and local citizens, as well as economic theory. It work will provide insight on local residents' relative values for ecosystem restoration and their willingness to pay for restoration activities. Examining ways that private action may provide for public goods has theoretical merit, but is also useful for local non-profits, such as TNC (a collaborator in this research), who work to further the ecological restoration in this area.

VCR-LTER ANNUAL REPORT 2009-2010 - FINDINGS

Watersheds and Lagoons

Watershed nutrient loading

Baseflow stream nutrient monitoring conducted in the creeks of 6 sub-watersheds in Virginia from 2001-2002 (Stanhope *et al.* 2009) was used to validate the modified Nitrogen Loading Model (NLM, Valiela *et al.* 1997a, Cole 2005). The six watersheds that were used were Assawoman, Nickawampus, Partings, Greens, Mill, and Holt. These watersheds ranged in area from 117-238 ha. Forested area ranged from 24-67%, developed: 0.6-13.5%, and agricultural: 29-69%. NLM loads (in kg N y^{-1}) were statistically similar to the N loads measured by Stanhope *et al.* (2009) (Fig. F1a; slope: 0.94, R^2: 0.69, F: 7.47, p: 0.07). Agriculturally-derived groundwater N was the largest terrestrial source of nitrogen delivered

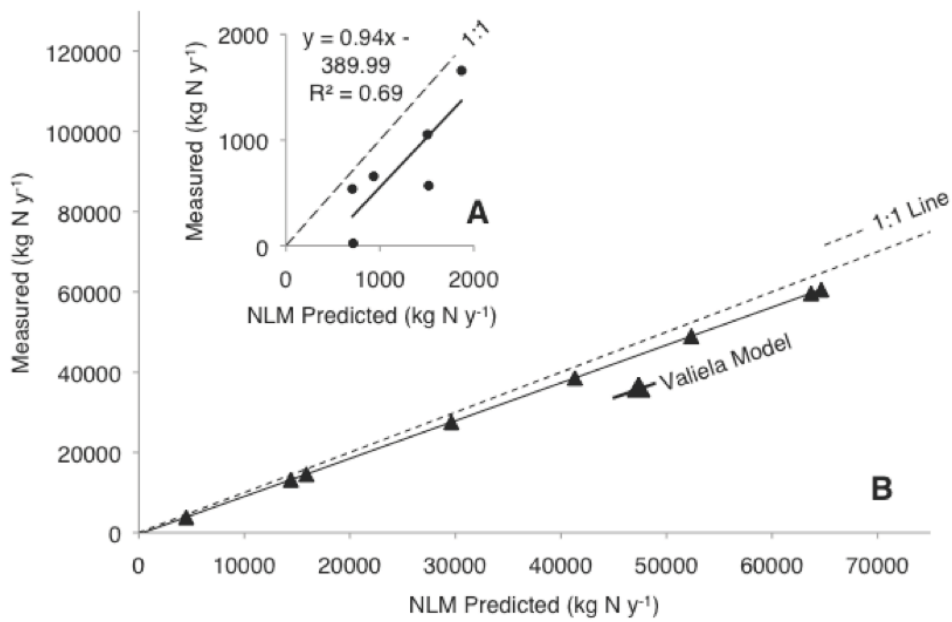


Fig. F1. Regressions showing nitrogen inputs from six subwatersheds (A) using the Valiela nitrogen loading model (NLM) and stream measurements of Stanhope et al. (2009) and nine watersheds (B) adjusted using the equation presented in (A) against the predicted values in the original NLM (Valiela et al. 1997).

to the Virginia coastal lagoons (Fig. F2). Direct deposition to the surface of the coastal lagoons was also a major input, particularly for watersheds with a small land to water ratio (*e.g.*, Machipongo, Quinby, Fisherman Island, and Sand Shoal; range: 16-98% total N; Table 1, Fig. F2). A latitudinal trend was seen in the N inputs normalized to lagoon area for the Virginia lagoons. Nitrogen input rates decreased from north (3.47-4.80 g N m^{-2} y^{-1}) to south (0.77-1.65 g N m^{-2} y^{-1}), driven primarily by a general increase in lagoon area (Table 2, Fig. F2).

The agricultural N is similar across the Virginia lagoon watersheds, but on the basis of lagoon area, the fertilizer loading rate to the northern lagoons is higher than the southern (2.62-3.57 g N m^{-2} y^{-1} and 0-0.77 g N m^{-2} y^{-1}, respectively; Table 2). The total nitrogen load (kg N y^{-1}) for the Virginia coastal lagoons was regressed with lagoon area, watershed area, agricultural area, and forested area (Fig. F3). Agricultural area was the best predictor of total nitrogen load for these systems (R^2: 0.99), followed by watershed area (R^2: 0.93), forested area (R^2: 0.75), and lagoon area (R^2: 0.20).

Table 1. Watershed Characteristics and areal loading rates of nitrogen to various coastal systems.

Location	Land Area (km^2)	Water Area (km^2)	Land:Water	Total N Loading Rate g N m^{-2} y^{-1}
Patapsco River, MD[1,*]	3415	261	13	49.0
St. Martin River, MD[‡]	96	8	11	39.7 (2.0)
Potomac River,VA/MD/WV/DC[1,*]	97938	3313	30	29.3
Narragansett Bay, RI/MA[3,*]	12194	850	14	27.6
San Francisco Bay, CA[1,*]	119178	1325	90	22.6
Chesapeake Bay, PA/DE/DC/MD/VA[1,*]	464732	25690	18	20.5
Delaware Bay, DE/PA/NJ/MD[2,*]	90222	5151	18	18.2
Mobile Bay, AL[1,*]	114415	1022	112	17.9
Patuxent River, MD[1,*]	2271	116	20	12.7
Pamlico River, NC[1,*]	26840	5588	5	12.0
Apalachicola Bay, FL[1,*]	52214	593	88	7.8
Albemarle Sound, VA/NC[1,*]	45036	2497	3.9	7.1
Isle of Wight Bay, MD[‡]	17.5	15.8	1.1	6.5 (0.7)
Assawoman Bay, VA	*36*	*7*	*4.9*	*4.8*
Choptank River, MD[1,*]	1886	411	5	4.3
Assawoman Bay, MD[‡]	24.7	22.5	1.1	4.1 (1.0)
Gargathy Bay, VA	*19*	*12*	*1.6*	*4.0*
Metompkin, VA	*67*	*49*	*1.4*	*3.5*
Wachapreague, VA	*56*	*84*	*0.7*	*1.6*
Chincoteague[1,†]	488	364	1.3	1.2 (0.9)
Machipongo, VA	*100*	*180*	*0.6*	*1.2*
Sand Shoal, VA	*60*	*169*	*0.4*	*1.2*
Smith, VA	*18*	*47*	*0.4*	*1.1*
Quinby, VA	*5*	*148*	*0.04*	*0.8*
Fisherman Is., VA	*0.25*	*5*	*0.1*	*0.8*

Watershed and Lagoon Characteristics
1. DOC/NOAA 2010
2. DOC 1985
3. Nixon *et al*. 1995
4. Valiela *et al.* 1997
5. Cole and Nixon *submitted*
italicized: this study

N Loading Rate Sources
* Boynton *et al*. 1995
† Cole and Nixon *submitted*
‡ parenthetical terms calculated from concentrations in Wazniak et al. 2004 and lagoon characteristics from Boynton et al. 1995

Table 2. Nitrogen loads to the Virginia coastal lagoons expressed in both cumulative and lagoon-area normalize loading rates. The groundwater column includes values from the agricultural, non-agricultural, and wastewater components.

	Watershed Area	Lagoon Area	kg N y^{-1} (g N m^{-2} y^{-1})					
Watershed	(ha)	(ha)	Groundwater	Ag. Component	Non-Ag.	Wastewater	Direct Dep	Total
Assawoman	3624	732	28520 (3.39)	26119 (3.57)	2401 (0.33)	1094 (0.15)	16571 (0.76)	35158 (4.80)
Gargathy	1875	1158	15316 (3.10)	12923 (2.62)	2393 (0.48)	565 (0.11)	8766 (0.76)	19644 (3.97)
Metompkin	6655	4877	61692 (2.62)	56306 (2.40)	5386 (0.23)	2009 (0.09)	36919 (0.76)	81495 (3.47)
Wachapreague	5619	8404	39619 (0.85)	35639 (0.77)	3980 (0.09)	1696 (0.04)	63618 (0.76)	76460 (1.65)
Machipongo	9987	18041	61649 (0.47)	54679 (0.41)	6970 (0.05)	3016 (0.02)	136570 (0.76)	164466 (1.25)
Quinby	528	14804	4333 (0.04)	3962 (0.04)	371 (0.00)	159 (0.00)	112066 (0.76)	77744 (0.80)
Sand Shoal	6037	16946	50520 (0.40)	46121 (0.37)	4399 (0.03)	1822 (0.01)	128281 (0.76)	147535 (1.17)
Smith	1841	4713	13849 (0.38)	12552 (0.34)	1297 (0.04)	556 (0.02)	35677 (0.76)	42320 (1.15)
Fisherman Is.	25	475	29 (0.01)	0 (0.00)	29 (0.00)	0 (0.00)	3596 (0.76)	2376 (0.77)

Agricultural area increased linearly with watershed area (R^2:0.911, Fig. F3), suggesting the uniformity of agricultural land with total land area and emphasizing the role of agriculture in this system. The percentage of the total N coming from direct deposition of N to the coastal lagoons was similar across the watersheds (0.76 g N m^{-2} y^{-1}, with direct deposition providing >50% of total N to 6 watersheds, and <50% to four. All watersheds received 75% or less of total N from agriculture, and <25% at only two watersheds (Quinby and Fisherman Island). All nine watersheds received <25% of their total N from both non-agricultural (forested, turf, impervious surfaces) and wastewater sources. Overall, annual N loading to the Virginia coastal lagoons terrestrial sources is 1.36 g N m^{-2} y^{-1} (0.009-4.0 g N m^{-2} y^{-1}), which is only 13% of the average loading rate for all of the shallow coastal systems listed in Table 1. These low nutrient loading rates are corroborated by 16 years of water quality data that show high water quality (low chlorophyll and dissolved nutrient concentrations) compared to other coastal lagoons along the U.S. Atlantic coast.

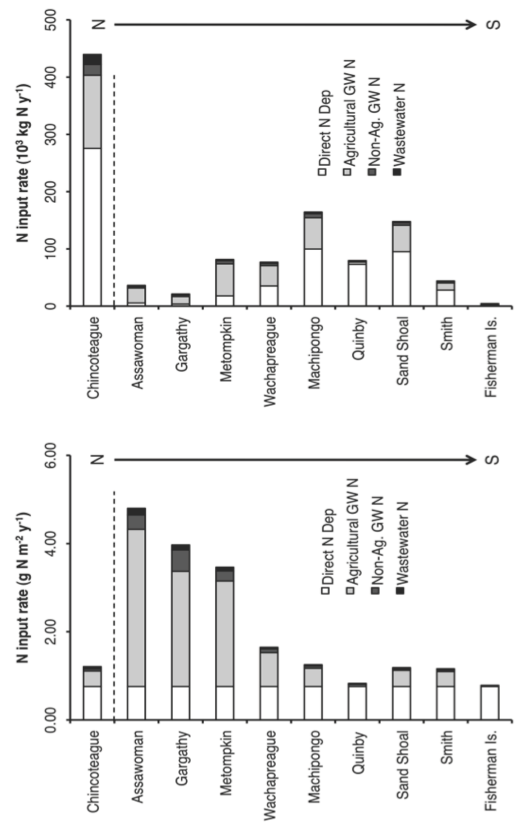


Fig. F2. Total N loads to the VCR lagoons. Watersheds are arranged North to South Data from Chincoteague Bay are from Cole and Nixon (submitted).

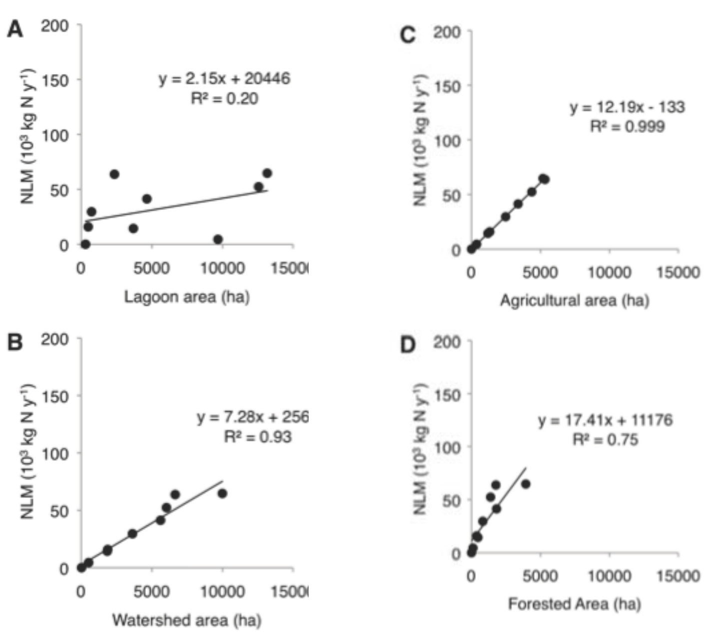


Fig. F3. Regressions showing the best predictor for the NLM for the Virginia coastal Watersheds. Agricultural fertilizer was often the largest source of terrestrial N.

Examination of diurnal patterns of groundwater to streams and the potential effect on overall nitrate removal

Previous work of Mills and his collaborators has indicated that the sediments in low relief coastal streams are a critical filter for groundwater NO_3^-, provided there is an adequate input of organic matter from the surrounding riparian zone. In Cobb Mill Creek, 80-90% of the nitrate discharging in groundwater entering the stream is removed before the water emerges from the stream sediments. They have also found that by influencing residence time, hydrology is a critical factor controlling the amount of nitrate removed from groundwater via denitrification. During small storms, the passage of a flood wave associated with storms over stream sediments can cause changes in groundwater discharge to the stream that range from a transient reduction in the discharge rate to a reversal of flow and temporary storage of stream water in the stream sediments, which would allow a greater reaction time for nitrate removal. During large storms, the flow rate increases substantially, and the solute residence time in the reactive zone is shortened resulting in a lesser extent of reaction, such that more NO_3^- is delivered to the stream water. In field measurements of storm events, large quantities of NO_3^- were quickly transferred due to the large volume of water albeit with low NO_3^- concentrations flowing in the stream Herman et al. (2008).

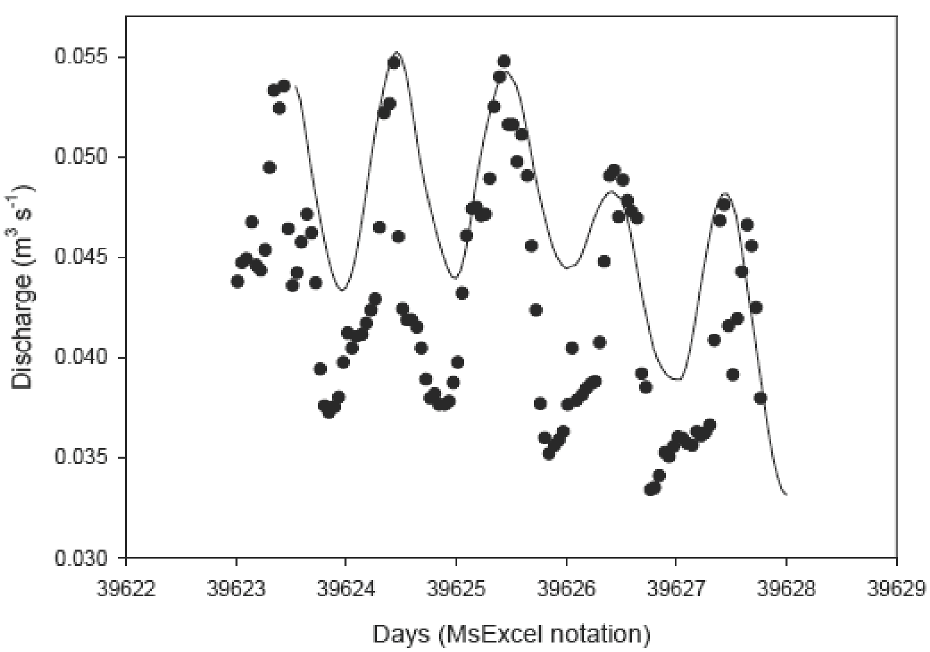


Fig. F4. Predicted and observed discharge in Cobb Mill Creek for a period in the summer of 2008. The model calculated discharge based on changes in the hydraulic gradient in the hillslope proximal to the stream. The model fits well in terms of the phasing of the observed fluctuations, but it appears to underestimate slightly the magnitude of the effect.

Mills and Herman now are determining if daily fluctuations in groundwater discharge to Cobb Mill Creek alter the retention time in the biologically active sediments sufficiently to create a change in NO_3^- discharge that is manifested in diurnal changes in stream NO_3^- concentration. Others have seen such fluctuations, but in many cases they have been attributed to water-column processes such as photosynthetic production (Rusjan & Mikos 2010). Data from our continuous stage recorders show a distinct periodic fluctuation (Fig. F4), and that fluctuation shows a clear diurnal signal (Fig. F5). Model simulations that successfully predict the change in stream discharge on a diurnal basis also indicate that NO_3^- concentration will fluctuate similarly (Flewelling, et al., in preparation).

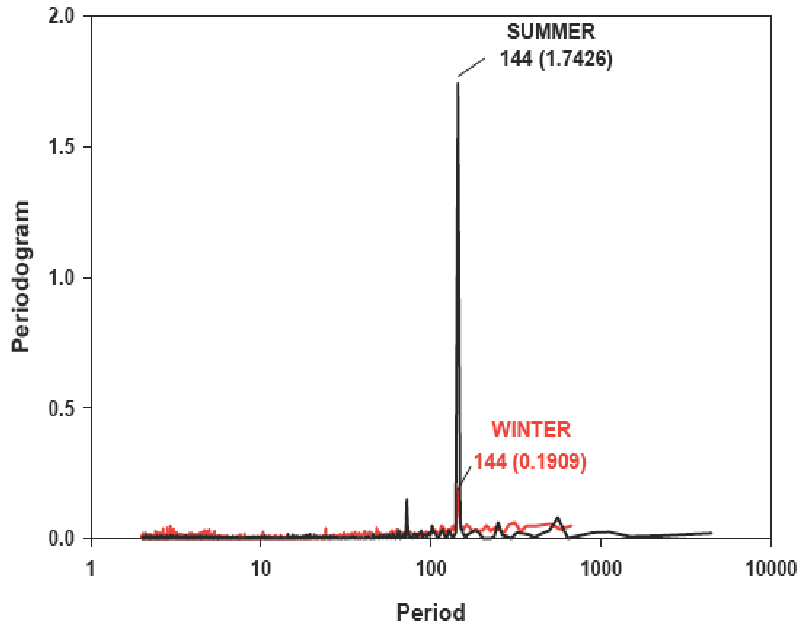


Fig. F5. Spectral analysis of daily stage fluctuations at Cobb Mill Creek. The period is the number of sample events at which autocorrelation is observed, and the "periodogram" represents the strength of the autocorrelation. Because samples were collected at 10-min intervals, the occurrence of the peaks at 144 indicates a strong signal that recurs exactly at 24-hr intervals (144 samples per day). The small winter signal is likely due to a few evergreen trees and some non-deciduous shrubs near the stream. Detrending of the data was done by the first difference method.

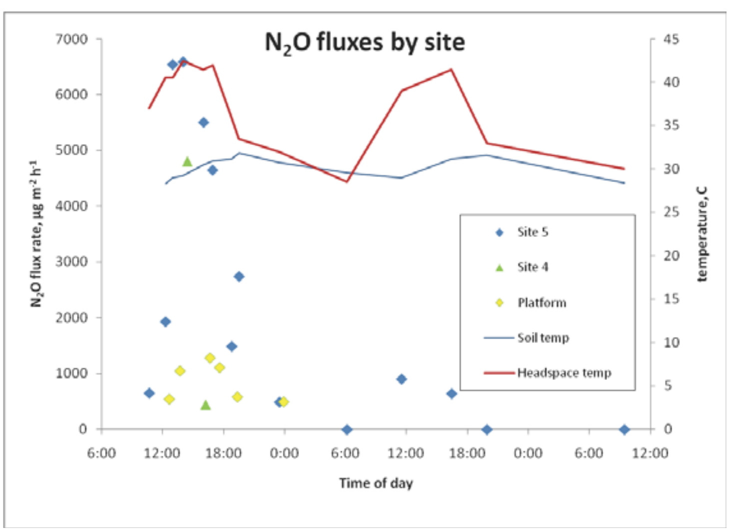


Fig. F6. Emissions of nitrous oxide (N_2O) from the Cobb Mill Creek marsh following application of nitrate-amended groundwater (10 mg L^{-1}) to the marsh surface. Flux measurements were made at three locations: Site 5 (near stream, with high ambient activity), Site 4 (near stream with low ambient activity), and the marsh platform (near marsh edge). The temporal responses of the N_2O fluxes for these three sites differed dramatically and seemed to correspond with diurnal variability in air temperature. Higher-resolution data from an automated chamber will allow us to better characterize the temporal drivers of these emissions.

Nitrous oxide fluxes from the marsh surface

The chamber flux measurements have revealed significant spatial variability in N_2O emissions, with the near-stream corridor appearing to be an emissions "hotspot". Our research seeks to determine why the fluxes are so high in this section of the marsh by characterizing physical, chemical, and biological factors such as soil texture, hydraulic conductivity, reduction potential, pH, and crab burrow density. Follow-up studies have included fertilizer treatments to determine the limiting factors influencing N_2O emissions. Figure F6 shows an example of emissions following the application of nitrate-amended groundwater (10 mg L^{-1} NO_3-N) to the marsh surface. Scanlon and Funk have developed an automated chamber to increase the temporal resolution of this sampling; this will be deployed during the next month.

Submarine groundwater discharge

Analysis of Seepage Meter Errors – In the past year, Berg and Koopmans have quantified problems associated with bag-equipped seepage meters and further developed dye displacement seepage meters as an alternative technique for quantifying SGD. This work has been submitted to Water Resources Research and is currently in review. Laboratory testing of the bags used on bag-equipped seepage meters demonstrated that a small but finite pressure is required for groundwater inflow. The amount of pressure required for inflow increases as the bag fills. Model results quantifying the SGD measurement error associated with this pressure suggested that 40% of groundwater may be diverted around a 57 cm diameter seepage meter in sediments with a hydraulic conductivity of 10^{-4} m/s at a flow rate of 1 cm/d (Fig. F7a). These results are in agreement with the poor reproducibility of seepage meters at SGD rates of less than 2 cm/d (Cable et al., 2006). On a 15 cm diameter seepage meter, the pressure required of inflow due to the presence of the collection bag could cause the diversion of all of the groundwater around the seepage meter (Fig. F7b). They also used the model to quantify the cumulative diversion of groundwater around a seepage meter as a collection bag fills. Collection bags attached by collapsing the open end of the bag around seepage meter tubing (Fig. F8a) caused the diversion of more groundwater than bags that were attached to seepage meters by a method that minimized folds in the walls (Fig.

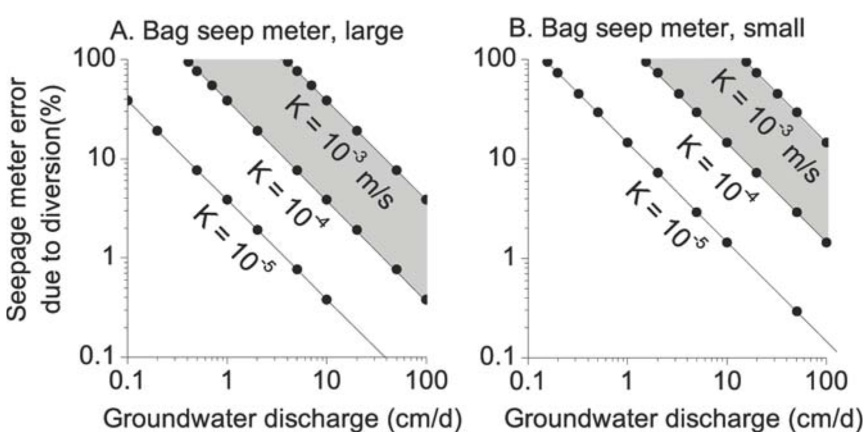


Fig. F7. Predicted groundwater diversion around 57 cm and 15 cm diameter seepage meters due to pressure required for flow into collection bags.

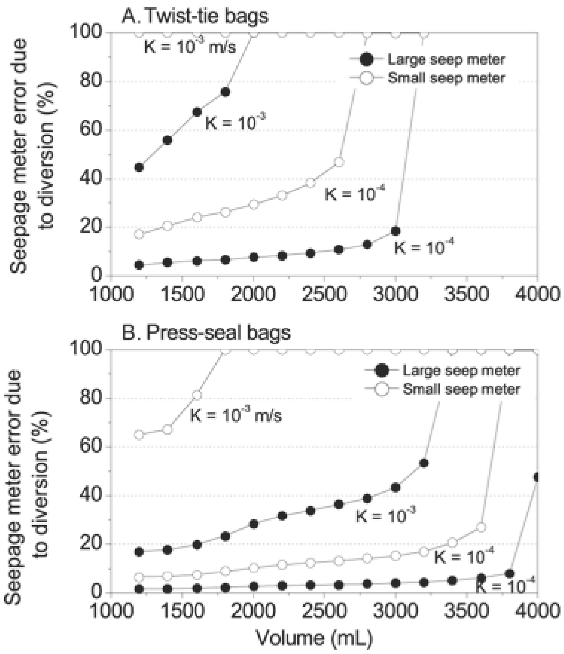


Fig. F8. Predicted cumulative diversion around seepage meters as collection bags fill.

F8b). Model results also suggested that the volume to which a bag is allowed to fill with groundwater may determine the efficiency of SGD measurement. At a fill volume of 1.6 L, 20 % of groundwater would have been diverted around a 57 cm diameter seepage meter in sediments with a hydraulic conductivity of 10^{-3} m/s and an SGD rate of 10 cm/d. If the fill volume was allowed to increase to 2.6 L, 40% of groundwater would have been diverted (Fig. F8a). These results give specific insights to improve the efficiency of SGD measurement with bag equipped seepage meters.

<u>Dye Displacement Seepage Meters</u> – Berg and Koopmans have developed a novel dye displacement technique that is a highly sensitive alternative to bags on seepage meters. Mathematical modeling of the Poiseuille-predicted, and laboratory measured, pressures associated with flow through tubing indicated that this technique would allow the measurement of SGD with far greater sensitivity to the small hydraulic gradients capable of driving pore water exchange (Fig. F9). A bag attached to a 57 cm diameter seepage meter in sediments with a hydraulic conductivity of 10^{-4} m/s and an SGD rate of 1 cm/d would be expected to divert 40% of SGD away from the seepage meter. More SGD would be diverted if the bag was allowed to approach capacity. By replacing the collection bag with a dye displacement tube the measurement error due to SGD diversion around the seepage meter would be reduced to 0.3% (Fig. F9a). An advantage of the sensitivity of the dye displacement method is that small dye displacement seepage meters may also be used to make highly accurate measurements of SGD (Fig. F9b). In addition to the advantages in sensitivity, dye displacement seepage meters are a more rapid measurement method than bag equipped seepage meters. An independent measurement of SGD can be performed in 5 to 10 minutes and can be made at many closely spaced seepage meters by one individual simultaneously. The reduced time requirements allow

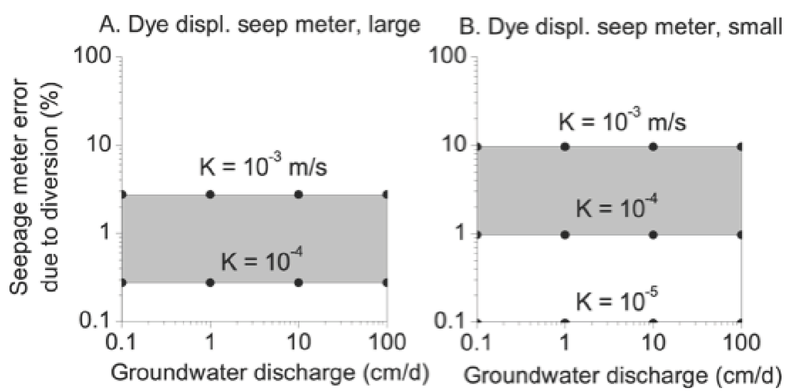


Fig. F9. Predicted error due to diversion around dye displacement seepage meters.

greater effort to be directed towards high temporal or spatial resolution of SGD. Field testing of small (15 cm diameter) dye displacement seepage meters confirmed that they were sensitive enough to reproducibly quantify low rates of SGD and the inflow of overlying water into sediments. They were capable of resolving tidally-forced SGD at a similar temporal resolution and sensitivity to far more expensive automated seepage meters (Fig. F10).

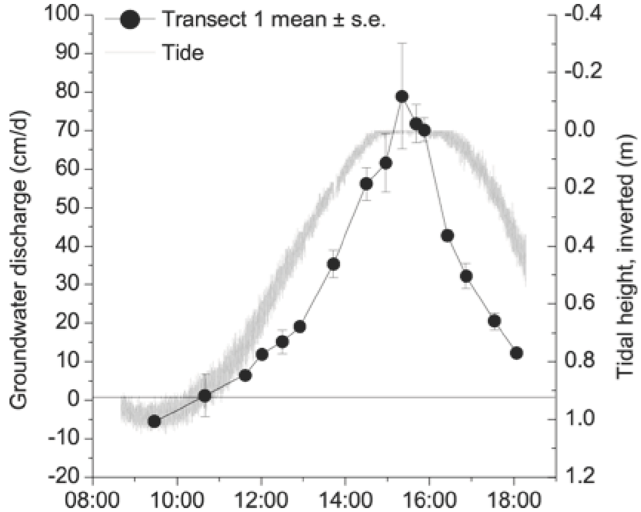


Fig. F10. Tidally-forced submarine groundwater discharge measured by dye displacement seepage meters.

Eddy Correlation Measurement of Groundwater Discharge - Mathematical modeling of groundwater discharge and the supply of nitrate to a creek following a storm suggest that high nitrate groundwater discharge through the base of tidal creeks will be suppressed during a flood wave, but will increase sharply as the flood wave moves out of the watershed (Gu et al., 2008). To test these model predictions Berg and Koopmans applied the eddy correlation technique to measure groundwater discharge through the base of a stream bed at low flow conditions and while a flood wave passed through a watershed. A heat balance was used to quantify groundwater discharge to Frogstool Branch by eddy correlation in October of 2009. Frogstool Branch is a sandy creek in a mixed forested and agricultural watershed that drains to the Machipongo River at the VCR-LTER. An acoustic Doppler velocimeter and fast temperature sensor were aligned so that they would simultaneously measure water velocity and temperature in a shared volume of water, 9 cm above the creek bed, 32 times/second (Fig. F11). Instantaneous deviations from the mean vertical velocity and temperature were used to calculate the vertical eddy flux of heat. For calculations, detail, and assumptions of the eddy flux method see Berg et al., 2003.

The pattern of calculated discharge of groundwater through the stream bed agreed with prediction by Gu et al., (2008). A series of rainstorms moved through the study area during a four day deployment in Frogstool Branch (Fig. F11). Heat fluxes were measured at two locations 30 m apart, Site I and Site II. Hourly rainfall is presented in Figure F11a, along with the response in mean stream velocity. The temperatures of the stream and of the creek bed are presented in Figure F11b, with light penetration to the stream bed. Pore water in the creek bed was consistently warmer than that of the creek, and the temperature increased with depth. Groundwater discharge through the creek bed, a positive heat flux, was observed over most of the four day deployment (Fig. F11c; breaks in the heat flux record at hours 33 and 60 are due to time required for data transfer). The heat fluxes and pore water temperatures were used to calculate a groundwater discharge rate presented in Fig. F11d (we assumed a source groundwater temperature of 16.5 °C based on measurements of groundwater temperature 70 cm below the stream bed). Water depth is also presented in Fig. F11d.

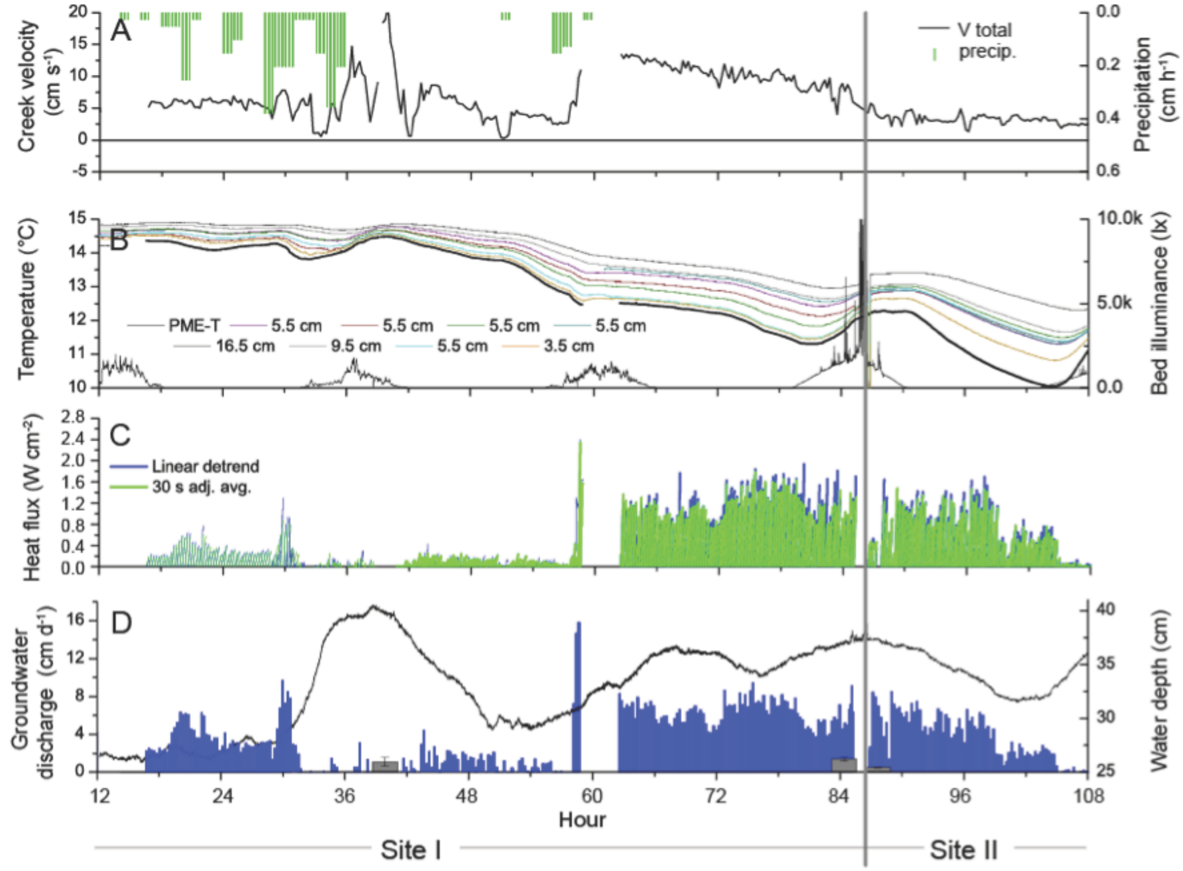


Fig. F11. Groundwater discharge to Frogstool Branch at the VCR-LTER quantified by eddy correlation. A) Hourly precipitation and the response of water velocity in the creek to rainfall. B) Creek and bed temperatures plotted with solar illumination of the creek bed. C) Heat fluxes calculated from the mean of the product of the instantaneous deviations in vertical velocity and temperature. D) Groundwater discharge rates derived from a heat balance. Groundwater discharge rates measured by seepage meters are presented as grey bars with standard errors.

Groundwater discharge followed expected patterns over the four days, with rainfall causing increases in groundwater discharge at hour 18 and again at hour 58. In addition there is evidence that the hydraulic pressure on the creek bed generated by a flood wave caused the suppression of groundwater discharge and a possible temporary reversal, a net movement of creek water into creek sediments. The subsequent discharge of this temporarily stored creek water would be expected to generate a small heat flux as was observed in hours 48 to 58. Dye displacement seepage meter measurements of groundwater discharge (grey bars in Fig. F11d) did not match groundwater discharge calculated from eddy correlation. Seepage meters measure vertical groundwater discharge absent any horizontal component, and may make spurious observations of discharge in high current environments where pressure gradients may interfere with seepage meters and their measurement devices. In contrast, eddy correlation measures heat exchange across a footprint on the sediment surface regardless of the vertical or horizontal component to groundwater flow (for details on the eddy correlation footprint see Berg et al., 2007). Additionally, eddy correlation incorporates the *in situ* pressure gradients that develop due to flow through a porous creek bed. Eddy correlation shows promise as a novel technique for quantifying groundwater and pore water discharge where a temperature gradient exists between sediments and overlying waters.

Lagoon hydrodynamics

Fagherazzi and Wiberg (2009) used a simple parametric wave model for shallow water to estimate sediment erosion potential in shallow tidal basins caused by wind-wave events in coastal bays like those of the VCR. Their method determines the aggregate response of the entire basin, combining in a simple framework the contribution from different landscape units. They have run the model with different tidal and wind conditions to quantify bed shear stresses and erosion potential of the lagoon bottom under different forcing conditions. Their wave analysis in the VCR lagoons unravels the interplay of basin morphology, tidal elevation, and wind direction on water depth, fetch, and the resulting wave-generated shear stresses. They identify four bottom shear stress regimes as a function of water elevation produced by wind waves in shallow micromesotidal systems. For water elevations below mean lower low water (MLLW), an increase in fetch is counteracted by an increase in depth, so that the average bottom shear stress and erosion potential is maintained constant (Fig. F12). For elevations between MLLW and mean sea level (MSL), the increase in water depth dominates the increase in wave height, thus reducing the bottom shear stresses. For elevations between MSL and mean higher high water

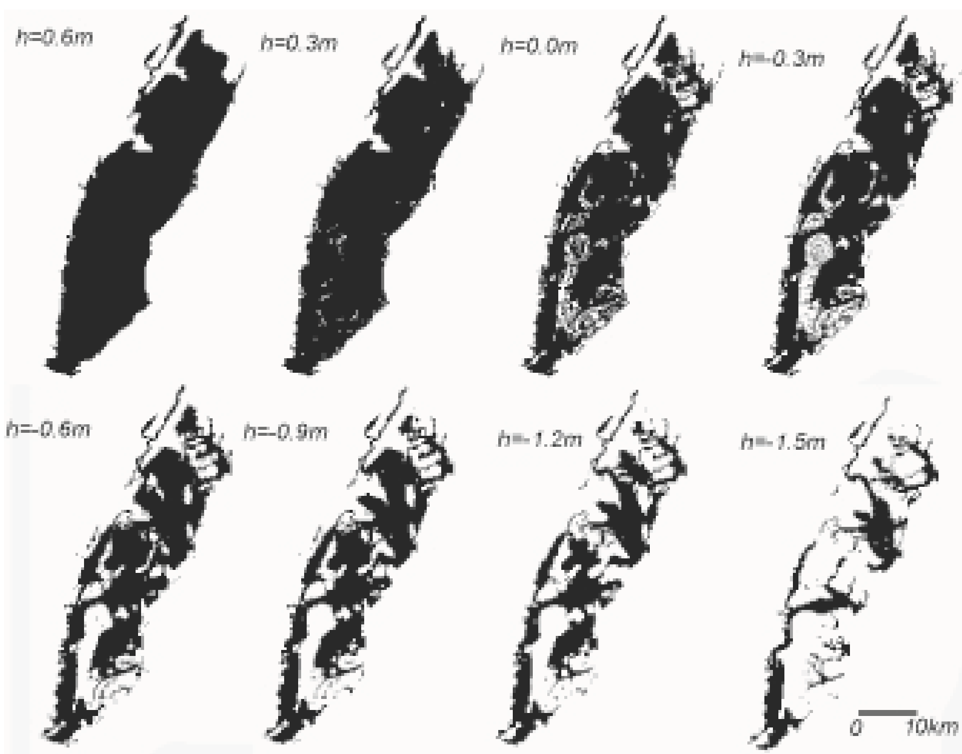


Fig. F12. Model runs to quantify bed sheer stresses and erosion potential of the lagoon bottom at different water depths.

(MHHW), the range associated with stable salt marsh platforms, flooding of salt marshes increases fetch, wave height, and bottom shear stresses, producing the largest resuspension events in the bay. For elevations above MHHW, the increase in depth once again dominates increases in wave height, thereby reducing average bottom shear stresses and potential erosion (Fig. F12).

Seagrass restoration

We began our annual synoptic monitoring of the newly seeded sites and the chronosequence sites in summer 2007. This marks the start of a new long-term data set that includes seagrass variables (density, canopy height, above- and below-ground biomass, productivity, epiphyte biomass, and tissue carbon and nitrogen contents), sediment variables (benthic chlorophyll, organic content, grain size, porosity, and carbon and nitrogen contents) and macroalgae biomass. In the Hog Island Bay restoration plots, germination rates and seedling survival is 7-12%, which is on par with what has been found in other regions, such as Chesapeake Bay and the Maryland coastal bays (R. Orth, pers. com.). Density has increased annually and is now approximately 100 shoots m^{-2} for all plots regardless of year planted (Fig. F13). Our preliminary data show that rates of productivity, faunal density and diversity (per shoot) are similar between treatments in the 1-2 year old meadows in Hog Island Bay, and between these meadows and the older (7 and >10 years) meadows in the chronosequence, suggesting that the change in seagrass density is the important driver of state changes in the system. The data also show an apparent tipping point in water

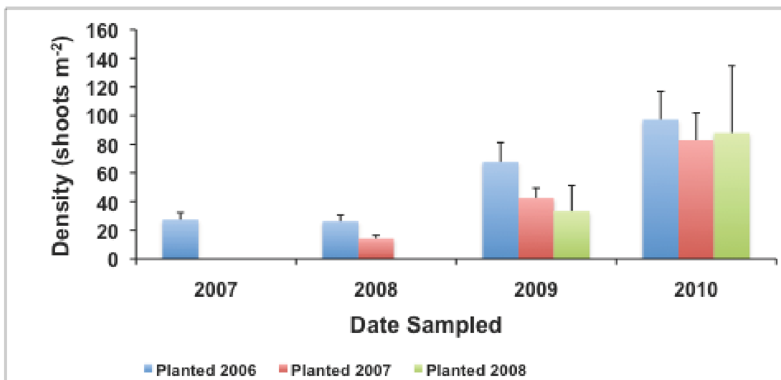


Fig. F13. Seagrass density in the Hog Island Bay restoration plots. In 2010, density was similar regardless of year planted. Density in nearby 10-year old plots was approximately 600 shoots m^2.

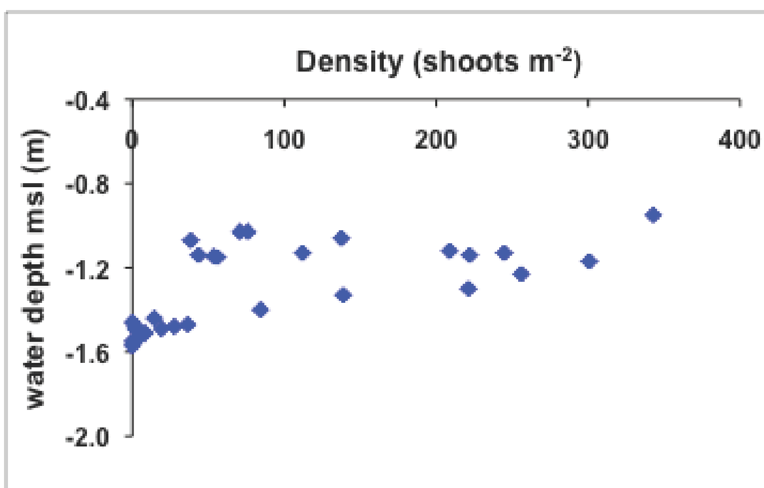


Fig. F14. Density of restored seagrass meadows at different water depths, indicating a likely tipping point for survival between 1.5 and 1.6 m MSL.

depth, with a maximum depth limit of 1.5-1.6 m MSL (mean sea level) (Fig. F14).

The results of the lagoon stability model indicate that under typical conditions the system is bistable; seagrass is stable in water depths < 2.2 m MSL (51% of the bay bottom deep enough for seagrass growth), and bistable conditions exist for depths of 2.2 – 3.6 m MSL (23% of bay), where the preferred state depends in initial seagrass cover. The remaining 26% of the bay is too deep to sustain seagrass (Fig. F15). Decreases in sediment size and increases in water temperature and degree of eutrophication shift the bistable range to shallower depths, with more of the bay bottom unable to sustain seagrass (Carr et al, 2010). These modeling results agree reasonably well with our monitoring data from the restoration experiment, although our monitoring data indicate a shallower tipping point.

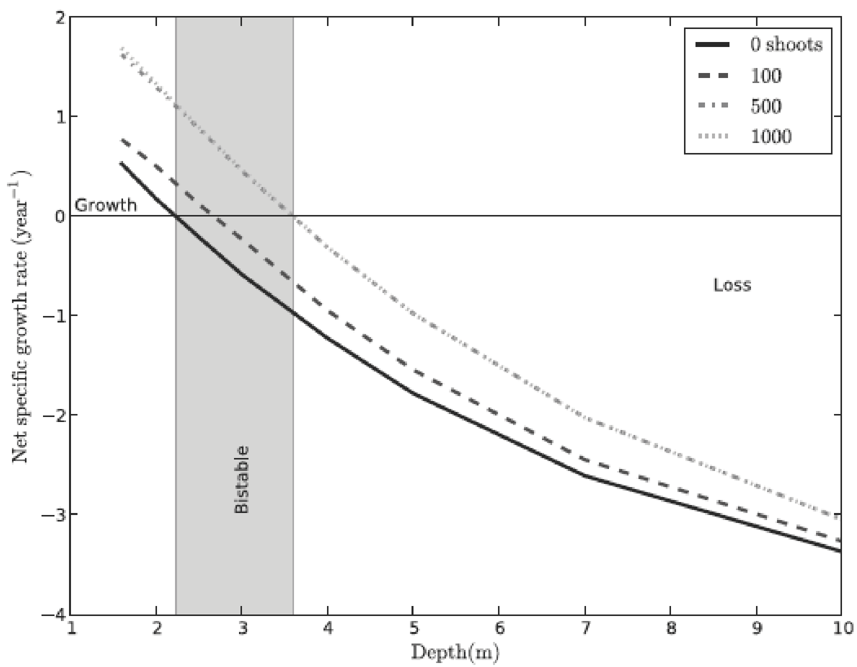


Fig. F15. Specific growth rate as a function of depth for varying shoot densities.

Genetic studies

Genetic diversity, structure, and population connectivity are important to the restoration success and stability of seagrass populations. The challenge for restoration efforts is to minimize the loss of genetic diversity due to collection of donor material from a limited area and low transplant survival and to understand the connectivity with extant populations. For the restored seagrasses in the VCR lagoons, we are using microsatellite techniques to: 1) assess the genetic diversity of the seagrass meadows on a local (VCR coastal lagoon) and latitudinal metapopulation (Eastern

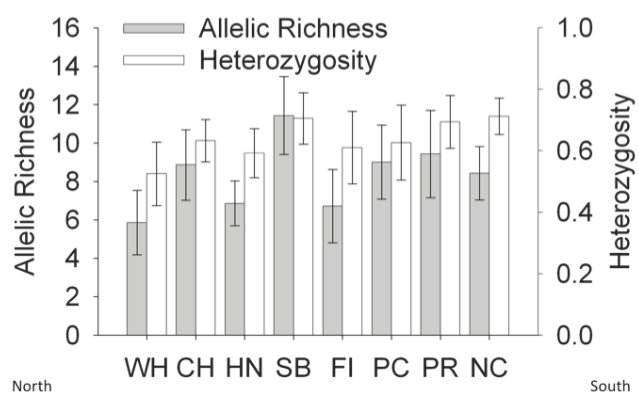


Fig. F16. Genetic diversity is similar along the U. S. East coast between Massachusetts and North Carolina. HB and SB are seagrass meadows in the VCR.

Atlantic Coast) scale to determine connectivity between meadows, 2) determine if using seeds from a broad range of donor sites increases the genetic diversity of restored seagrasses and if this is related to metrics of restoration success, and 3) identify the origin of the plants naturally recruiting to the area.

There has been concern about restorations in general and seagrass restorations in the VCR that they may lack genetic diversity. Since the entire population shrank to very low numbers in the 1930s, we expected population bottleneck effects including a high degree of inbreeding and lack of genetic diversity. The literature suggests that seagrass restoration itself, at least when done using adult transplant techniques, further creates a bottleneck and reduced diversity (Williams 2001). A survey of the eelgrass meadows in and near the VCR reveals that our populations show little evidence of bottlenecks or reduced genetic diversity (Fig F16). In addition, a comparison of donor and recipient meadows show that our method of restoration by seed does not reduce genetic diversity suggesting that when logistically possible, this method of restoration might be more desirable (Fig. F17). This survey also revealed genetic similarities in the Chincoteague Bay meadows and the areas of natural recruitment within the VCR, suggesting that Chincoteague Bay may be the source of that natural recruitment.

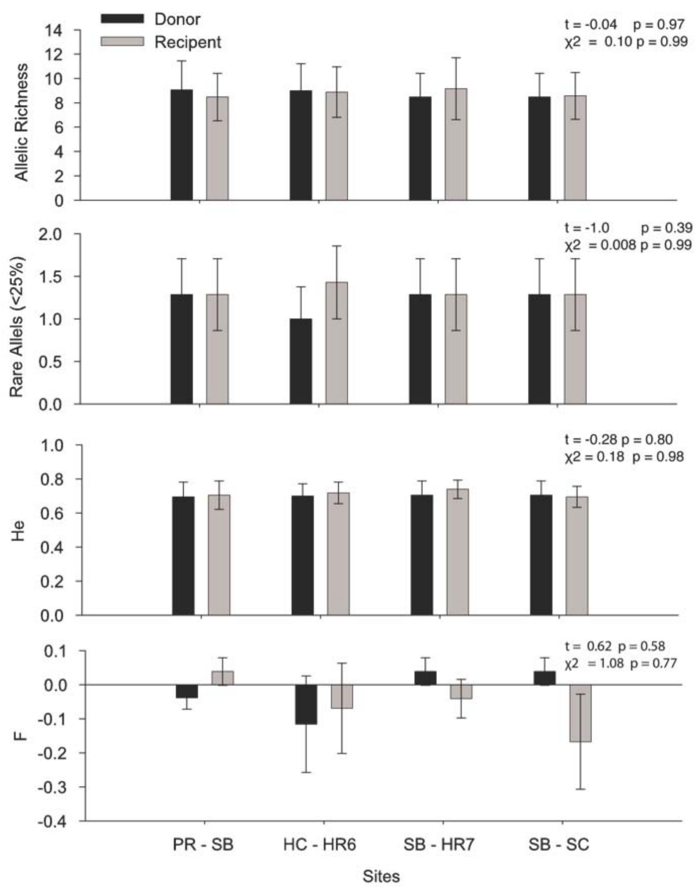


Fig. F17. Comparison of diversity indices between donor and recipient populations in the seagrass restoration plots showing that seeding does not reduce genetic diversity.

Results from the experiment to test whether increased genetic diversity of donor populations increases restoration success indicate that genetically diverse plots do have higher ecosystem functions. The higher-diversity plots have a higher seagrass density (Fig. F18), are marginally more productive, and while they do not harbor greater numbers of invertebrates, there is a greater diversity of associated invertebrates. If these ecosystem services are used as measures of restoration success, this experiment suggests that genetic diversity is important to restoration success.

The experiment was also designed to test for stresses associated with light limitation by blocking the plots along a depth gradient. The deepest plots eventually died, while the shallow plots are still expanding. Plots with a low diversity died at a significantly younger age than those with a higher genetic diversity (Fig. F19). There is evidence from the literature that genetic diversity is associated with higher resistance to large disturbances, this experiment shows that diversity is important to the resistance of smaller stresses as well.

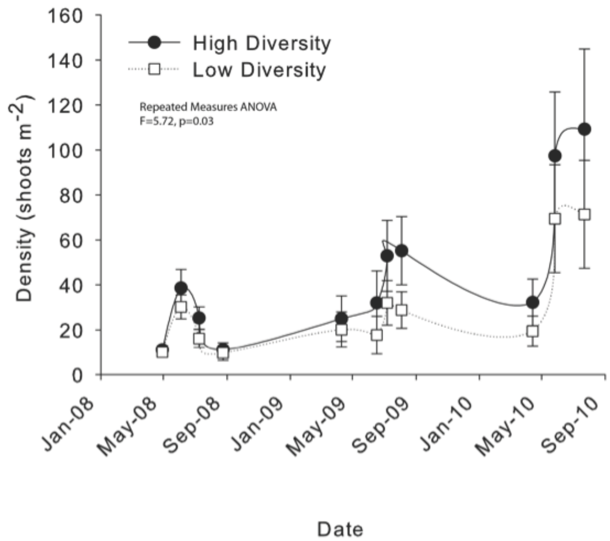


Fig. F18. Seagrass shoot density in plots seeded from donor populations with different levels of genetic diversity.

Nitrogen cycling

Nitrogen fixation rates were measured in restored *Z. marina* meadows in Hog Island Bay and South Bay. These meadows were initially seeded in 1-acre plots at 100,000 seeds acre^{-1} in 2006 and 2001, respectively. In 2009 and 2010, 4 vegetated plots and 4 bare plots were sampled seasonally in each of the two lagoons and nitrogen fixation associated with sediment was quantified using the acetylene reduction technique. The bare and vegetated sediments in Hog Island Bay showed very little difference in nitrogen fixation rates (Fig. F19). Although the bare sediment had wider ranges, the means were comparable. There was a more pronounced difference in South Bay, where the bare sediments had lower and less variable nitrogen fixation rates than vegetated sediments (Fig. F19).

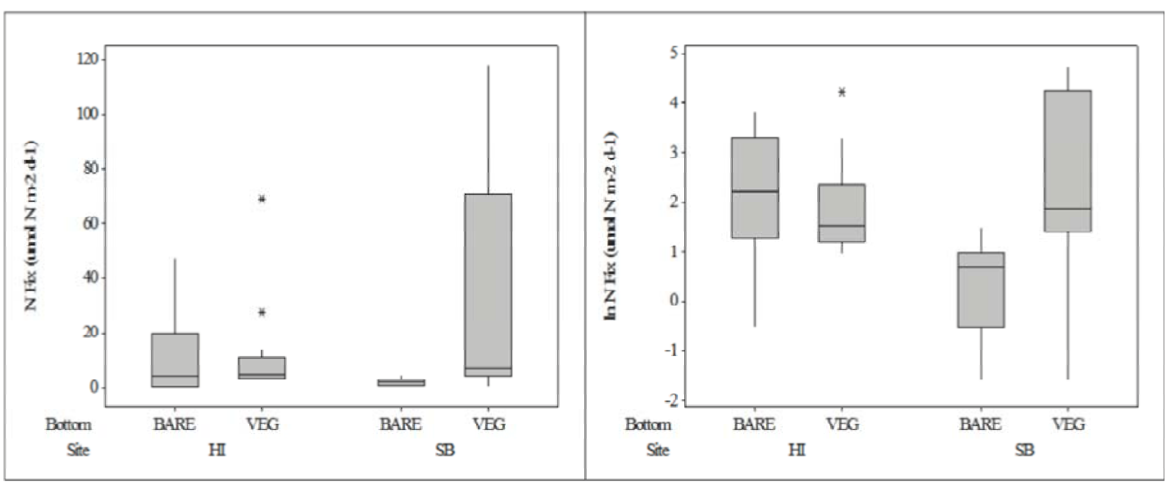


Fig. F19. Nitrogen fixation associated with sediments in bare and seagrass-vegetated sediment in Hog Island Bay (HI) and South Bay (SB).

Older seagrass meadows (like those in South Bay) tend to have higher productivity and belowground biomass than younger meadows, potentially providing more organic carbon to nitrogen fixers in the rhizosphere and thus increasing nitrogen fixation. Furthermore, older, more established seagrass beds create greater drag on the overlying water column, causing light-diffusing particles to fall out of suspension; this increased light availability drives higher sediment nitrogen fixation rates in seagrass beds. We suggest these mechanisms are responsible for the comparatively high rates of nitrogen fixation in the vegetated sediments of South Bay, and for the low rates elsewhere. Future work will examine in more detail the seasonal, age, and site-specific influences on nitrogen fixation rates.

Sediment fluxes

Hydrodynamics and sediment motion within seagrass beds - Three seagrass sites were characterized, totaling 700 m^2 of area of *Zostera marina.* These sites had densities of 563, 390, and 152 shoots/m^2 (Table 3). A bare site was also monitored as a reference for flow characteristics in the absence of benthic structure.

Table 3. Morphometric analysis of *Z. marina* blade geometries for the sites tested

	mean length (cm)	median length (cm)	max length (cm)	density (shoots/m^2)
Jan. Site 1	9.2±5.5	8.2	20.6±2.9	261.3±39.0
May Site 1	23.0±6.5	22.4	8.2±0.2	409.2±86.9
Jun. Site 1	20.6±7.6	20.4	32.6±2.9	562.6±70.5
Jun. Site 2	28.3±13.3	20.2	51.3±3.6	389.5±83.2
Jun. Site 3	15.5±9.0	14.8	34.0±4.2	151.8±82.8

Water column profiles over the high density seagrass site show increasing velocities toward the surface of the water column (Fig. F20). Within the seagrass there are lower velocities where the flow is attenuated by the seagrass structure. Further, high velocities penetrate the upper part of the seagrass meadow but only at low tide. With deeper water, the flows within the meadow are on average less than 1 cm/s. At high tide, longer blades shelter the bed from high velocities, but when the water column depth decreases, there are notable increases in sediment concentration. Within the meadow the suspended sediment concentrations are generally lower than in unvegetated areas. Resuspension events causing high suspended sediment concentrations are present on days 160.75 and 161.75 when there is a marked increase in the significant wave height. Spikes in suspended sediment concentrations are generally more random at the bare site, with one notable exception. After time 147.5 there is an extended resuspension event where suspended sediment concentrations increase and sediment stays suspended for a number of hours. This corresponds to larger wave heights, a

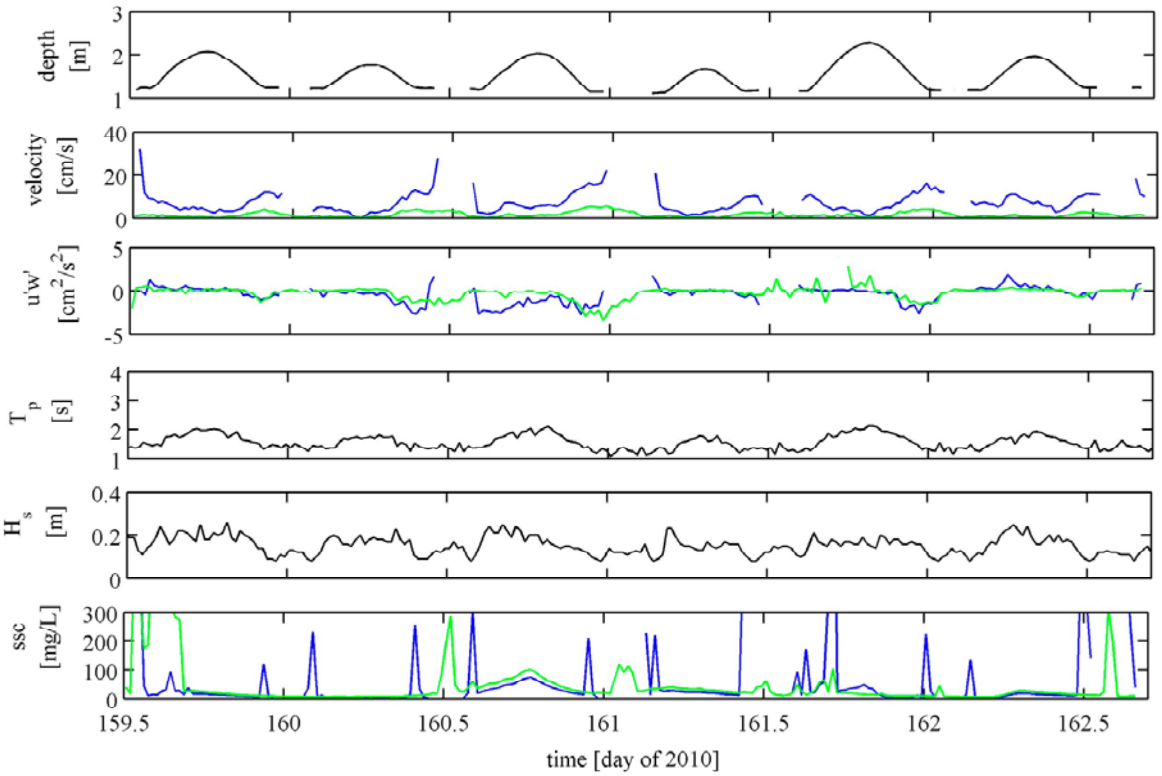


Fig. F20. Time series of hydrodynamic and sediment data within the high density seagrass meadow. From top to bottom are water depth [m], velocity [cm/s], <u'w'> [cm^2/s^2], T_p [s], and H_s [m], and suspended sediment concentration [mg/L]. The x-axis represents time in decimal days beginning January 1, 2010. The blue lines correspond to the ADV at 50 cm above the bed (cmab) and the green lines to the one at 5 cmab. Discontinuous lines are due to the instrument coming out of the water at low tide.

slightly longer wave period, and a peak in the turbulent fluctuations. The concentrations drop immediately at the end of the wave event.

When waves are present in seagrass meadows, oscillating velocities can be seen penetrating the meadow even at relatively low velocities (Fig. F21a). Mixing rates and energy transport are estimated from Reynolds stress values (<u'w'>) and the spatial distribution of turbulent kinetic energy (TKE). TKE was determined on the scale of a few seagrass blades *in situ* using a submersible PIV system. The production and dissipation of turbulent kinetic energy can be determined by the following equations:

$$\mathrm{Pr}\,oduction = \overline{u'w'}\frac{du}{dx} \qquad Dissipation = \frac{15}{7}\nu\left[2\left\langle\frac{\partial u}{\partial x}\right\rangle^2 + 2\left\langle\frac{\partial w}{\partial z}\right\rangle^2 + \left\langle\frac{\partial u}{\partial z}\right\rangle^2 + \left\langle\frac{\partial w}{\partial x}\right\rangle^2 + 2\left\langle\frac{\partial u}{\partial z}\frac{\partial w}{\partial x}\right\rangle\right]$$

Turbulent kinetic energy production and dissipation is concentrated at the top of the seagrass canopy along the boundary (Fig. F21b). Most of the production is around the blades themselves and the dissipation balances production until just above the canopy boundary where a shear layer in the mean velocity profile forms and production becomes dominant.

There is a net transfer of TKE away from this shear layer and TKE is non-locally dissipated above the canopy, higher in the water column.

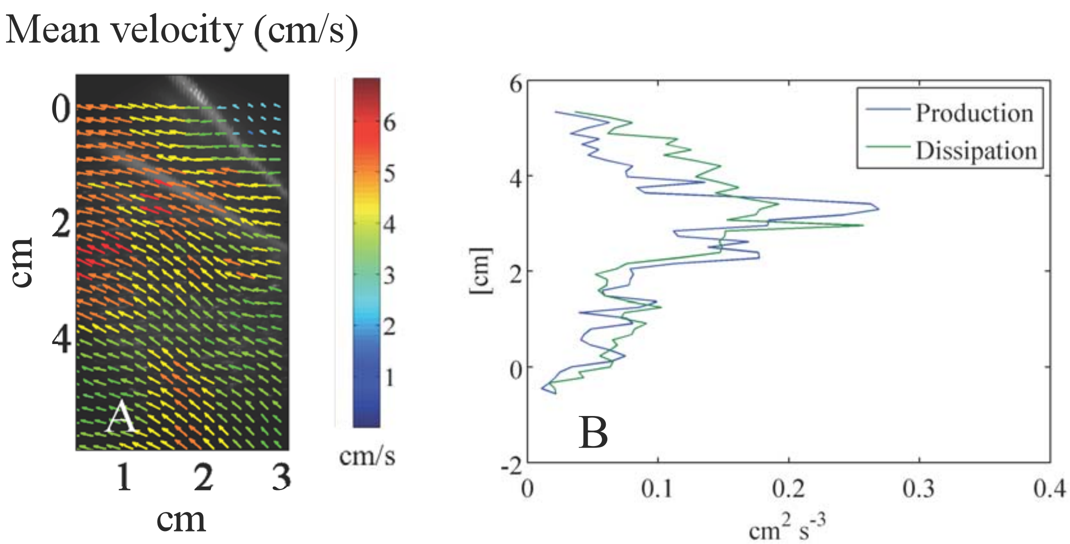


Figure F21. Particle image velocimetry at Site 1 in South Bay, Virginia. (A) Mean velocity are represented by vector arrows whose length and direction reflect the magnitude and direction of velocity. The colorbar also corresponds to velocity magnitude in cm/s. (B) Vertical distribution of TKE production (blue) and dissipation (green) with TKE values [cm^2/s^3] on the x-axis and the vertical spatial scale [cm] on the y-axis. The top of the canopy occurs at approximately 3 cm elevation where a peak in production occurs.

Overall, measurements have shown that unidirectional flow skims over seagrass beds but wave action causes blades to oscillate back and forth, increasing fluid exchange between water within the canopy with that above the canopy. The degree of flow reduction by the canopy is a function of velocity, wave frequency, and meadow morphology (distance from the edge of the canopy, shoot density, strap-bladed or cylindrical blade morphology), and depth below the surface, the result of which can cause variability in sedimentation, altered nutrient availability, and enhance bed stability. The interaction of waves and currents can increase bottom shear, which can result in increased sediment suspension. The resulting increase in seagrass blade motion can intensify flow within the meadow. This leads to dissipation of TKE above the canopy with production of TKE occurring at the shear layer formed at the top of the canopy along the blades.

Modeling of seagrass state change and resilience to climate change effects

With the hydrodynamic model alone, under typical conditions for Hog Island Bay, the system favors the presence of a stable seagrass bed ("vegetated state") at locations with water depths, $Z < 2.2$ m. In this stable vegetated state, shoot density, N is not determined by light but by other limiting factors (e.g., nutrients). For $Z > 3.6$ m the light availability is not sufficient for the growth and survival of seagrasses because partial light saturation would occur less than 50% of the time. In this case, bare sediment conditions are stable. For depths of 2.2 m $< Z <$ 3.6 m the system exhibits bistable behavior. Depending on the initial seagrass cover conditions, the system converges to a state with either bare sediment or vegetated conditions. Overall, the light environment depends on seagrass shoot density, *N*. However, when *N* exceeds a limiting value an increase in stem density has only a minimal impact on suspended sediment concentrations and associated light attenuation. *Z. marina* is typically found at depths in the range from 1 to 10m, with light availability limiting the lower depth limit. In the case of Hog Island Bay, using 1m as the shallow depth growth limit for *Z. marina*, 23 % of the area deeper than 1m is found to be bistable, while seagrass beds are stable in 51% of the bay. The remaining 26% of the bay is unable to sustain seagrass. Further results are reported in Carr et al. 2010 (see Fig. F15).

Combined hydrodynamic and seasonal growth model simulations, the steady state scenario - Years were evaluated by days above 26 degrees C and below 5 degrees C, as these are the temperatures at which the difference of the scaled specific growth and loss rates,

$$max_{pht} F_I(I)\, F_{pht}(T) - max_{resp} F_T(T),$$

becomes negative. This was also compared to just the days above 26 degrees C to evaluate long winters or hot summers. Similarly the peak values of scaled net growth rates occur when the temperatures are between 16 and 24, and these 'growing days' were totaled for each year. In general, the 'good' years are accordingly years when the number of growing days were high, and the number of loss days low. Years were also evaluated by both the average shear stress exceeding the critical shear stress for a given year as well as the total number of hours when the shear stress acting on a bare sediment bed exceeds the erosion threshold critical shear stress. This provides an estimate of storminess, or at least the transport capacity of the various years (Table 4). The model was run repeating each individual year until "steady state" conditions for individual years were achieved. 'Good' or 'bad' years were graded by comparing the wintering shoot densities at steady state for runs at 1.6 m water depth (Table 5).

Table 4. Effects of the presence or absence of a steady state canopy on the bottom shear stress, and the number of growing hours undergoing transport events for steady state arriving from the base scenario, or from the good scenario. Only in 1996 is the presence of a canopy unable to reduce the average shear stress below the critical shear stress for entrainment.

	$\tau_b > \tau_{crit}$	Mean τ_b	Mean τ_b with canopy	Growing hours with $\tau_b > \tau_{crit}$	
Year	hours	Pa m^{-2}	Pa m^{-2}	base (hours)	good(hours)
2004	1969	0.0570	-	1056	1056
1996	2003	0.0481	0.0419	1080	816
2002	1661	0.0441	0.0361	984	528
1998	1922	0.0497	0.0336	936	312
1997	2041	0.0478	0.0322	912	264
2003	1806	0.0457	0.0306	240	240
1999	2144	0.0461	0.0298	408	408
2000	2121	0.0476	0.0280	288	288
2001	1912	0.0471	0.0248	312	312

The worst year 2004, was unable to sustain any amount of seagrass due to low number of growing days as well as significant sediment transport and adverse light conditions. In 1996, the days of loss exceeded the days of growth. Looking at the difference in growing days to loss days across all the years, the best year, 2000, had the highest number of net growing days. This pattern extends throughout the years used with the exception of 2002 and 1998. 2002 had only a low value of 100 growing days resulting in low net growth. 1998 had a moderate 115 growing days, however shear stresses were higher increasing water column turbidity and impacting growth. The years of 2005 and 2006 were omitted due to severely sparse or missing temperature data, and the years 2007 through 2009 were due to incomplete or missing wind field information.

Table 5. Steady state wintering shoot density, and the number of years to reach steady state from the base scenario of 4 shoots, and good scenario of a fully developed meadow, along with days of growth and loss for the nine years.

	base	base	good	good	Grade	Growing	Dying	T>26
Year	shoots m^{-2}	Years to SS	shoots m^{-2}	Years to SS		days	days	days
2004	0	4	0	18	poor	102	86	40
1996	0	3	309	11	poor	100	120	50
2002	0	10	385	5	medium	100	64	12
1998	0	6	417	3	medium	115	80	8
1997	0	10	461	2	medium	104	77	17
2003	496	23	497	1	medium	109	89	41
1999	547	13	546	1	medium	145	63	18
2000	568	7	569	1	good	140	32	19
2001	602	7	603	1	good	155	56	53

The steady state seasonal above and below ground biomass (Fig. F22) demonstrates similarities and differences between the years. Most years undergo a significant above ground and below ground biomass loss during the hot water temperature periods followed by a regrowth during the fall. During the fall regrowth, the rhizome biomass is essentially constant as the new leafs and shoots are produced prior to the winter loss (Fig. F22, panels a-i). For most years the summer loss is greater than the loss of biomass during the winter, the exception being 2001 where the spring growth extends till early August rather than late June and a short summer die off, followed by a longer winter (Fig. F22, panel f).

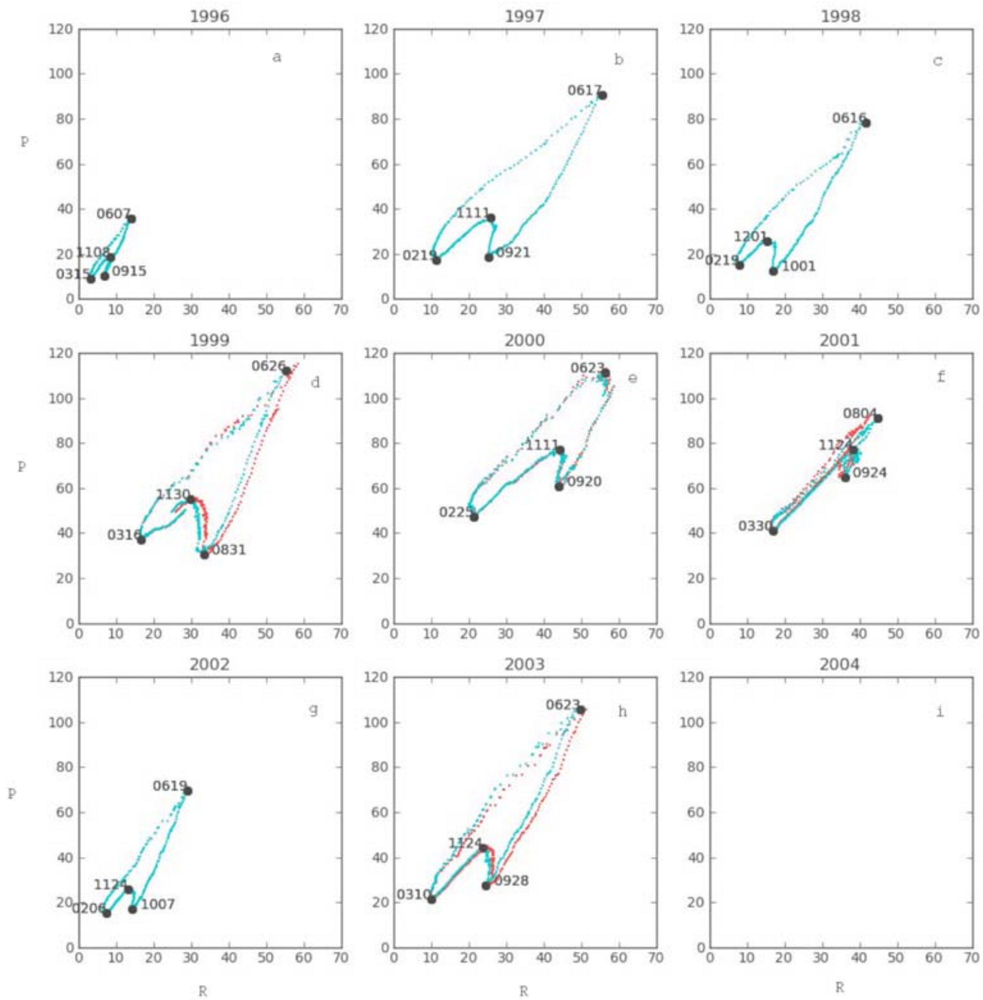


Fig. F22. Steady state seasonal above ground biomass, P (gC/m^2) and below ground biomass R (gC/m^2) for 1996-2004.

Flow dynamics and metabolism of oyster reefs

Comparing hydrodynamics over different benthic substrates gives insight into the varying recruitment success for localized bed conditions. In this study four velocity profilers were deployed at four different sites all adjacent to one another. The first Aquadopp was placed on the historical (healthy) reef, HLCR2, the second was placed on HLCR WELK, the third was placed on a mound of fossil shell within HLCR 2008, and the 4th Aquadopp was placed at the mud site to get a bulk flow baseline (Fig. F23). The mud site, due to low friction values, had the highest mean velocities, and the healthy oyster site had the lowest.

Detailed flow profiles adjacent to the roughness elements indicate that the high roughness found at the healthy reef sites creates regions of slow flow adjacent to the oysters, promoting conditions favorable for larval settlement. As the roughness decreases, higher velocities are found adjacent to the bed, increasing the likelihood that larvae will be washed away before successful recruitment.

Structure manipulation experiments - Although experiments are still in progress, visual surveys indicate that a critical steepness is necessary to prevent sediment accumulation on surfaces, which is a known complication that limits settlement success (Figure 4). These initial findings also are evidence of why the taller, steeper topography formed by the healthy oyster reefs or whelk shells are better recruitment substrate and have higher yields than fossil oyster shells which typically lay flat on the surface and accumulate more sediment.

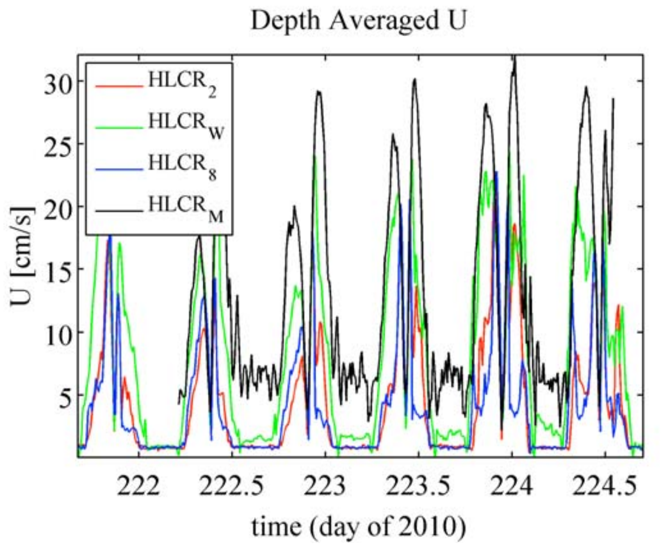


Fig. F23. Depth averaged horizontal profiles for the 4 study sites tested.

Invasion of the red macroalga, Gracilaria vermiculophylla

Previous work in the VCR has shown that *Gracilaria vermiculophylla* may be an important non-native algae of East Asian origin in the coastal bays. *G. vermiculophylla* can only be identified using genetic analyses and therefore this cryptic invader was misidentified in the VCR as the native *G. verrucosa*. In the summer of 2009 we measured algal biomass and collected samples for genetic analyses from 40 sites within the VCR (Fig. F25). Of 192 samples analyzed, 189 were one of 11 different haplotypes of *G. vermiculophylla*.

Fig. F24. Structure manipulation experiments showing three different geometries of slate plates. Note the large sedimentation and no visible recruitment on the tray with flat plates.

G. vermiculophylla colonizes marsh, mudflat and seagrass habitats and therefore this non-native has the potential to affect all of these different ecosystems. In order to determine if the invasive enhances nitrogen availability to the cordgrass, *Spartina alterniflora*, we set up an experiment on a marsh in the VCR in summer 2010 where we elevated ^{15}N levels in *G. vermiculophylla* tissue and then allowed it to decompose on the marsh, and expect to find that sediment, cordgrass and herbivore ^{15}N levels are elevated during this experiment.

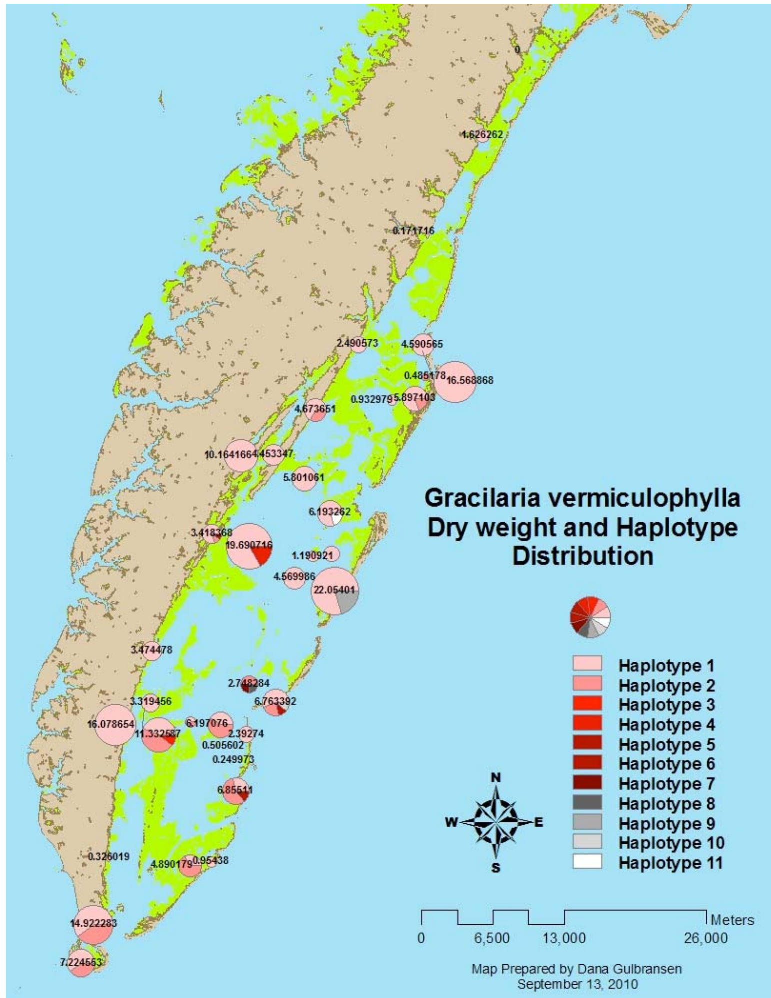


Fig. F25. Map showing relative dry mass of *G. vermiculophylla* collected at each site in the VCR (numerical value in g/m^2 written on top of circles). Larger circles indicate that more algae were found at that site. Each circle is partitioned based on the number of *G. vermiculophylla* haplotypes found at each site

Tidal Marshes

Marsh accretion relative to sea-level rise

The long-term data set (13-year) of the surface elevation tables (SETs) to measure overall elevation change, root SETs (RSETs) to measure change associated with root zone, and marker horizons for estimating surface accretion at our core study site, Phillips Creek Marsh is shown in Figure F26. Recent data analysis of 12 years of marsh elevation/accretion measurements (Fig. F26) has not identified correlations with anticipated hydrological forcing including groundwater elevations, patterns of tidal flooding, and rainfall. While this was unexpected, it has become clear in the analysis that the connection between tides and the more isolated portions of the high marsh zone is quite weak, especially for those areas dominated by *Spartina patens, Distichlis spicata, and Juncus roemerianus.* This new information changes our view of accretion in the high marsh and how it is related to sea-level rise.

At the Phillips Creek Marsh, hydrologic monitoring in tidal creeks, on the marsh platform, and in surrounding upland wells is done to capture the frequency, duration, and flooding depths by semidiurnal tides, and is summarized to correspond to the frequency of SET data collections (Fig. F27). Surrounding upland wells are monitored monthly for water table and conductivity to capture longer term effects of sea level influences beyond the marsh margin. In addition, annual root and rhizome dynamics between a monoculture of short-form *Spartina alterniflora* in the low marsh and a mixed community of *Spartina patens* and *Distichlis spicata* were compared in the high marsh by Blum UVA undergrad, Bridget Long (Fig. F28).

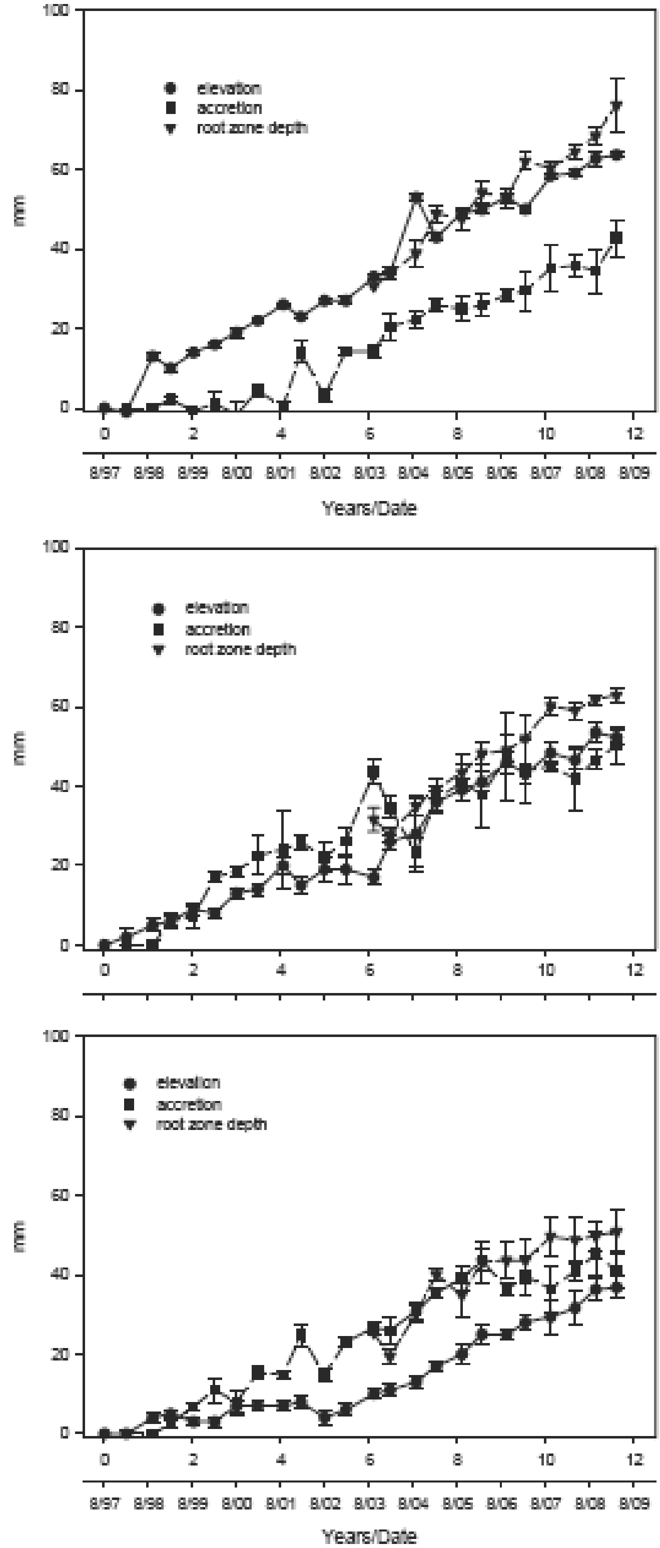


Fig. F26. Relationship of elevation (SET, circles) change to surface accretion (marker horizon, squares) and root zone accretion (RSET, triangles) measured semi-annually from August 1997 for elevation and surface accretion and from August 2003 for root zone accretion. Low zone (top panel), mid zone (center panel), high zone (bottom panel). Error bars represent standard error for n=3.

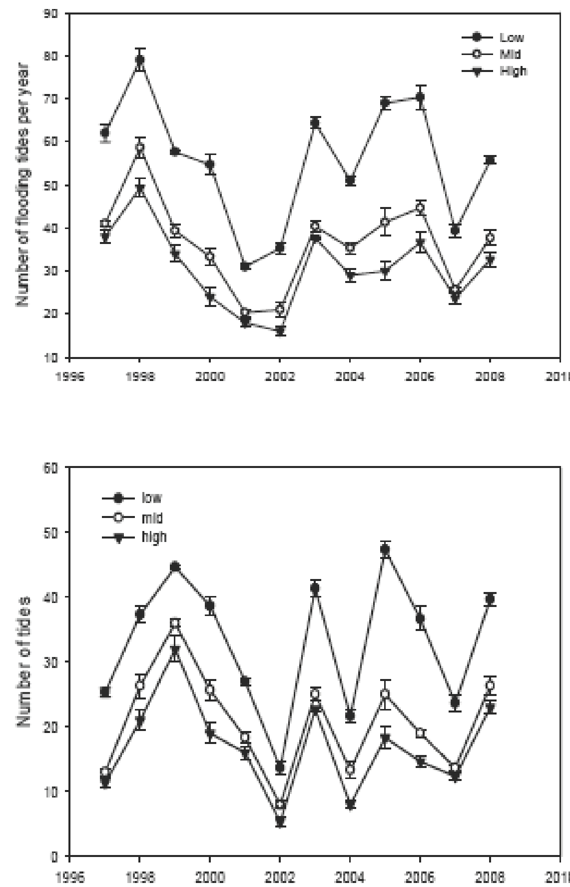


Fig. F27. Number of tides that flooded the low, mid, and high zones of the marsh platform during each year (top panel) and during the growing season (bottom panel) at sites where the SETs have been measured in Upper Phillips Creek marsh. Each point is the mean of the number of tides flooding replicate SETs in each zone (n=3). Standard error bars are shown.

Vegetation dynamics – long-term studies

Brinso, Blum and Christian continue to harvest aboveground biomass at the annual peak with the intent of detecting climatic influences in an otherwise marine-dominated environment (Fig. F29). Patch dynamics of *Juncus* also continues to be collected on an annual basis at the Phillips Creek Marsh.

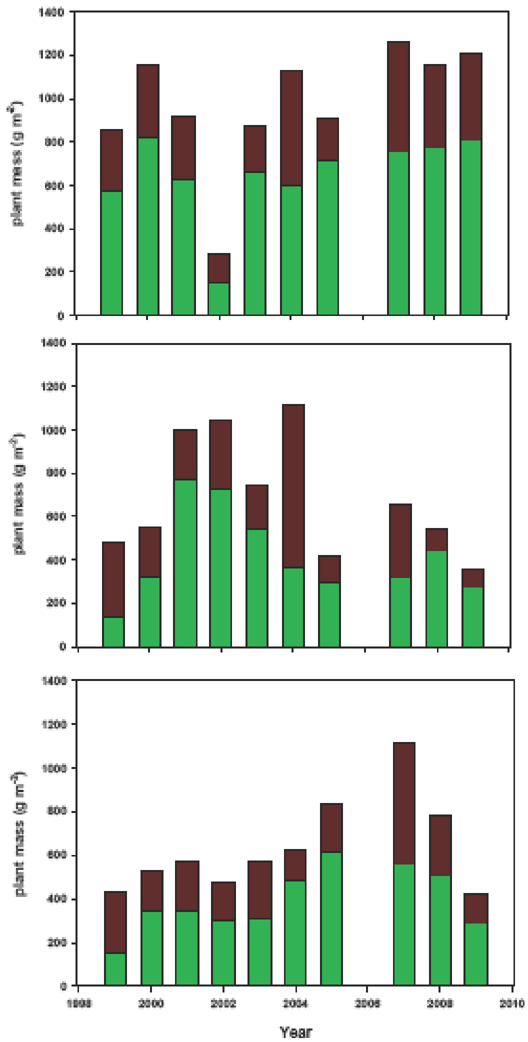


Fig. F29. End-of-Year-Aboveground Biomass for three of eight salt marshes sampled since 1999. Samples were not collect in 2006. Live (green bars) and standing dead plants (brown bars) are shown for Oyster Harbor marsh (top panel), Box Tree marsh (middle panel), and GATR Tract marsh (bottom panel).

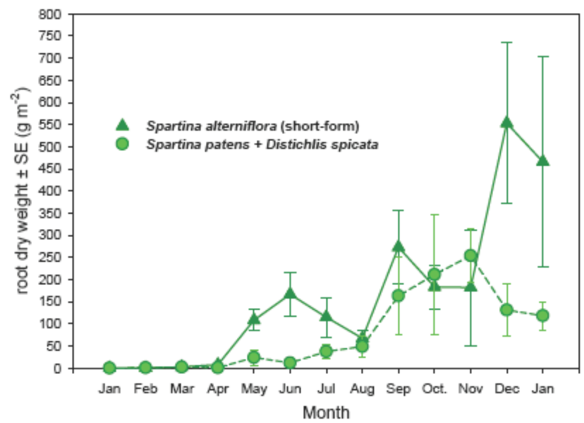


Fig. F28. Comparison of annual root and rhizome dynamics between a monoculture of short-form *Spartina alterniflora* in the low marsh and a mixed community of *Spartina patens* and *Distichlis spicata* in the high marsh. *S. alterniflora* annual root productivity was 744 g m^{-2} yr^{-1}, while productivity in the mixed community was 267 g m^{-2} yr^{-1}.

Marsh erosion and changes in marsh area

Characterization of marsh edge properties and erosional mechanisms - Results from the sediment grain size analysis indicate that grain size differs significantly among the four sites (Fig. F30). Sediment size decreases with distance from the barrier island, which is consistent with the findings of Lawson (2004) for Hog Island Bay. The lone exception is Fowling Point, our mainland marsh site, which has the coarsest sediment. This is unusual because there is not a sandy sediment source present in that vicinity to replenish the marsh. These sediment results, along with the low-lying topography, relatively stable edge, and large adjacent mudflat, seem to support a previous suggestion by Oertel and Woo (1994) that Fowling Point is a hammock marsh, which develops from relict beach or strand plain ridges.

While the marsh edge at Fowling Point has remained relatively stable over time, the edge at the other three sites (Hog Island, Chimney Pole, and Matulakin Marsh) has been rapidly eroding at rates of over a meter per year. Despite similar erosion rates, the mechanisms for erosion appear to differ among the three sites. At Matulakin Marsh (MM), large, interconnected burrow structures dominate the marsh edge, the result of communal burrows formed by the crab species *Sesarma reticulatum, Panopeus herbstii*, and *Uca pugnax*. The dominance of silty sediment likely increases the ability of these crabs to rework sediment near the edge. As water passes through these burrows through ebbing and flooding of the marsh and wave impact along the edge, large cracks form in the marsh that connect adjacent burrow openings. Over time, these cracks cause large blocks of marsh to separate from the edge. This is the dominant erosional mechanism at site MM.

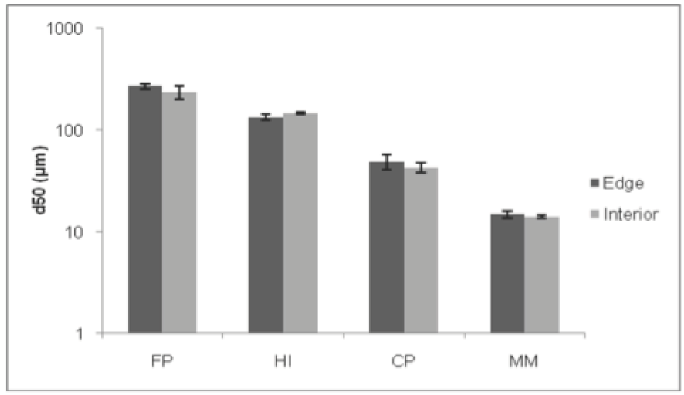


Fig. F30. Median grain size at four marsh sites. Edge samples taken from marsh edge, interior samples taken 10 m from edge. Error bars are ± 1 S.E.

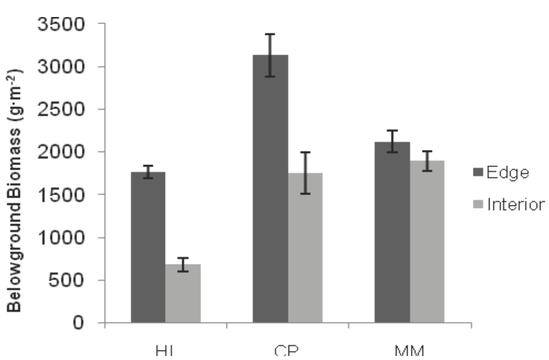


Fig. F31. Total belowground vegetation biomass at 0-5 cm depth interval.

Fig. F32. Webcam recording marsh edge erosion on Chimney Pole marsh.

Belowground biomass appears to play a significant role in stabilizing the marsh at Chimney Pole (CP), particularly the top 5 cm of the root mat (Fig. F31). As waves repeatedly attack the marsh edge, this top layer of the root mat begins to separate from the underlying material. Eventually, this layer finds a weakness in the marsh, likely along the crab burrows that line the edge, and separates completely from the marsh. Without the stabilization of the thick root material, the underlying sediment is more susceptible to erosion, which may lead to a relatively quick retreat of the marsh edge. To help document this process, a network video camera was installed on the marsh (Fig. F32). The camera focuses on a single location of the marsh edge and stores a picture every thirty minutes during daylight hours. The camera is powered by a solar panel and battery and is capable of transferring images from the marsh to a computer in Charlottesville. While installed on the marsh, the camera has captured significant erosion events and has increased our understanding of the underlying processes.

The erosion processes at the edge of our back-barrier marsh site on Hog Island (HI) are not as immediately evident as those at CP and MM, however, both block detachment and terracing are apparent in some locations. The less cohesive nature of the coarser marsh sediment at this site may leave this marsh more susceptible to undercutting and persistent erosion from wave attack. As waves attack the edge, they remove sediment more easily than at the muddier marsh sites. This may lead to a continuous cycle of erosion. It is unclear how barrier overwash may affect progradation or movement of the marsh edge at this site.

<u>Influence of storm surges and sea level on marsh boundary erosion </u>– The results of the finite Element model WWTM applied to the VCR lagoons were analyzed in terms of bottom shear stresses on the tidal flats, a measure of sediment resuspension potential, and total wave energy impacting the marsh boundaries, which is the chief process driving lateral marsh erosion. Results indicate that wave energy at the marsh boundaries is more sensitive to wind direction than are bottom shear stresses. Wave energy on marsh boundaries and bottom shear stresses on the tidal flats increase with sea level elevation, with the former increasing almost ten times more than the latter. Both positive and negative feedbacks between wave energy at the boundaries and bottom shear stresses were predicted, depending on the fate of the sediments eroded from the salt marsh boundaries (Fig. F33).

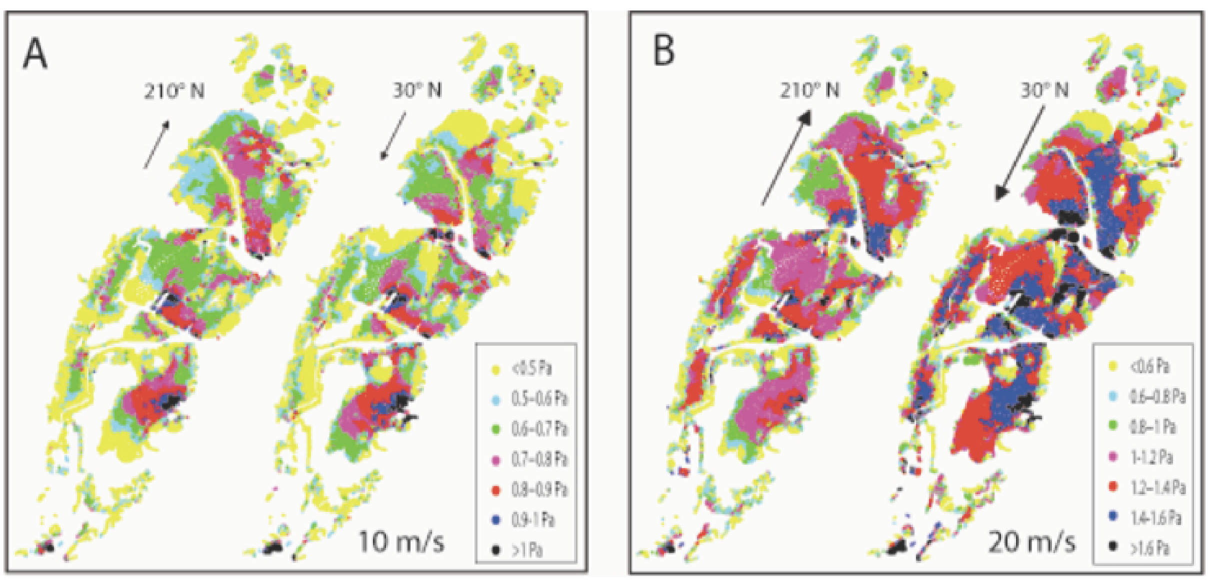


Fig. F33. A) Wave induced bottom shear stress over the tidal flats, averaged over 48 hours of simulations, calculated for a wind speed of 10 m/s and two different directions (30, 210N). B) Same as A with wind speed of 20m/s.

Flooding frequency and water table elevation - Water-level data recorded near the Chimney Pole marsh edge show significant dry-down of the water table for periods > 1 week during some neap tides (Fig. F34). High temperatures and low precipitation during the summer of 2010 may be playing a role in these dry-down periods. Historical tide and weather data will be used to put these results in context (Fig F35).

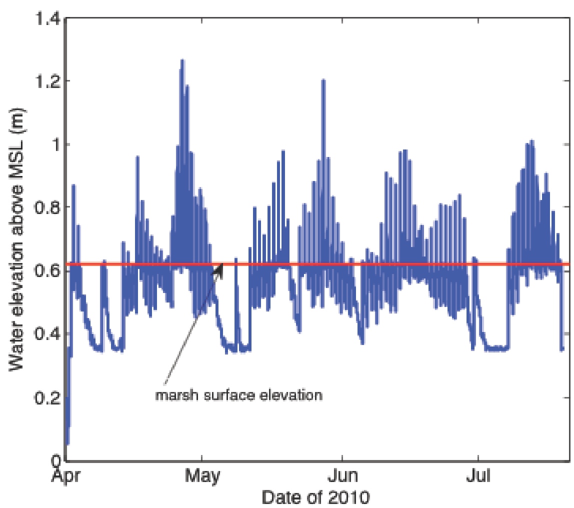


Fig. F34. Water-level measurements near the edge of CP.

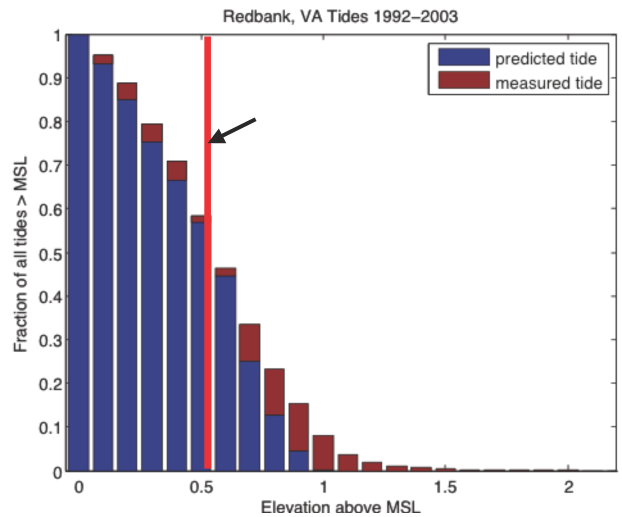


Fig. F35. Fraction of the time that water-level exceeds the indicated depths in Hog Island Bay.

A numerical model for the coupled long-term evolution of salt marshes and tidal flats - Numerical results of the coupled salt marsh-tidal flat model show that vegetation determines the rate of marsh progradation and regression, and plays a critical role in the redistribution of sediments within the intertidal area (Fig. F36). Simulations indicate that the scarp between salt marsh and tidal flat is a distinctive feature of marsh retreat. For a given sediment supply, the marsh can prograde or erode as a function of sea-level rise. A low rate of sea-level rise reduces the depth of the tidal flat and increases wave dissipation. Sediment deposition is thus favored and the marsh boundary progrades. A high rate of sea-level rise leads to a deeper tidal flat and therefore higher waves that erode the marsh boundary, leading to erosion. When the rate of sea-level rise is too high the entire marsh drowns and transforms into a tidal flat.

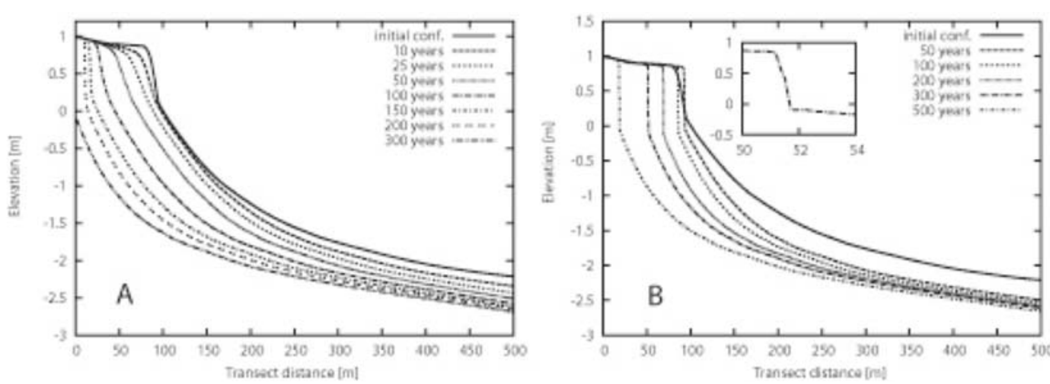


Fig. F36. Salt marsh deterioration. The evolution of the profile starts from a fully developed salt marsh, imposing a sediment concentration equal to 0.1 g/l at the seaward boundary: a) without vegetation, b) with vegetation.

Modeling wave impact on salt marsh boundaries - The results of the Boussinesq model applied to a marsh boundary show that the wave thrust on the marsh scarp strongly depends on tidal level (Figs. F37, F38). The thrust increases with tidal elevation until the marsh is submerged, then it rapidly decreases. The wave thrust is maximum for a vertical scarp and minimum for a terraced scarp. Similarly, wave energy dissipation is maximized just above the marsh platform elevation, when wave reflection is reduced and wave breaking occurs at the marsh edge.

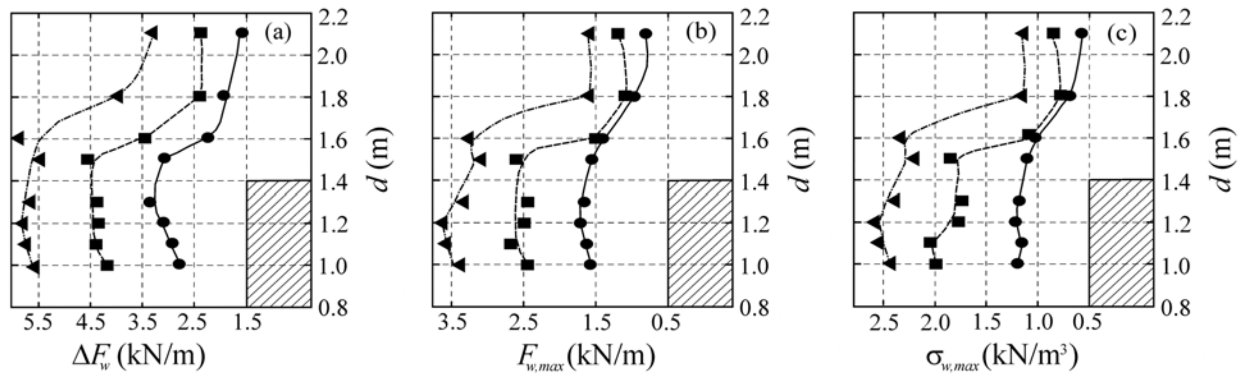


Fig. F37. Wave thrust variation with tidal elevation and wave height: triangles H=40cm, squares H=0.30cm; circles H=0.20m; (a) difference between maximum and minimum wave thrust; (b) maximum wave thrust; (c) maximum stress.

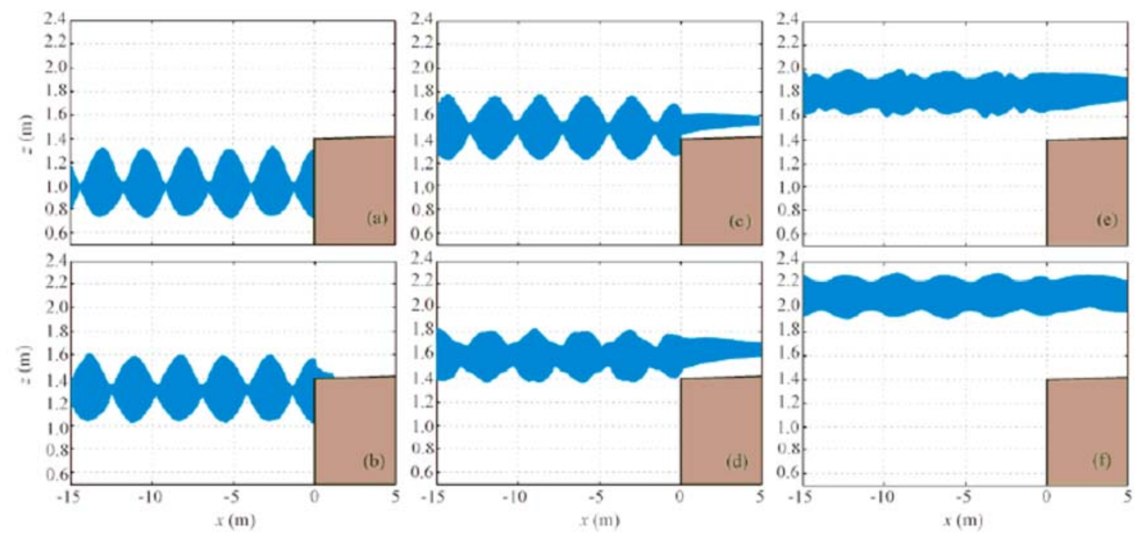


Fig. F38. Simulation of the impact of wind waves on marsh boundaries: water surface elevation envelope as a function of tidal elevation d for waves of 0.3m: (a) d = 1.0 m; (b) d = 1.3 m; (c) d = 1.5 m; (d) d = 1.6 m; (e) d = 1.8 m; (f) d = 2.1 m. Maximum impact of waves on the marsh edge occurs in case (a).

Trophic interactions – environmental impacts on waterbirds - We are comparing a relatively pristine region (the VCR) with a highly disturbed and human-dominated landscape (the New York metro region) to determine if feather growth of young birds can be used as a bioindicator of the quality of prey and hence, estuarine conditions,. Early results support the hypothesis for the ibises; i.e. the width of the growth bars in young ibis is greater in VA than in NY (Figs. F39, F40). Also, the occurrence of "fault bars" (and indication of food stress or contaminant load such as mercury) was greater in NY than in VA (Figs. F41, F42). Research continues tying the feather growth with the food boluses collected, and with mercury analyses.

Fig. F39. Pictures of Glossy Ibis feather. Note the distinct growth bars running perpendicular to the rachis of the feather. In order to measure growth bars, insect pins are used to mark the 10 distal growth bars and digital calipers are used to determine the

Fig. F40. Average growth bar width for young Glossy Ibis primary feathers, 2009 and 2010, comparing the relatively pristine Virginia Coast Reserve (VCR-LTER) and the human-modified New York Metro region. The width of a growth bar is an index of the nutritional condition of the developing nestling and indicates quality of diet. These measures are known to correlate with survival in first year birds.

Fig. F41. Fault bars are weak areas of the feather where a reduction of resources are placed into the developing integument due to an acute stress faced by the bird.

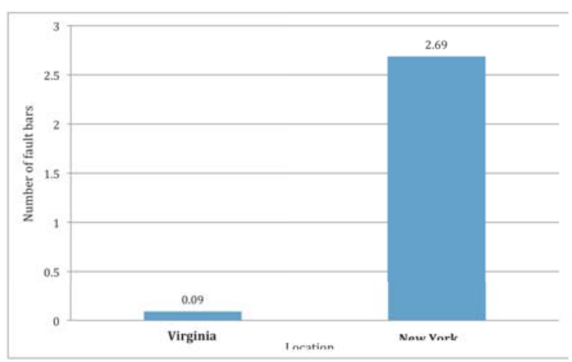


Fig. F42. Average number of fault bars for developing Glossy Ibis nestlings in waterbird colonies within the VCR –LTER (Chimney Pole and Chincoteague) and the New York Metro Region (Lower New York Harbor and Jamaica Bay). The presence of fault bars indicates acute stress experienced by the individual at the time of feather generation.

Barrier Islands

Island vegetation

The barrier islands represent a collection of landforms that are both independent and dependent on one another. Our past work has shown that each island may respond in a unique fashion to sea level rise; however, sediment movement among islands and island position dictate that islands are affected by their neighbors. This is true of both physical processes (e.g sediment transport) and biological processes (e.g. movement of propagules, including organisms, seeds, and pollen). Our goal is to link the external drivers of storm disturbance (overwash, sand deposition, flooding, salt spray) that modify the land surface and water table to patterns of vegetation on the barrier islands. We are building on our long-term work on Hog Island, including permanent plots in the dune chronosequence, to include islands in the 2 new box transects. Our earlier work has shown that there is predictable spatial variation across the island landscape due to differences in microtopography and the decrease in disturbance magnitude and frequency with distance from the beach face, which result in different vegetation patterns across the islands (Fahrig et al. 1993). Thus storm-related effects should vary among islands as a function of island size and topography.

Seed dispersal - Quantifying seed arrival provides insight into potential patch dynamics and community structure across the Virginia barrier island landscape. Island complexity was an important component for seed arrival, as was location of artificial perches (Fig. F43).

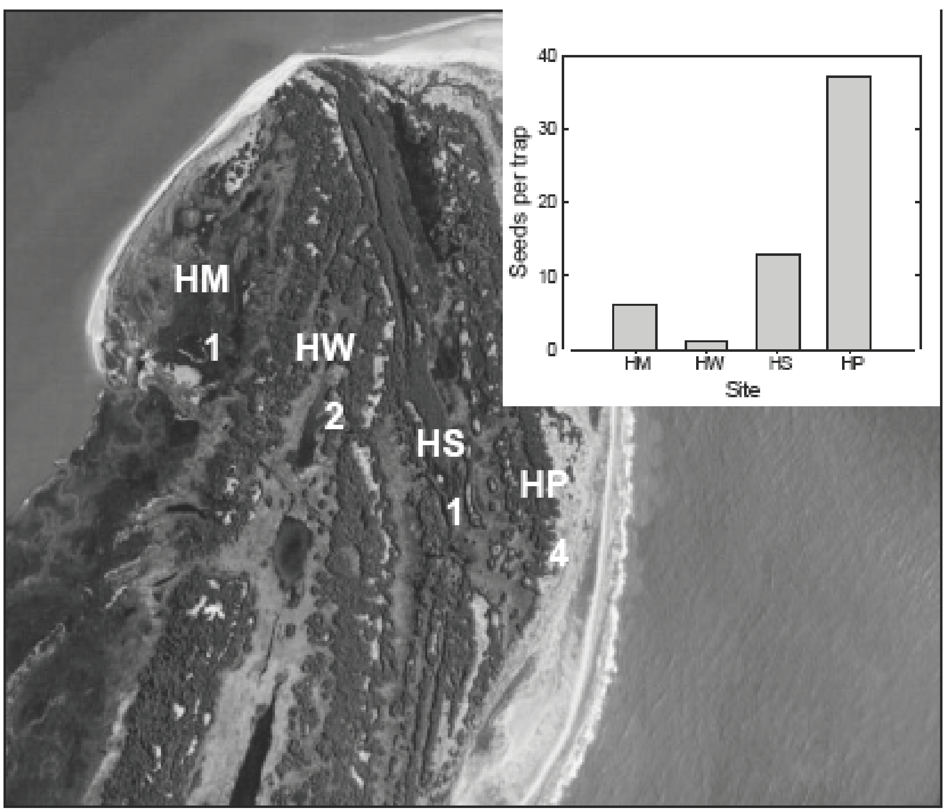


Fig. F43. Aerial image of the northern end of Hog Island, Virginia, showing the approximate location of transects positioned on this portion of the island with: M = marsh, W = woody, HP = primary dune and HS = secondary dune. Below each site name is seed species richness collected from artificial perches. The inset figure shows the number of seeds per trap captured at each site.

Variations in climate and phenology were potential factors that influenced the magnitude of seed dispersal during the course of this study. There were seasonal differences such that seed dispersal was greatest in the spring and least in the summer. Spatial variation at an intermediate-scale influenced seed dispersal because perch position relative to habitat type affected the magnitude and diversity of seed input. Lastly, there was considerable variation between the composition of the seed community and the surrounding vegetation.

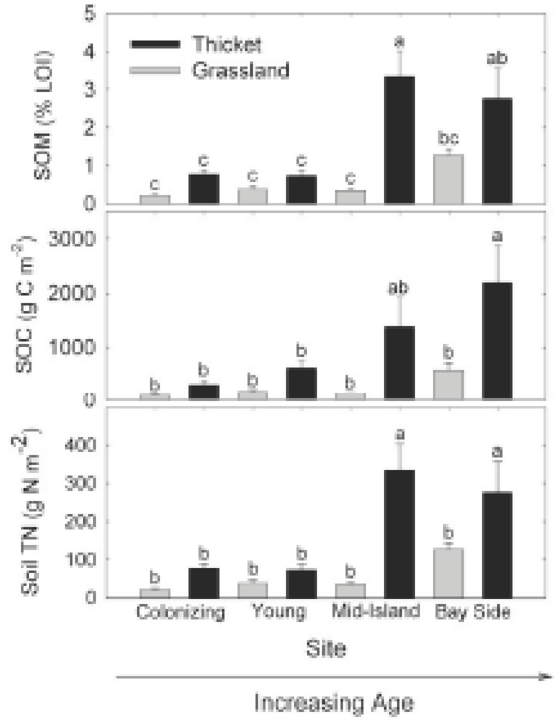


Fig. F44. Variation in soil organic matter (SOM), soil organic carbon (SOC) and total nitrogen (TN) in the top 10 cm of soil across a chronosequence of shrub expansion on a barrier island. SOC and TN were calculated from SOC and TN concentrations and soil bulk density of 1.09 g cm^{-3}. Significant differences among communities are noted with letters.

<u>Shrub expansion and carbon sequestration</u>
The data indicate that mesic ecosystems with young and/or infertile soils may rapidly sequester C after woody encroachment, and the high C accumulation rates observed suggest that, under certain circumstances, barrier islands have potential to sequester relatively large amounts of C (Fig. F44). The implications of these findings for global C cycling have yet to be determined. While there are ~2200 barrier islands worldwide fronting ~12% of the world's open ocean shoreline (Pilkey and Fraser 2003), the combined area of all of these islands is relatively small compared to other terrestrial systems that drive C cycling globally. However, these results may not be limited to barrier islands, but may also be applicable to other coastal shorelines with similar dynamic soil properties. More importantly, these results add to the body of literature suggesting that the impact of woody encroachment on ecosystem C cycling may be more complex than previously thought and generalizations must account for factors such as soil history.

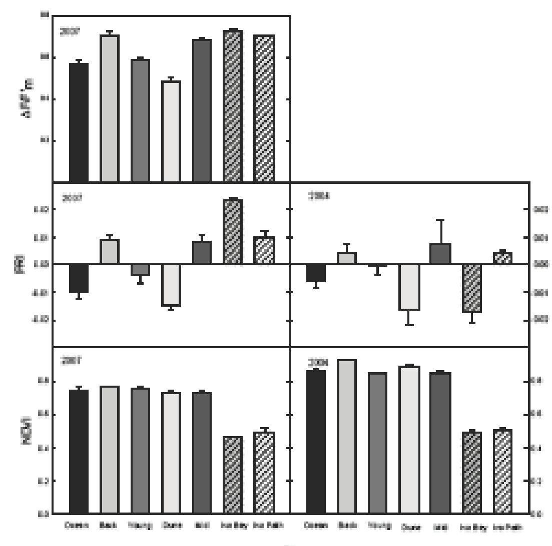


Fig. F45. Variations in DF=F0m (a), PRI (b), and NDVI (c) across the island during 2007 for both *M. cerifera* and *I. frutescens* sites. Variations in PRI (d) and NDVI (e) during 2004 are also presented. Values represent means ± 1 S.E.

<u>Landscape vegetation patterns</u> - Salinity appeared to be a factor responsible for patterns of stress across the landscape, and

was detectable using PRI from airborne hyperspectral imagery (Fig. F45). Variations in PRI remained constant during a wet and dry year for *M. cerifera*, while NDVI, CI, and WBI970 were higher during the wet summer, but varied little across the island. Thus, PRI was the most useful index for stress detection in *M. cerifera*. For *I. frutescens*, PRI was related to chloride concentrations during the dry year, but a different pattern in PRI emerged during a wet year, suggesting that this index is useful in detecting stress, but the cause may not always be obvious. These findings, especially for *M. cerifera*, have implications for monitoring the effects of climate change in coastal systems. Our results suggest that PRI may be used for early identification of salt stress that may lead to changes in plant distributions at the landscape level as a result of rising sea level and increased storm intensity.

Barrier islands provide a host of critical ecosystem services to heavily populated coastal regions of the world, yet they are quite vulnerable to ongoing sea level rise and a potential increase in the frequency and intensity of oceanic storms. Worldwide, these islands are being degraded at an alarming rate, in part because of anthropogenic attempts at stabilization. Sustainability strategies must incorporate the natural degree of substrate instability on these sedimentary landscapes. Focus for managing barrier islands must be place on maintaining ecosystem function and process development rather than emphasizing barrier islands as structural impediments to wave and store energy.

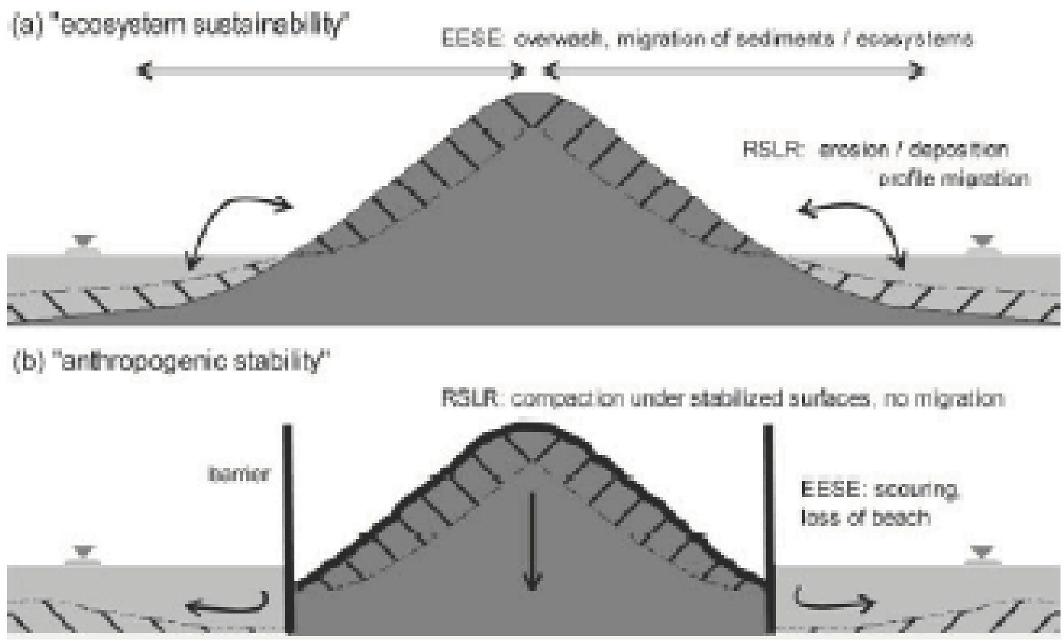


Fig. F46. Sustainability'' and ''stability'' are often contradictory terms, as shown on a cross-section of a typical barrier island landscape. Native vegetation is adapted to the movement of sediments during extreme episodic storm events (EESE) and builds elevations through the process of succession, countering relative sea level rise (RSLR). Anthropogenic barriers such as paved surfaces, housing, hotels, bulkheads, and seawalls inhibit the natural sedimentary exchange between the land and the sea, interrupt ecosystem migration and processes of ''ecological engineering'' by plants, and result in net sediment and elevation loss.

Interisland variability of dune plant community structure – Data from monitoring of permanent vegetation plots and groundwater wells on Hog, Metompkin, Smith, and Parramore islands reveals significant variation in vegetation patterns among islands. Analysis of the biomass data through 2009 indicate a decrease in aboveground plant biomass on all Hog Island dunes to lows in 1999 and 2003 followed by increases in subsequent years. In 2009, the oldest dune on Hog Island had the lowest biomass and the youngest dune had the most. The dunes sampled on Metompkin and Smith were similar to the youngest dune on Hog. *Ammophila* progressively declined and was eventually lost completely on the oldest Hog Island dune, peaked and then decreased on the intermediate age dune, and maintained a presence on the youngest dune. Again, Metompkin and Smith had *Ammophila* biomass values similar to the youngest dune on Hog. *Schizachyrium* appeared to dramatically increase to a peak and decline on the oldest and intermediate aged Hog dunes with a time lag between the two. The youngest Hog Island dune spiked dramatically between 2006 and 2009. *Schizachyrium* was lacking on the Metompkin and Smith dunes in 2009. *Spartina patens* approximated the temporal trends of total biomass with some differences among dunes.

Completion of a four-year study of Hog Island and Parramore Island "pimple" dunes indicated that there were distinct assemblage types that segregated themselves by habitat type: marsh, shrub thicket, and dry summit. Shrub assemblages were less diverse than either marsh or summit habitats. There was no relationship between pimple size and diversity or location. Differences in diversity and composition among pimples were as great as differences among transects within pimples. Fresh water availability was important in differentiating differences, both among transects and among species, but it was not the only factor. Nutrients, such as boron, were also important in describing variation among species. It is likely that interactions between water and other factors (e.g. the accumulation of some mineral nutrients in the marsh after they are leached from the dune summits) are the most important determinants of species abundance.

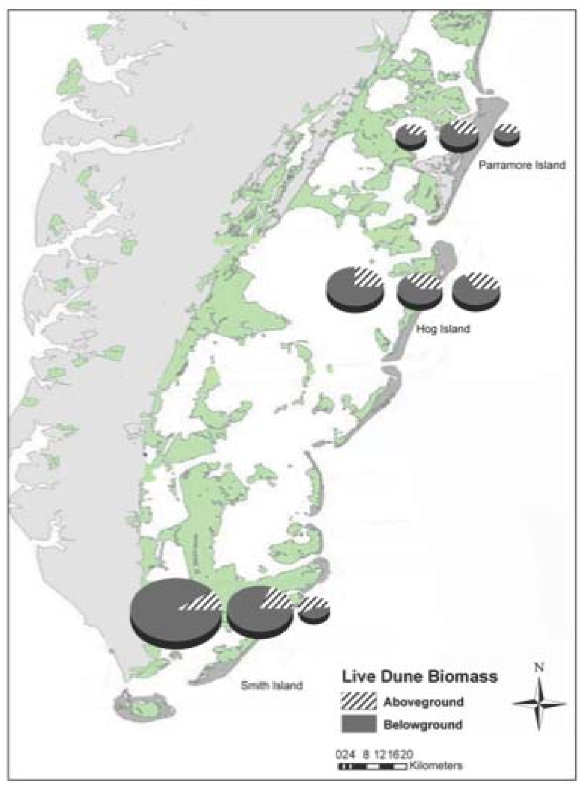


Fig. F47. Interisland variation in live dune biomass.

There were significant differences in biomass (Fig. F47) and diversity both among the islands and the different age dunes. These differences likely relate to variations in dune age and morphology, plus the effect on and interaction with environmental factors such as depth to water and soil nutrient content. Parramore, where conditions were found to be relatively more stressful, exhibited different trends in biomass than Hog and Smith Islands, which were more similar in their geomorphology. Though the system as a whole is highly stressed and resource limited, small changes in dune height, dune position or the availability of water and nutrients can lead to significant differences among islands. Adaptations to low soil nutrients and water availability are evidenced by high root biomass close to the surface where organic matter is higher and water accumulation after rains and in pore spaces can be most effectively utilized. Increased allocation of biomass to roots with increased dune age also supports nitrogen as a limiting factor. Correlations between morphological characteristics, such as dune position and height, and diversity suggest that biomass and diversity are both increasing with dune age.

Overall, the marshes were also different with respect to salinity, amount of soil nitrogen available, depth of water table, and root:shoot biomass ratios (Fig. F48). Each marsh had different species compositions and different diversity indices. Salinity, soil nitrogen availability and water table depth appeared to influence the amount of biomass above and belowground.

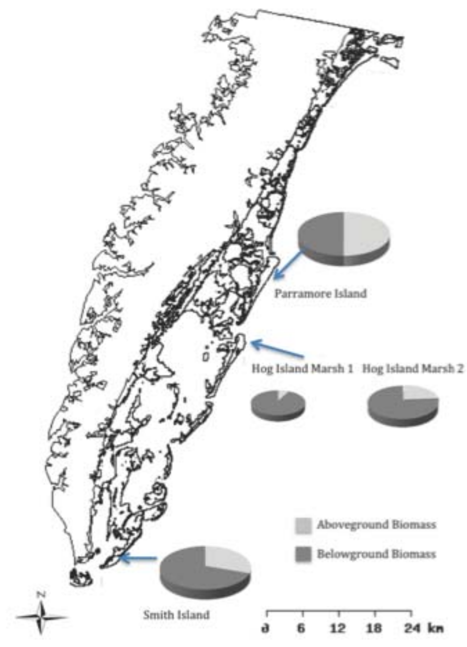


Fig. F48. Interisland variation in marsh biomass.

Predator-prey interactions

Nest predation by mesopredators has had a huge impact on breeding populations of ground-nesting birds on the Virginia barrier islands. Dueser and collaborators found that (1) 99% of all eggs were predated on Parramore, with 97% attributable to mesopredators, (2) only 19% of eggs were predated on Metompkin, with 0% attributable to mesopredators, (3) egg predation dropped to 21% after initiation of predator removal, with 18% attributable to mesopredators, and (4) there was no compensation in predation rates by ghost crabs, gulls and crows following predator reduction. Predation management appears to have substantial potential for reducing egg predation on the islands.

Spatial least-cost path analysis used to determine movement of mesopredators both between the mainland and islands and among islands revealed the following key results. For raccoons: (1) 12 islands were identified as potential hosts for breeding populations, (2) the median "travel costs" of reaching an island from the mainland was 10.55 cost units, with costs ranging from <1 cost units for islands attached to the mainland by causeways (Assateague and Fisherman) up 35 cost units for the most isolated island (Cobb), (3) least-cost pathways tended to cross marsh "bridges" rather than large expanses of open water, (4) immigrants arising from a mainland source often crossed intermediate “bridge” islands, (5) the median travel cost between a potential source island and a non-source island was 3.09, and only two islands required more than 10 cost units, and (6) inter-island movements had lower travel costs in general than mainland-island movements of reaching an island from a “source” island . For red foxes: (1) only four islands were observed as potential hosts for breeding populations, (2) the median cost of movement to an island from a source island was 32.76 units, and 20 islands required more than 10 cost units, and (3) inter-island movement costs were generally higher than mainland-island travel costs.

There was thus wide variation in the relative difficulty of reaching different islands from source locations, from 0.03 cost units across a narrow channel between Wallops and Assawoman islands up to 32.95 cost units to move from the mainland across >5 km of open water to Little Cobb Island. We found that potential sources of immigrants differed between predator species, as did the overall costs associated with immigration. Raccoons had lower overall immigration costs, and raccoon least-cost pathways originated primarily on the islands. Foxes had higher overall immigration costs, and fox least-cost pathways originated primarily on the mainland.

Landscape studies

Landscape-scale observation of ecosystem state change

Observed decadal trends in landscape change – Analysis of published land cover data layers from the NOAA Coastal Change Analysis Program (CCAP) from 1973 – 2001 for the VCR

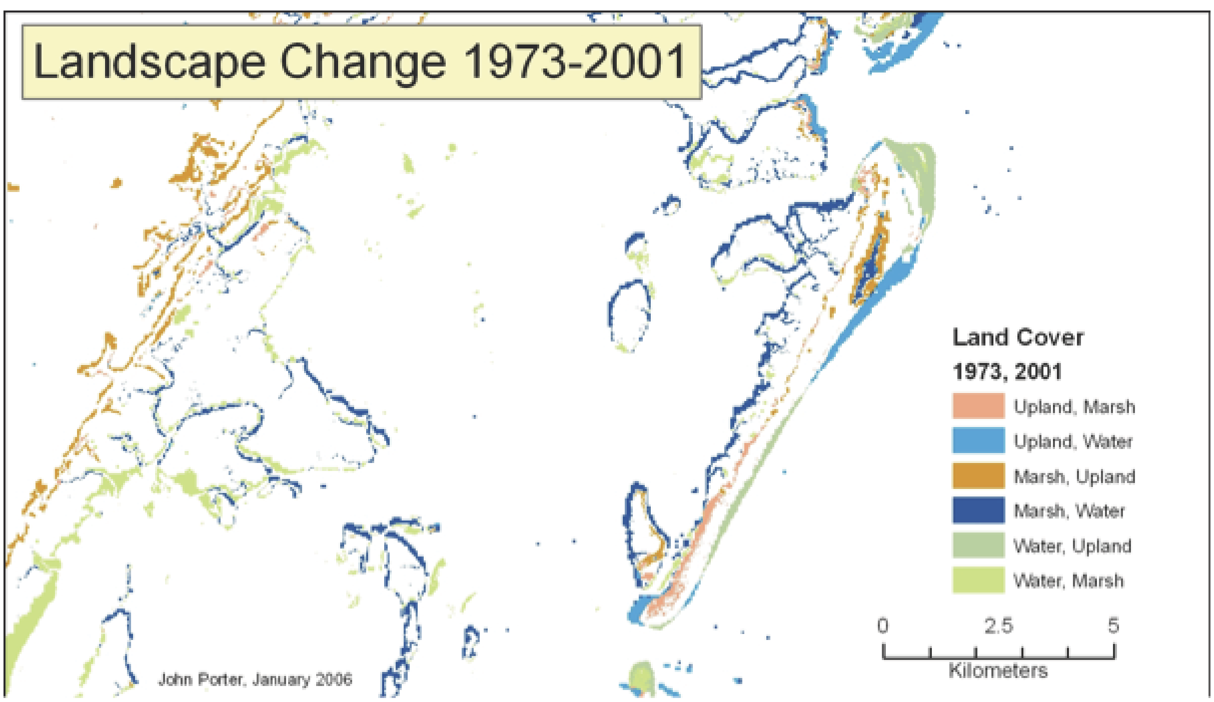


Fig. F49. Landscape change analysis based on LANDSAT data showing changes in major habitat types.

shows two important trends with respect to decadal changes in land cover under the current conditions of storminess and sea-level rise. For a given point on the landscape 43% of the island upland has changed since 1973, and 44% of the marshes have changed over that same time period. Yet, despite this rapid rate of landscape change, there has been only a 6% net loss of uplands and a 7% net loss of marshes over that same time period for the aggregated area of the VCR (Fig. F49). This redistribution of habitats may be typical of landscapes that are relatively little impacted by human activities such as the VCR, where there are no barriers to movement (e.g., island overwash, marsh transgression) and no human engineering that can modify natural processes of erosion and accretion.

Landscape modeling – Reyes used the NOAA data to assess habitat changes that could be used to calibrate the biophysical habitat model. The agreement between two maps was quantified with a goodness of fit spatial statistics routine comparing the spatial pattern of habitat cells at multiple resolutions (Costanza 1989), which returns a value out of a possible maximum of 100. The multiple resolution approach allows a more complete analysis of the way the spatial patterns match. The algorithm gradually degrades the resolution with which the fit is measured by gradually increasing the size of the sampling window in which the fit is calculated (Costanza et al. 1990). The total fit is a weighted average of the fit at all window sizes, with the smaller windows given the most weight. Each of the historical maps was compared amongst each other. The results of this analysis for a one-to-one comparison and the overall fit are presented in Table 6.

Table 6. Multiple Resolution Fit Index Analysis

Map Comparison	Fit at size 1	Total Fit
1992 - 2005	72.7859	83.6588
1996 - 2005	71.8919	82.1631

Model testing for hydrodynamic stability - The exchange of water between the islands and the open ocean has proven critical for model stability. Ten-year test runs were done using the same multiple resolution index, and simulated results could then be compared with historical images. Table 7 shows the values at the pixel-to-pixel resolution and overall fit.

Table 7. Multiple Window Fit Index Analysis

Map Comparison	Fit at size 1	Total Fit
92 real 05 sim	72.6207	80.6828
92 real 10 sim	72.5960	80.5822
96 real 05 sim	88.7782	87.9410
96 real 10 sim	88.7330	87.8251
05 real 05 sim	72.7553	80.1684

Geomorphic modeling

Biogeomorphic Controls on Barrier Island Evolution in Response to Sea Level Rise - An early outgrowth of the interdisciplinary project between geologist Moore and ecologist Young was refinement of their framework for addressing the geomorphic and biological (i.e.,biogeomorphic or, ecomorphodynamic) feedbacks they are exploring within the Virginia Coast Reserve. This refined framework is itself an important result of the first year of work—it is presented in the following two paragraphs and is followed by a summary of results from historical observations and field surveys to date.

Barrier islands are dynamic, disturbance-prone landscapes that support complex, sensitive ecosystems. As sea level rises and storms potentially become more intense, overwash disturbance events on barrier islands will likely become more common. Following an overwash event, if given sufficient time without subsequent disturbance, dunes are generally expected to recover as dune-building grasses like *Ammophila breviligulata* recolonize overwash fans. Dune-building grasses prefer high topographic roughness and aid vertical accretion by trapping sand, thereby expanding their own suitable habitat in a positive feedback loop. However, if overwash recurs before the dune-building grasses can reestablish, overwash-adapted "maintainer" species like *Spartina patens* (upright), which do not contribute significantly to dune building but rather preserve flat topography, may preferentially survive, causing low topographic roughness to last longer and thereby

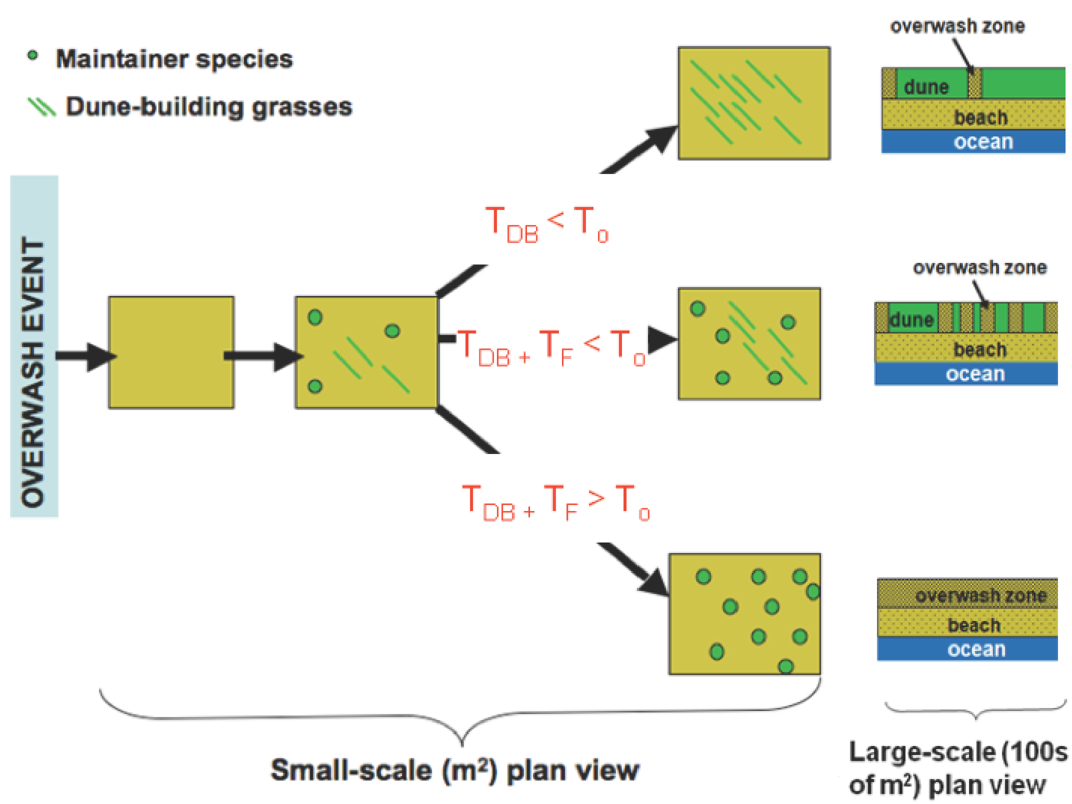


Fig. F50. Possible scenarios for ecomorphodynamically-influenced barrier evolution based on the relationship between T_o (time between overwash events), T_{DB} (time needed for dune-building grass recovery), and T_F (time added to dune recovery by the maintainer feedback), showing that the maintainer feedback may affect large-scale landscape patterns as disturbance frequency increases (i.e., T_o decreases).

increasing the likelihood of subsequent overwash. In a climate of potentially increasing storminess, this opposing positive ecomorphodynamic feedback (henceforth the "maintainer feedback") may ultimately prevent dune development, allowing zones of low topographic roughness to persist through time. As a result, barrier response to climate change may be intensified and accelerated non-linearly, with the potential for large-scale shifts from dune-dominated to overwash-dominated morphologies (Fig. F50).

Preliminary Results from Field Mapping, Aerial Photo Analysis and Vegetation Surveys - Results to date are useful in beginning to address whether or not the maintainer feedback is likely affecting barrier island evolution in the Virginia Coast Reserve (VCR), located on the Eastern Shore of Virginia. Initial field mapping and aerial photo analysis suggest that the distribution of overwash on Hog Island may be linked to a possible recent shift from clockwise to counterclockwise rotation: active overwash is associated with areas of recent beach erosion on the northern end of the island—including an apparently persistent overwash zone where rotation has forced the exposure of an interdunal swale to direct wave action

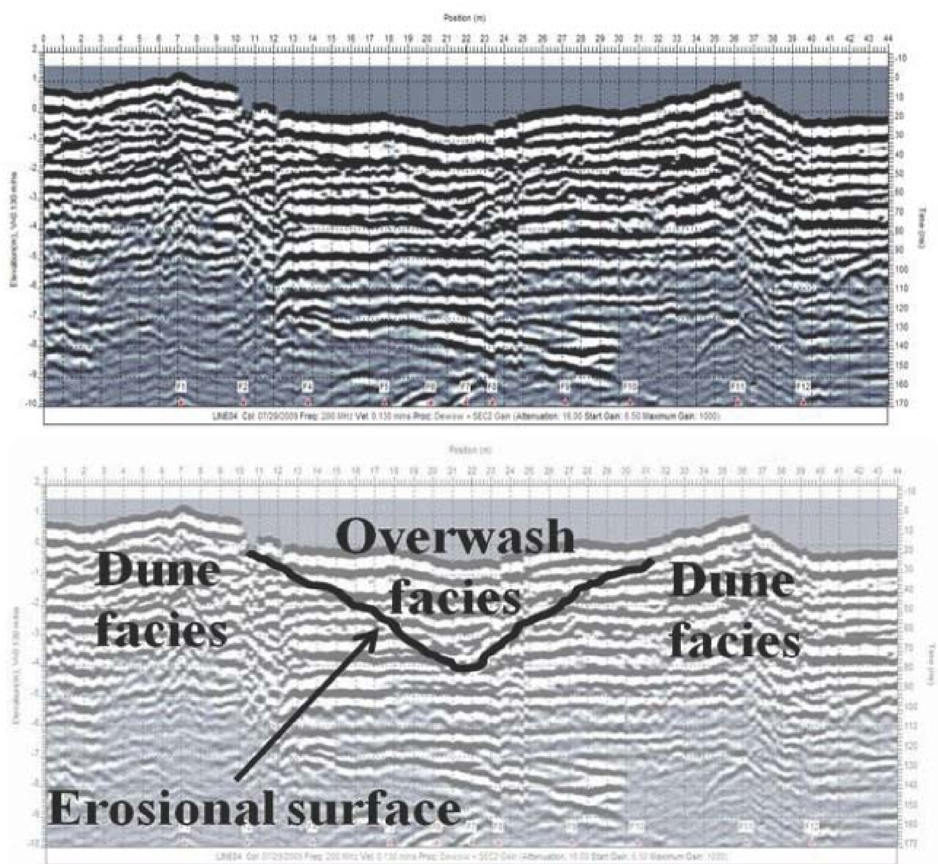


Fig. F51. Alongshore GPR transect of relict overwash in a dune field on south Hog Island, VA, with horizontal distance on the x axis and elevation (depth) on the y axis. Original transect is above; the same transect with our interpretations is below. Note the distinctive radar signatures: horizontal, comparatively widely-spaced reflectors are associated with the overwash facies, whereas dipping, more closely-spaced reflectors are associated with the dune facies.

(Harris, 1992)—whereas relict overwash is associated with areas of recent beach and dune accretion on the southern end of the island. In this latter area, GPR transects reveal buried overwash channels surrounded by recovered dunes (e.g., Fig. F51). The abandonment of overwash zones on southern Hog Island should not necessarily be viewed as an indication that the maintainer feedback is not at work on this island, since the associated topographic lows are still preserved on the landscape, but rather that recent accretion due to the potential rotation reversal may have confounded the effect of the feedback by buffering these overwash zones from wave action. However, the high topographic roughness and relatively limited extent of active overwash that characterize Hog Island as a whole suggest that the maintainer feedback is likely to be subordinate to the dune-builder feedback here.

The maintainer feedback is more likely to be a dominant process on Metompkin Island, where overwash plays a more significant role in determining island movement and topography. The northern half of Metompkin Island has recently been transgressing rapidly in comparison to the southern half (Byrnes, 1988) and, as expected for such a scenario, is characterized by widespread, coalesced overwash terraces, whereas a discontinuous dune line is present in the south. The northern half of Metompkin Island closely resembles the expected morphology for frequent overwash disturbance (i.e., relatively small value of T_o, or time between overwash events—see upper panel of Fig. F50) in the presence of the maintainer feedback. The southern half, on the other hand, appears similar to the morphology expected for less frequent overwash disturbance (i.e., moderate value of T_o—see middle panel of Fig. F50) in the presence of the maintainer feedback. Although these morphologic patterns may result from physical conditions alone, the overall low topographic roughness and history of extensive overwash on Metompkin Island suggest that the maintainer feedback could be an important dynamic on this island.

Vegetation for the four community classifications was analyzed for %cover, species richness, and diversity (Shannon Index) (Table 8). Additionally, an Indicator Species Analysis (ISA) was conducted in PC-Ord 5 to determine whether each community could be distinguished based on presence and abundance of one or more species. Fourteen species were found in active overwash fans and Shannon diversity was low at 0.75. Active sites were also characterized by the lowest vegetation cover (<5%). No species were significant indicators of active overwash sites, likely because of the low cover and prominence of bare sand in the study quadrats. Recovering/intermediate overwash sites had similar diversity (0.71), marginally higher species richness (16) and higher cover (14%). Most importantly, these sites were largely dominated by the dune-building grass *Ammophila breviligulata* and the dune grass *Panicum amarum* which were both significant indicator species. Relict overwash channels had highest cover (22%), highest species richness (18) and highest Shannon index diversity (0.92) of all habitat classifications. Although reference sites had higher cover than active or intermediate sites (18%), these relatively undisturbed dune and swale sites had the lowest species richness (10) and lowest diversity (0.68) of all habitat classifications. This suggests that some level of overwash activity, whether recent or historic, may promote species diversity.

The strong presence of *A. breviligulata* in recovering/intermediate overwash sites could be considered a typical recovery response after disturbance and further supports the hypothesis that *A. breviligulata* provides an important ecomorphodynamic feedback to barrier island stability in promoting increased elevation after overwash events by building dunes. Because *S. patens* was both the most common species and had the highest percent cover (although that value was very low) in active overwash sites and was relatively uncommon in recovering/intermediate sites, the role of this species as a maintainer of low topography was also supported although more sampling and analyses remain. Further analysis of community composition, based especially on differences in elevation and habitat type (i.e. dune v. swale), needs to be completed before further conclusions can be made. This analysis will be especially important in reference sites where *S. patens* and *A. breviligulata* co-occur in relatively high numbers. Future analysis will include a Canonical Correspondence Analysis (CCA) to determine whether species composition and cover are related to environmental

Table 8. Indicator values for significant indicator species (*$p < 0.05$) from three categories of overwash fans and undisturbed dune/swale reference sites on Hog Island, VA. 17 additional species were not significant indicator species of the sampled sites.

	Habitat			
Species	Reference	Active	Intermediate	Relic
Spartina patens	34*	3	3	8
Conyza canadensis	26*	0	14	9
Panicum amarum	25*	1	36*	2
Ammophila breviligulata	14*	0	33*	6
Rumex acetosella	0	0	0	40*
Solidago sempervirens	0	0	1	35*
Panicum dichotomiflorum	0	0	4	27*
Morella cerifera	0	0	0	23*
Andropogon scoparius	0	0	0	16*
Gnaphalium purpureum	0	0	1	14*

parameters such as elevation, sediment size, distance to the high tide line and slope of the beach. These procedures will begin in Fall 2010 after all field surveys have been completed.

Morphological-behavior modeling of barrier island vulnerability to increased rates of sea level rise - This project is still in its early stages. However, early efforts already indicate that some of the previously drawn conclusions regarding barrier island evolution in the Virginia barrier islands are incorrect. For example, in developing initial conditions based on observations from the geologic literature regarding the likely timing and location of barrier island initiation we have found, geometrically, that the islands must have formed farther seaward than the 0.9 to 1.1 km suggested by the work of Byrnes et al. (1988) coming closer to the 4 km distance suggested by Finkelstein and Ferland (1987) (Brenner et al., 2010).

Shoreline changes

Preliminary results from the shoreline change analysis using the updated database (1940 – 2006) show that the northern "arc of erosion" (Richardson and McBride, 2007), characteristic of the northern parallel beach retreat islands (landward shoreline migration along the entire island), has extended southward to Parramore Island (Fig. F52). Hog Island has not been affected yet by this erosion trend and, outside of the ends of the barrier island chain – Wallops Island to the north and Fisherman Island to the south – Hog Island has experienced the greatest amount of accretion during this 66-year period. However, Hog Island could be at risk of changing from a rotational instability barrier island to a parallel beach retreat island, as has Parramore Island to the north, if current trends continue.

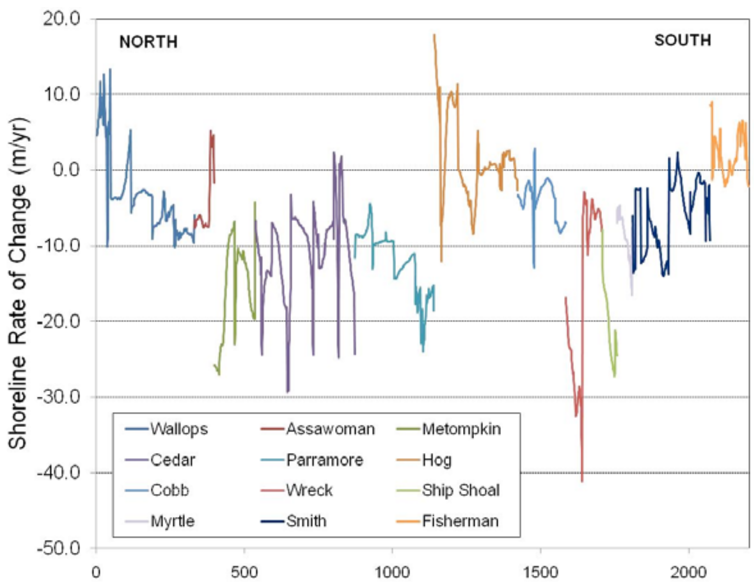


Fig. F52. Shoreline rates of change along the Virginia barrier islands for the period 1940-2006. Note the ubiquitous erosion occurring north and south of Hog Island.

Sub-bottom geology and barrier island antecedent geological framework

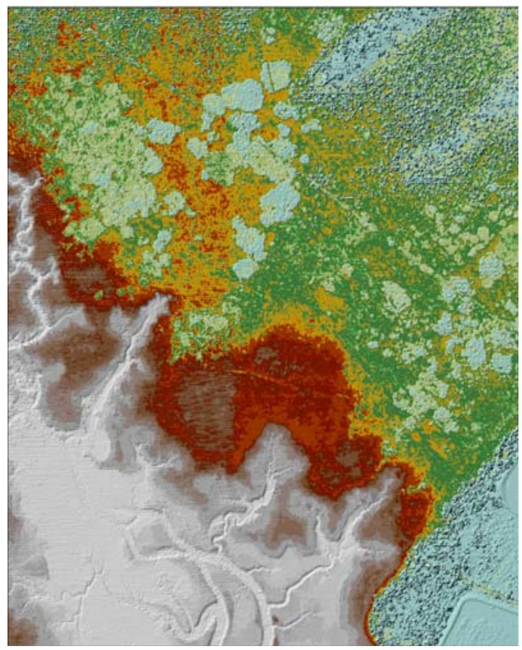
The seismic reflection profile data indicate reworking of the upper 4 m of the nearshore over a 400 km^2 area. This seismic unit contains approximately 1.56 billion m^3 of sediment potentially available to supply the barrier islands. Bedforms visible on side-scan sonograms (average estimated ht < 1 m; wavelength ≈ 250 m) indicate sediment mobility and an onshore migration direction. However, the high shoreline erosion rates of the barrier islands demonstrate that neither the longshore nor the nearshore sediment supply can offset the amount of erosion.

Sediment samples from the islands and seafloor in this area indicate that the average island grain size (0.25 mm ± 0.05 mm) does not match the average nearshore grain size (0.14 mm ± 0.05 mm). Consequently, only patchy, fine-grained surficial nearshore sediments are a potential sediment source for the VBIs. Finally, a seismic facies analysis using the subbottom data showed that the nearshore geology contains older stratigraphic units (Miocene – Pleistocene; 20 m.y.a. – 10 k.a.), which strongly control the location of the present-day tidal inlets and barrier islands.

LiDAR

Preliminary LiDAR data was evaluated for utility in ecological analyses, and we were extremely pleased with the results. The preliminary LiDAR data (which was not processed for ground return, but also includes the height of vegetation) for Phillips Creek Marsh clearly shows boundaries between different vegetation types, tidal creeks and even the research boardwalk that runs about 30 cm above the surrounding marsh. At least in shallow areas, and those flown during the lowest tides, the LiDAR also provides information on sub-aqueous structure that would be difficult or impossible to obtain without seriously disrupting the system, due to the muddy bottoms.

Phillips Creek Marsh via LiDAR



In some cases, LiDAR data seems to provide better resolution on vegetation types than does conventional aerial and satellite imagery. However, it is by combining the LiDAR with other data sources that the ultimate benefits will be realized.

Remote sensing

Hyperspectral imagery was used to assess properties of the beach and lagoon. Initial focus of the effort of the land-based effort focused on remote retrieval and mapping of beach properties (composition, moisture, grain size, geotechnical meta-properties such as bearing strength/dynamic deflection modulus) and vegetation retrievals such as biomass from the airborne hyperspectral imagery flown during the experiment, primarily from the NRL CASI-1500 hyperspectral sensor. Results from this analysis are shown in Fig. F54. In the water, primary emphasis of the experiment was on shallow water bathymetry. Fig. F55 shows results the marsh and tidal flat area behind Wreck Island. Long-term goals for this analysis include monitoring of SAV and water constituents. They hyperspectral imagery has also been used to calculate standing biomass in salt marshes. Fig. F56 shows biomass in the marshes behind Smith Island.

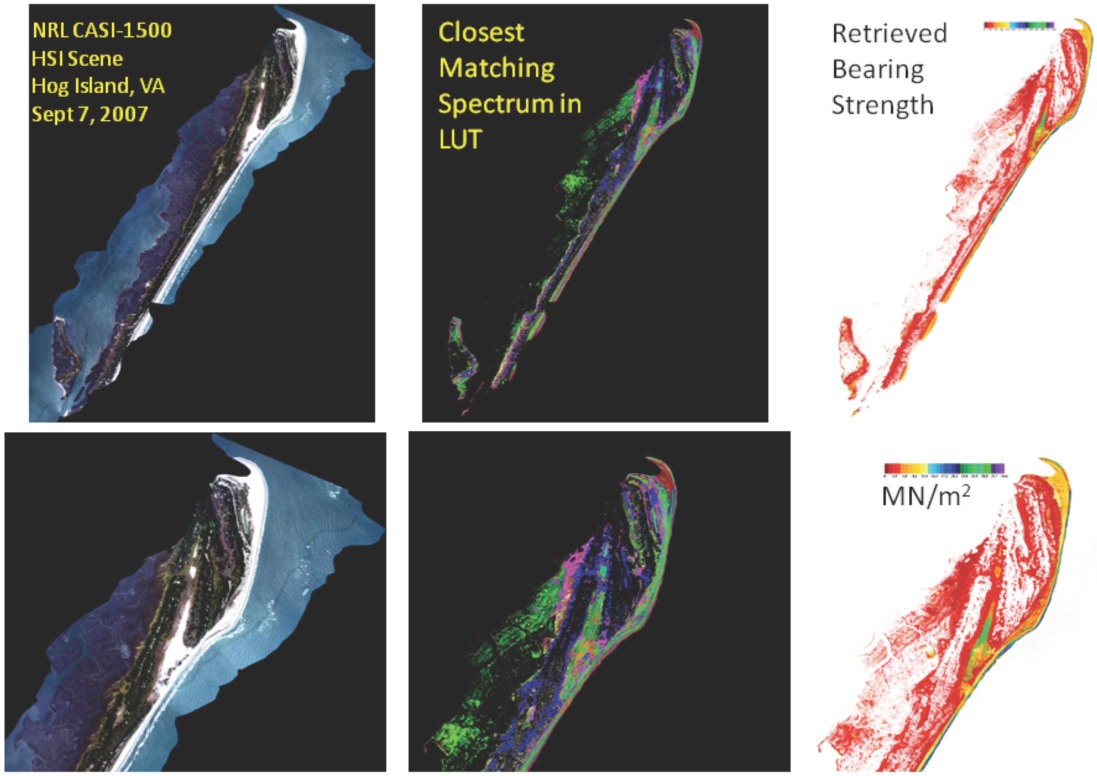


Fig. F54. (Left) NRL CASI-1500 hyperspectral scene of Hog Island, VA, one of several passes at different tidal stages acquired over Hog Island, VA during VCR'07; (middle) closest matching spectrum from calibration/validation field efforts across multiple islands; (right) retrieved bearing strength (dynamic deflection modulus) from the hyperspectral imagery (after Bachmann et al. 2010).

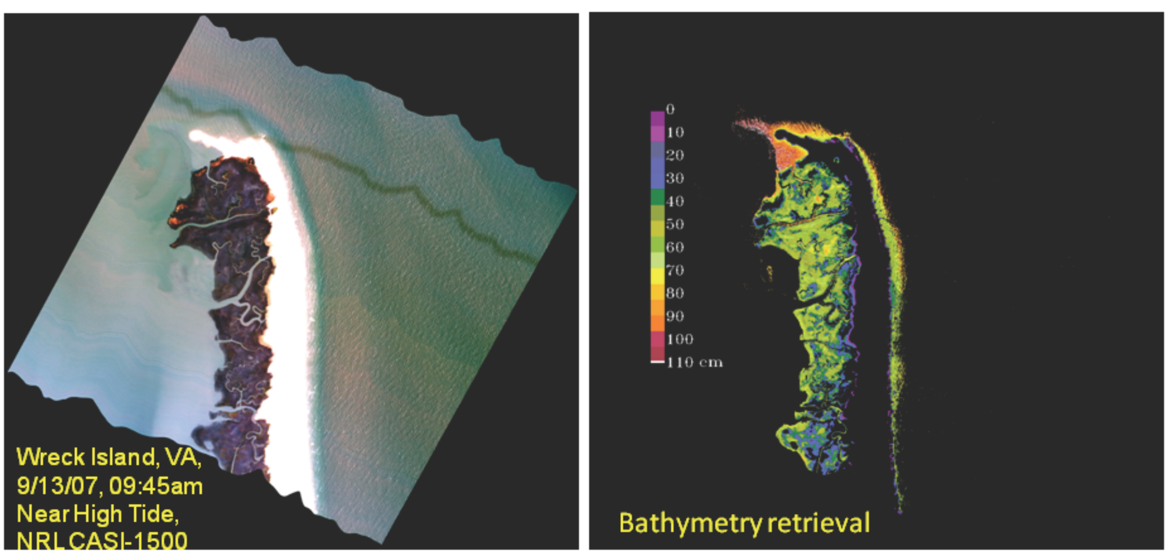


Fig. F55. (Left) NRL CASI-1500 image of Wreck Island, one of several acquired at different tidal stages over Wreck Island, VA; (right) retrieved very shallow water bathymetry in the salt marsh, and cove on the western shore, and in the surf zone on the eastern shore (after Bachmann et al. 2010)

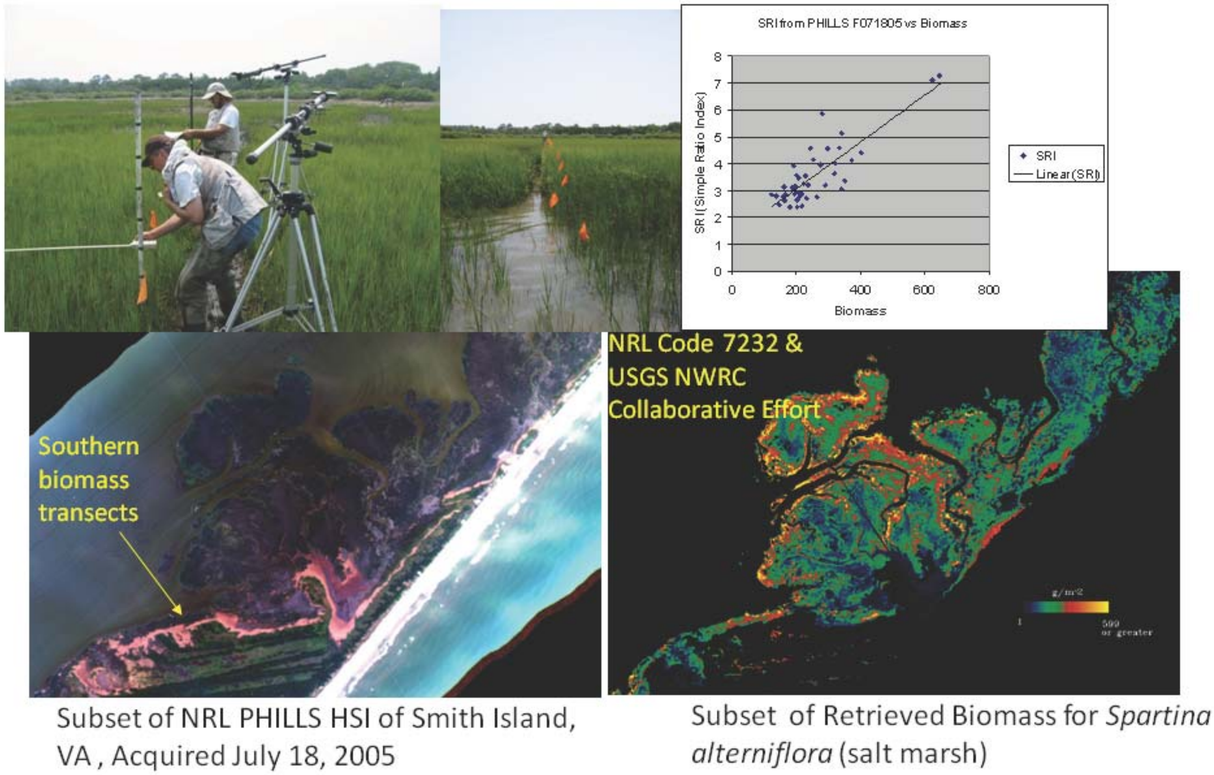


Fig. F56. (Bottom left) NRL PHILLS hyperspectral imagery acquired in 2005, a predecessor experiment to VCR'07; (bottom right) retrieved biomass in g/m^2. (Top left and middle) Field calibration efforts on Smith Island, VA; (top right) Relationship between index derived from narrow-band hyperspectral wave-bands and the ground biomass measured during field cal/val efforts (after Bachmann, Ramsey, Christian, et al., Wetlands Conference, Williamsburg, VA, 2007).

Social Science

Analysis to-date indicates that participants did reveal support for higher quantities (e.g., more acres) of ecosystem restoration, yet for the average individual there is minimal variation across individual restoration activities, as estimated using a conditional logit model (Table 9). This result may be specific to the presentation used in this experiment or be part of a broader trend indicating that consumers do not identify all the benefits accruing to them from a particular type of ecosystem restoration. However, the sign on the individual personal cost is negative. This is noteworthy because preliminary results and participant feedback from the 2008 pilot indicate that factors beyond the purely theoretical assessment of incentive compatible properties (such as framing effects or science-information) may have played an integral role in individuals' choices (votes). With this in mind, the 2009 field experiment

Table 9: Choice Model: 2009 Field Experiment

Variable Name	B	Std. Err.	P<
Birds	2.1942	0.4073	0.001
Sea Grass	1.8977	0.3845	0.001
NU2	-0.1029	.0467	0.027
Individuals' cost	-0.0358	0.0052	0.001
LR chi2 (df)	284.79 (4)	0.0001	

included additional science information in early instructions and reminders that money not used for restoration was money that they could take home. Preliminary results suggest that the typical participant offered between $26 and $65 per half-acre of bird or sea grass restoration, with higher bids per acre offered for the first half-acre. These offers bracket an estimate of $34 to $42 per half-acre as the maximum *marginal* willingness to pay of typical participants, suggesting the auction process may generate revenues near the full marginal value of ecosystem restoration.

The second approach used in the field experiment establishes individual (marginal) prices for increments of each of the ecosystem restoration activities. Results from the interval regression show that as the number of increments increased, participants' offered price declines, consistent with the concept of diminishing marginal benefits. Table 10 summarizes a single treatment that includes the proportional rebate mechanism for 4 total units of sea grass restoration. Mean offers decrease with additional units and this holds consistent for all restoration treatments. The individualized pricing approach for each activity does support our conclusion that Lindahl-based methods have promise to generate revenues for public good funding, particularly when used with rebate mechanisms such as those found in the experimental literature.

Table 10: Sea Grass Restoration - Mean Offers

Unit	Mean	Std Dev	Min	Max
1	64.82	41.20	0	150
2	37.18	20.43	0	75
3	26.08	12.34	0	50
4	21.11	8.16	0	37

A simple summary of the different treatments is outlined in Table 11. Some differences exist across the treatments, with the conditional PR (PR(CON)) treatment, which provides an additional unit of restoration for reaching the first unit with a secondary unit of restoration, having a noticeably higher starting point. However, all treatments are consistent with the conclusion that an individualized pricing approach has potential to generate revenues for the provision of local public goods.

Table 11: Treatment Comparison Across Mechanism

Treatment	PR(ALL)	PR (4)	PR(8)	PM	REVISON	PR(CON)
Constant	57.97	59.65	64.07	58.87	58.55	75.64
Nunits	-7.821	-10.842	-7.513	-7.514	-8.175	-7.916
Sig_u	13.99	12.23	12.40	15.43	15.43	52.37
Sig_e	16.29	12.64	17.96	18.06	18.06	13.45
Rho	.4236	.4873	.3273	.4208	.4203	.9475
# observation	1421	918	503	236	118	300
Log-likelihood	-3541.9	-1315.3	-2192.9	-1051.5	-1051.5	-437.3

Incentive mechanisms were also tested using an induced value approach in the Policy SimLab to evaluate mechanism properties and test for validity. Results from the Simlab suggest minor differences across alternative payment mechanisms. Treatments with 8 decision-making rounds (v. 4) do show initial offers that are larger. Mechanisms including a rebate across all units, (e.g. money collected from a group that exceeded the total funds needed to provide the good was rebated to individuals in proportion to their offer) perform somewhat more efficiently than the mechanism that is based on the Clarke-Groves pivotal mechanism, creating a rebate on the last unit offer only.

Conclusion

The study is intended to initiate development on new approaches for financing public goods, beyond government and philanthropic efforts. Individualized pricing based on the Lindahl approach has long been considered impractical in microeconomics. This study initiates a direct test of this long-held assumption. Preliminary results suggest it may be possible to generate sufficient funds for public good provision. Our results indicate that participants were making decisions consistent with theory while simultaneously generating adequate funds to provide the public goods. The methods explored in this study may be most appropriate for localized public goods, but there is potential to adapt such incentive mechanisms for use with existing programs by which government pays landowners for ecosystem services. Auction methods could serve as an alternative (or complementary approach) to stated preference methods as a means for guiding the investment of public funds for ecosystem services.

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