

Duke University Wetland Center Completed Research Projects

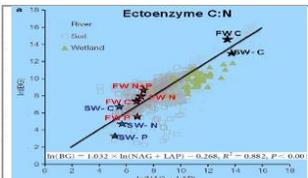
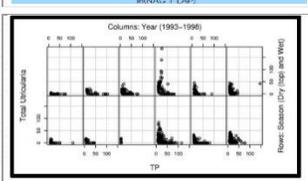
1989 - present

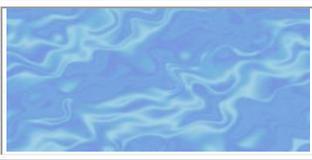


The Duke University Wetland Center
Nicholas School of the Environment
Durham, NC

Selected Summaries of Completed DUWC Projects, 1989 to the Present

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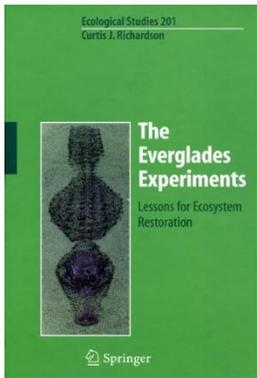
Beginning in 1989, the Duke University Wetland Center began an extensive research project in the Florida Everglades. The project emphasized experiments with controls in contrast to observational data. Experiments were long-term, often covering years. The project involved different spatial scales of approaches (laboratory, microcosm, mesocosm, field-scale, gradient studies, watershed-level studies). Various aspects of that research included:

- ✔ Restoration of the Everglades and the effects of dynamic interactions and effects of fire, hydrology, and nutrients on plant communities.
- ✔ The effects of agricultural runoff on Everglades nutrient cycling and storage.
- ✔ Effects of phosphorus and hydroperiod alterations on ecosystem structure and function in the Everglades.
- ✔ Designing effective water management strategies to sustain ecological integrity of the Everglades.
- ✔ Effects of hydrologic management decisions on marsh structure and function in Water Conservation Area-2A (WCA-2A) of the Everglades.
- ✔ Low Intensity Chemical Dosing in the Everglades Nutrient Removal Project (ENRP).
- ✔ Microbial and chemical transformations of mercury in wetlands: Factors controlling mobility and rates of methylation and demethylation.
- ✔ Paleoecological studies of wetlands and estuaries: the history of vegetation changes in the Florida.



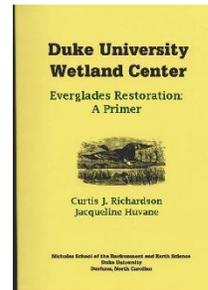
DUWC research took place in the Water Conservation Areas of the Everglades.

An overview of the [Duke University Wetland Center's Everglades Research Programs 1990-2002](#) is available in PDF format.



Encyclopedic in scope, *The Everglades Experiments: Lessons for Ecosystem Restoration* brings together key findings from 14 years of experiments in the Everglades by the Duke University Wetland Center and its partners. The 702-page book was published in 2008 by Springer Press.

"The findings presented in this book are the result of extensive experimental research from 1989 to 2003 on the effects of water, nutrients and fire on the Everglades communities," says DUWC Director Curtis Richardson. "It's a synthesis of what we learned and how it can be applied to managing and restoring this irreplaceable resource."



Available as PDF

[Richardson and Huvane, 2001. *Everglades Restoration: A Primer*](#)



Dosing Channels



Restoration Potential of the Iraqi Marshes

2003-2006

The Mesopotamian marshlands in Iraq, which some scholars identify as the historical model for the Biblical Garden of Eden, began being degraded more than 20 years ago as a result of upstream damming along the watersheds of the Tigris and Euphrates rivers. Saddam Hussein's regime then did more damage through a calculated campaign of murder, destruction, and displacement to eradicate the Ma'adan culture that has inhabited the marsh for more than 5,000 years.

DUWC Director Curtis J. Richardson first visited the area in the summer of 2003 as part of an exploratory team of experts sponsored by the U.S. Agency of International Development (USAID) that evaluated the extent of damage to the marshlands. The team also included a hydrologist-engineer, an agronomist and an anthropologist. Traveling as many as hundreds of miles a day under the protection of armed guards, the group visited parts of former marshlands that had dried into salt-encrusted dustbowls.



Ma'adan guides and Curt Richardson glide through the marsh in a *mashuf*, a type of canoe.

In the intervening years, researchers have studied the area to determine whether this massive environmental disaster can be at least partially reversed. More information is available at the links below.

[WetlandWire newsletter story, 2003](#)

[Nature Iraq webpage](#)

[UNESCO World Heritage Site \(2016\)](#)

Related Articles

Richardson, C.J. 2017. Ecological and hydrological constraints on large-scale wetland restorations in the Iraq Mesopotamian Al-Ahwar (marshes) and the Florida Everglades: A comparison. pp. 72-95 in: *Proceedings. U.S.-Iran Symposium on Wetlands, March 28-30, 2016, Irvine, CA*. University of Arizona College of Engineering: Tucson.

Richardson, C.J. 2010. The status of Mesopotamian marsh restoration in Iraq: A case study of transboundary water issues and internal water allocation problems. pp. 59-72 in: Korhonen-Kurki, K., and M. Fox (eds.). *Towards New Solutions in Managing Environmental Crisis: Proceedings of the USA-Iran-Finland Environmental Workshop, 14-15.9.2009, Haikko, Finland*. Helsinki, University, Helsinki.

Richardson, C.J. 2009. Wetlands of mass destruction. *Environmental Forum* 26(4):36-41.

Richardson, C.J. 2008. Wetlands of mass destruction: Can the "Garden of Eden" be fully restored? *National Wetlands Newsletter* 30 (3):1, 3-7, 33.

Richardson, C.J., and N.A. Hussain. 2006. Restoring the Garden of Eden: An ecological assessment of the marshes of Iraq. *BioScience* 56 (6):477-489.

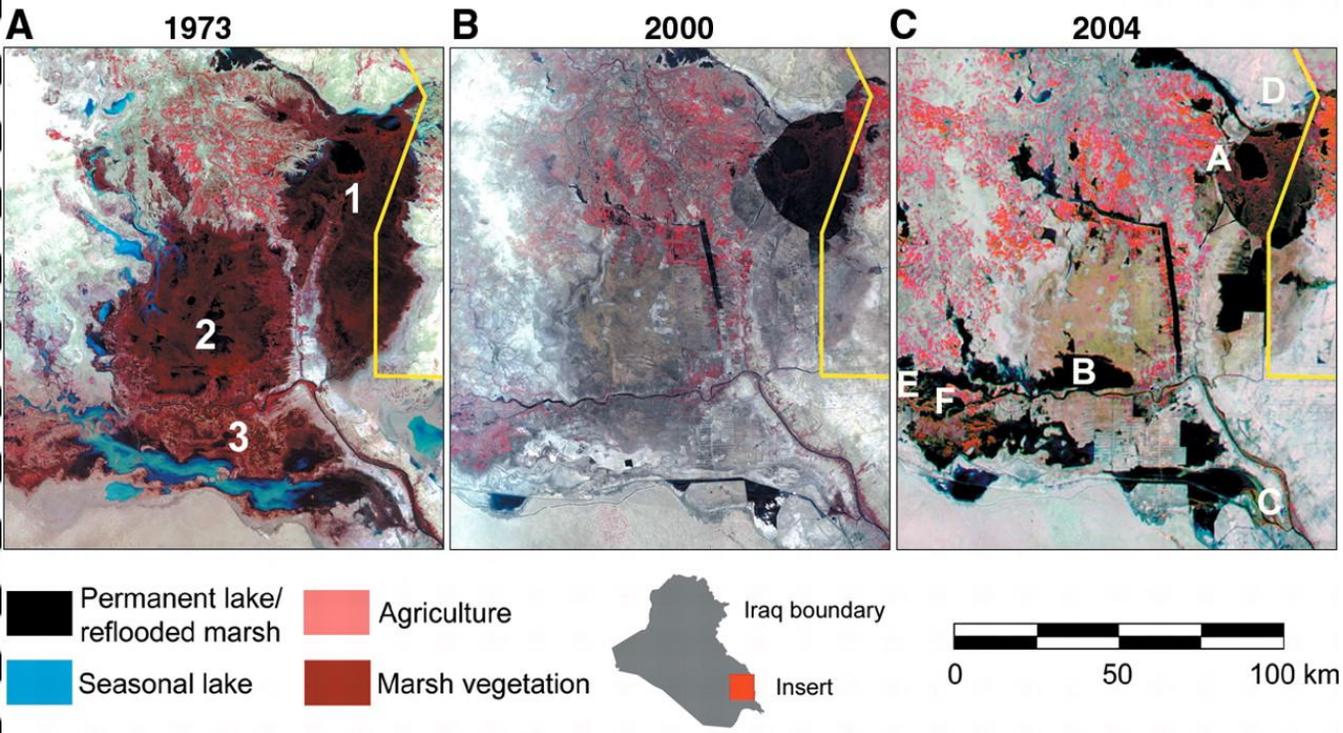
Richardson, C.J., P. Reiss, N.A. Hussain, A.J. Alwash, and D.J. Pool. 2005. The restoration potential of the Mesopotamian marshes of Iraq. *Science* 307: 1307-1311.



Ma'adan harvest reeds in a marsh in natural condition.



A dry stream bed crosses a drained marsh.



Phenolic Compounds and Black Carbon Feedback Controls on Peat Decomposition and Carbon Accumulation in Southern Peatlands under Regimes of Seasonal Drought, Drainage and Frequent Fire: A New Model for Management of Carbon Sequestration

2014-2018

The Duke University Wetland Center undertook a study on phenolic compounds and black carbon feedback controls on peat decomposition and carbon accumulation in southern peatlands. The project was funded by a grant from the U.S. Department of Energy's Office of Biological and Environmental Research Terrestrial Ecosystem Science Program.

Peatland ecosystems are among Earth's most efficient carbon sinks. Carbon captured from the atmosphere can be stored in the saturated peat for millennia due to the presence of naturally occurring phenolic compounds which inhibit microbial decomposition. In recent years, however, large areas of peat wetlands worldwide are being burned or drained for agriculture, forestry and to harvest the peat for energy. The organic carbon that is normally stored underwater is exposed to air, dries and decomposes, and emits carbon dioxide back into the atmosphere. Climate change is adding to the problem.

"The main question we are addressing is how southern peatlands continue to store carbon and release lower amounts of greenhouse gases compared to northern peatlands, even under climate-driven increases in temperature and extended droughts," says DUWC Director Curtis Richardson. "The research focuses on the role of phenolics and black carbon, both antibacterial carbon compounds, as biogeochemical controls on peat decomposition along a latitudinal gradient from Minnesota to Peru. What we are learning will provide us with new approaches for managing storage and losses of carbon from millions of acres of peatlands worldwide."

Globally, approximately 1/3 of peat stores are found in subtropical and tropical peatlands (STPs) formed from high-lignin woody biomass. These peatlands have persisted through changing climate and sea level over the last 4000 years and continue to accrete peat along the Atlantic coast from Virginia and North Carolina, to Florida, and to tropical Peru, even under climate driven conditions of drought, warmer temperatures and fire.

Our questions are: 1) why do these stressed non-*sphagnum* peatlands accumulate C, and 2) what insights can we gain from studying their natural processes and control mechanisms to provide management and conservation of the vast STPs and boreal peatlands subject to increasing climate forcing.

While most studies focus on northern peatlands, globally important STPs remain woefully underrepresented in Earth System Models. The Wetland Center conducted a multi-year experimental comparison across STPs to reveal the key process-level mechanisms controlling soil C stabilization, accumulation, and long-term storage. Our work will enable new hydrologic, fire and community management strategies and predictive threshold models to facilitate recovery of disturbed STPs subjected to climate change and lower water tables either by drainage or drought. Elucidation of these mechanisms will also yield perspective towards understanding the effects of global warming and drought on boreal *Sphagnum* peatlands undergoing climate-induced shifts to wooded plant communities.



Left. DUWC researchers work in a study site at Pocosin Lakes National Wildlife Refuge in eastern North Carolina. Pocosins are nutrient-poor, freshwater, evergreen shrub bogs found in coastal areas of Virginia, North Carolina, and South Carolina. Over the past 4 millennia, such subtropical and tropical peatlands have accumulated and stored over 20% peat of the continental United States. Right. Globally, accidental fires and commercial deforestation and burning account for significant releases of carbon into the atmosphere. The DUWC study will provide much needed information for management of hydrology and fire intensity in natural and degraded shrub/tree peatlands, central to maintaining peat/litter quality (phenol/black carbon) and enhancing long-term carbon accumulation. *Photos: DUWC & USFWS*

Our main hypothesis was that the STP native-fire-adapted shrubs/trees communities produce higher polyphenol litter than *Sphagnum/Carex* communities. This production difference, in conjunction with climate induced regimes of frequent low-intensity fire, creates recalcitrant decomposition-resistant peat by a dual "latch key mechanism" consisting of high phenol and black carbon (BC, complex aromatics). Together these retardants reduce GHG flux, and C decomposition of STP peats even under altered hydrologic conditions, higher temperatures and drought.

Specific objectives include:

I: Identify and compare process-level mechanisms controlling peat accretion and C losses from shrub-bogs in North Carolina, subtropical *Cladium*/shrub peats in the Florida Everglades, and tropical *Myrica-Cyrilla* bogs in Peru. This never-before-studied latitudinal gradient allows experimental quantification of biotic (plants type) and abiotic (low-intensity fire and drought) contributions to resultant high phenol/low carbon quality litter and specific BC aromatics;

II: Assess the composition and origin of aromatic compounds in peat and porewater at the molecular level and the importance of fire derived aromatic compounds limiting peat decomposition using multiple advanced analytical techniques including Pyrolysis GC-MS, GC-MS, LC-MS, NMR, FTIR, FT-ICR-MS and 3-Dimensional Excitation-Emission Matrix (EEM) fluorescence spectroscopy;

III: Experimentally (field to microcosm scale) determine peat decomposition, GHG fluxes and DOC loss integrated with soil C chemistry, soil bacterial/fungal composition, enzyme activities, and hydrologic properties to enhance our understanding of controls on C storage and fluxes. The field fire study leverages data and research site infrastructure at an ongoing drainage GHG study at the USFWS Pocosin Lakes Wildlife Refuge in North Carolina and with Oak Ridge National Laboratory and USFS investigators working at the [Spruce-Peatland Response Under Climate and Environmental Change \(SPRUCE\)](#) experiment site in Minnesota and with scientists at the [Los Amigos Biological Station](#) in Peru. Our research provides the first latitudinal comparative analysis of peatland C chemistry, tests a new dual control model for sustaining C, advanced C chemistry data, and analytical methods, and data for modeling in support of DOE's climate change research program and Earth System Models.



Left The DUWC research sites in Florida's Loxahatchee NWR are accessible only by airboat. Researcher Suzanne Hodgkins from collaborating institution Florida State University prepares porewater samples while DUWC scientist Neal Flanagan looks on. *Right*. The Spruce-Peatland Response Under Climate and Environmental Change (SPRUCE) Project in northern Minnesota is a prime component of the DOE Terrestrial Climate Change Program. The SPRUCE sphagnum bog forest, like most boreal peatland forests, is considered especially vulnerable to climate change.

An important result of the study is the discovery of a previously unknown dual mechanism that slows peat decay and may help reduce carbon dioxide emissions from subtropical peatlands during times of drought. The naturally occurring mechanism was discovered in the North Carolina pocosins. Preliminary field experiments suggest it may occur in, or be exportable to, peatlands in other regions as well. "When we took peat extracts from the southern peatlands and put them into Canadian peatlands, they slowed down decomposition there, too," said DUWC's Richardson. "The accepted scientific paradigm is that prolonged drought, coupled with global warming and increased drainage of peatlands for agriculture and forestry, will lower water levels. This could cause peatlands to dry out, decay and release massive amounts of carbon back into the atmosphere. Our research supports a less dire scenario. It finds that moderate long-term drought might have less impact on the release of carbon dioxide from peatlands than expected."



Left. DUWC Research Scientist Hongjun Wang checks a set instrument that measures peat accretion at a DUWC research site in eastern North Carolina's Pocosin Lakes NWR. Right. The Los Amigos Biological Station, part of the Amazon Conservation Association, is in lowland Amazonian forest at the base of Peru's southern Andes. DUWC researchers collected peat samples from palm swamp locations there.

The reason lies buried in the peatland soil itself. By comparing the chemistry of soil from pocosin bog peatlands in North Carolina with soil from boreal peatlands in Canada, the DUWC team discovered a significant and previously unrecognized difference between the two. Southern wooded peatlands are 5,000 to 8,000 years old and have more complex plant-derived compounds that have allowed them to adapt to drought through a mechanism that regulates the buildup of phenolics and helps slow down decomposition. This natural adaptation, which was not found as abundantly in soil from boreal peatlands of the north, protects stored carbon directly by reducing decay-promoting phenol oxidase activity during short-term drought. The mechanism also indirectly protects stored carbon by spurring a shift in the peatlands' plant cover in response to moderate long-term drought. As water levels drop, plants that contain low levels of phenolics, such as sphagnum moss, ferns and sedges, are replaced by trees and shrubs, which are high in the decay-retarding compounds. "This dual mechanism helps peat resist decay and adapt to climate change," Wetland Center researcher Hongjun Wang said. He believes that high-phenolic shrubs could naturally expand into northern peatlands or be introduced there as water levels drop, offering the hope that scientists might be able to reduce the future risk of large carbon releases. Researchers still need to identify the specific aromatic components or groups of phenolics that are responsible for the decay-retarding mechanism. Plants produce and contain thousands of compounds, so this may take time. But it will be worth the effort, providing new approaches for managing storage and losses of carbon from millions of acres of peatlands worldwide.

Selected Publications

Hodgkins, S.B., C.J. Richardson, R. Dommain, H. Wang, P.H. Glaser, B. Verbeke, B.R. Winkler, A.R. Cobb, V.I. Rich, M. Missilmani, N.E. Flanagan, M. Ho, A.M. Hoyt, C.F. Harvey, S.R. Vining, M.A. Hough, T.R. Moore, P.J.H. Richard, F.B. De La Cruz, J. Toufaily, R. Hamdan, W.T. Cooper, and J.P. Chanton. 2018. Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. *Nature Communications* 9:3640. DOI: 10.1038/s41467-018-06050-2 .

Wang, H., C.J. Richardson, M. Ho. 2015. Dual-controls on carbon loss during drought in peatlands. *Nature Climate Change* 5:584- 587. <https://www.nature.com/articles/nclimate2643>

Winton, R.S., N. Flanagan, and C.J. Richardson. 2017. Neotropical peatland methane emissions along a vegetation and biogeochemical gradient. *PLoS One* 12(10):e0187019. <https://doi.org/10.1371/journal.pone.0187019>



Carbon Sequestration Potential in Restored North Carolina Pocosins

2009-2013

In 2013, the Duke University Wetland Center completed the project "Carbon Sequestration Benefits of Peatland Restoration" with funding from the US Fish and Wildlife Service.

The three-year project studied and quantified the anticipated benefits of peatland restoration in the USFWS-run Pocosin Lakes National Wildlife Refuge in North Carolina.

Outside the Florida Everglades, the primary type of peatland found in the southeastern United States is the pocosin, an evergreen shrub bog located on peat deposits. There were originally over 900,000 ha of pocosin peatlands on North Carolina's coastal plain, but many pocosins were drained during the 20th Century to convert the land for agriculture, silviculture, and peat mining. Today, less than a third of pocosins remain in their natural state.

The drained pocosins lost much of their ability to retain carbon, nitrogen, and metals, which were released back into the atmosphere and adjacent waters.

When drained pocosins southeast of Lake Phelps, NC were incorporated into the newly established Pocosin Lakes National Wildlife Refuge in 1990, refuge managers began restoring peatland water levels. Restoring the pocosins to a more natural state is expected to sequester tons of nutrients (including nitrogen and carbon) and prevent runoff of ions and heavy metals (e.g., mercury) into adjacent estuaries.

Verification and quantification of the expected environmental benefits of restored peatlands will be important for effective ecosystem management and promotion of restoration efforts.

To this end, the project had the following objectives.

- 1) Quantify changes in soil carbon flux and nitrogen dynamics in response to restoration of appropriate hydrological conditions in drained histosols (dominantly organic soils such as bogs, moors, peats, or mucks).
- 2) Complete a carbon and nitrogen budget to determine storage and losses from refuge peatlands in natural state, drained state, and restored state.
- 3) Use research data to quantify carbon and nitrogen sequestration benefits from the restoration work, comparing these to the benefits of other climate-change projects (e.g., reforestation or conservation tillage.)

The DUWC project contributes to the ultimate US Fish and Wildlife Service goals of improving water quality and finding climate-change solutions.

In addition, The Nature Conservancy provided a \$50,000 grant in support of the Center's study of the carbon benefits of peatland restoration. The Nature Conservancy's involvement was part of the organization's larger effort undertaken with funding from Duke Energy to build the adaptive capacity of the Albemarle-Pamlico Peninsula's ecosystems to climate change and sea-level rise.

Richardson, C.J., N.E. Flanagan, H. Wang, and M. Ho. 2013. *Impacts of Peatland Ditching and Draining on Water Quality and Carbon Sequestration Benefits of Peatland Restoration. Report Year 3*. Submitted to U.S. Fish and Wildlife Service, Region 4. Duke University Wetland Center: Durham, NC.



The Duke University Wetland Center participated in a multi-institution effort* to develop a new methodology for high-accuracy mapping of peat thickness using airborne electromagnetics (AEM). AEM can provide cost-effective and accurate mapping at a large scale.

The AEM method utilizes the contrast between the electrical resistivity of peat and the underlying substrate to image the distribution of peat. Using a helicopter-deployed system (Figure 1), 250 to 300 line kilometers can be flown every day, acquiring the data needed to determine peat thickness every 30 m along the flight lines.

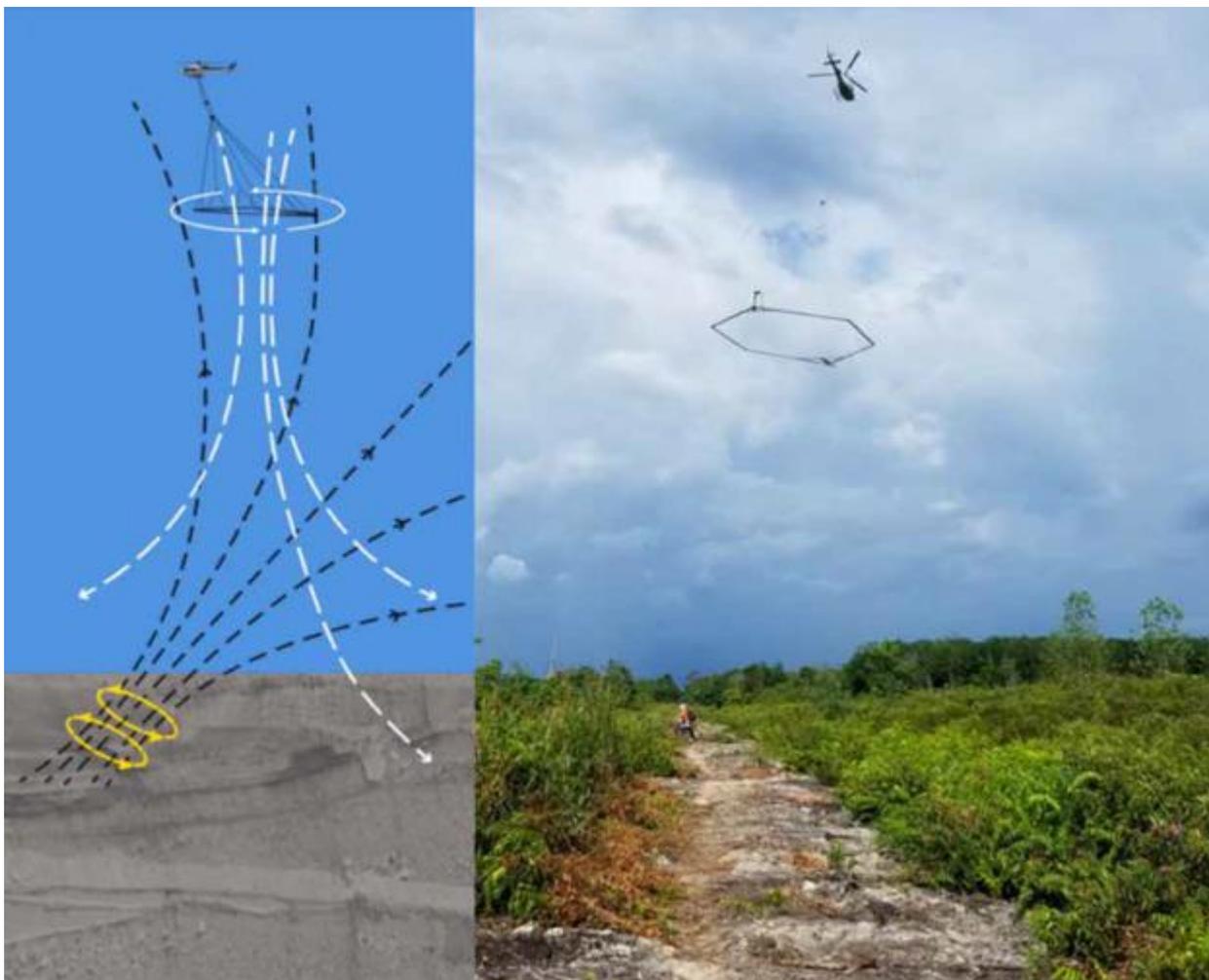


Figure 1. The AEM system generates primary electromagnetic fields using a loop transmitter, and conducting coil antennas are used to measure the secondary magnetic field caused by the ground's conductive inhomogeneities.

In late 2017, the research team tested the AEM methodology at a peatland in West Kalimantan, Indonesia (Figure 2). Field work involved: (1) planning flight lines using satellite imagery analysis; (2) acquiring airborne electromagnetic data for the entire

study area (3) coring to confirm peat depth; (4) testing electrical resistivity in the field and in the laboratory on core samples to determine electrical resistivity contrasts between peat and underlying materials; (5) imaging electrical resistivity to confirm understanding of electrical resistivity contrasts; (6) acquiring ground-penetrating radar data along lines perpendicular to flight lines to assess the variability in peat thickness between flight lines

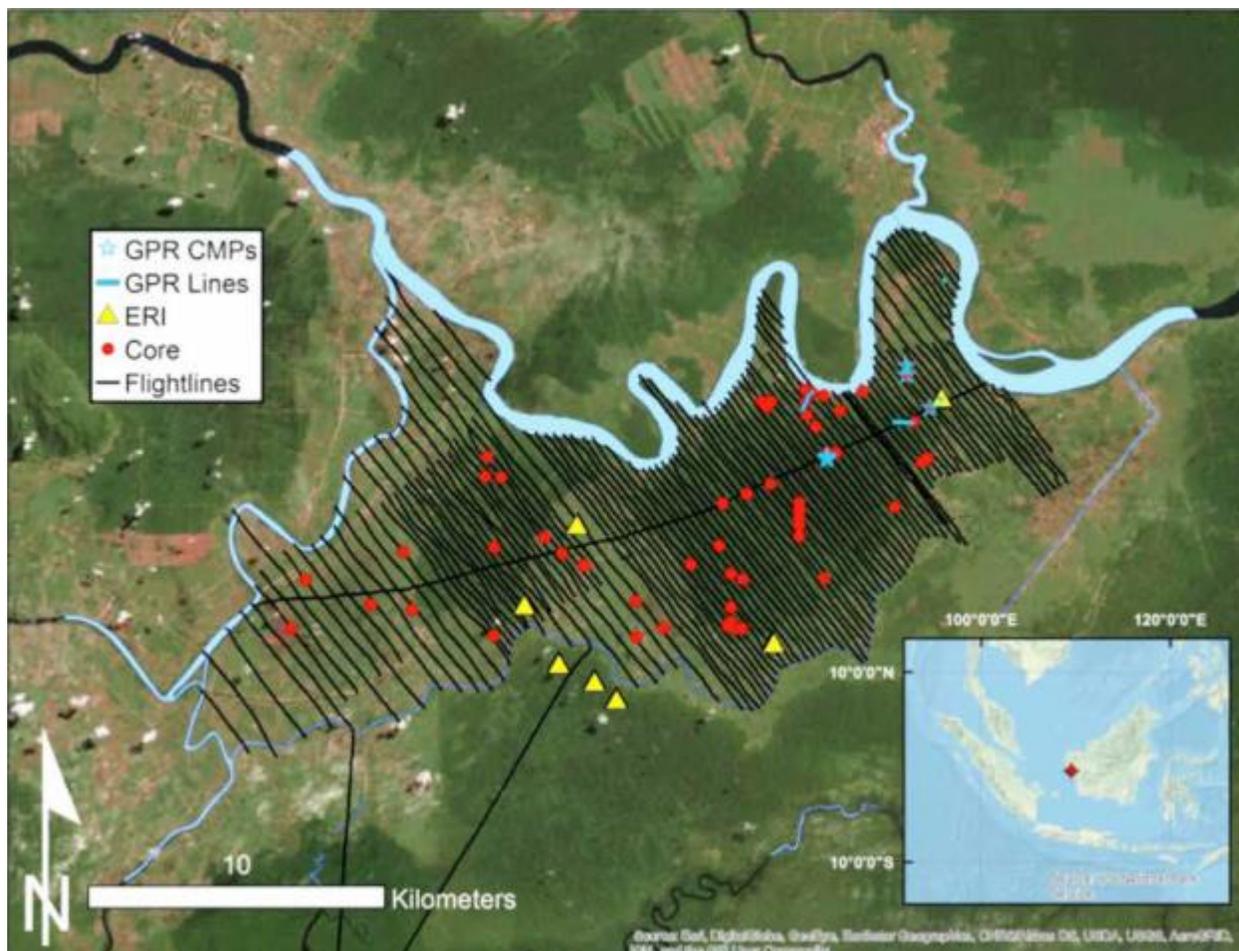


Figure 2. Map of flight lines at the AEM test site at West Kalimantan, Indonesia.

Based on the results and the accuracy analysis performed (see Figures 3 & 4), the team concluded that AEM can accurately and cost effectively map peat thickness. The researchers are unaware of any other method that can provide the same level of areal coverage, accuracy, and speed of data acquisition for comparable costs.

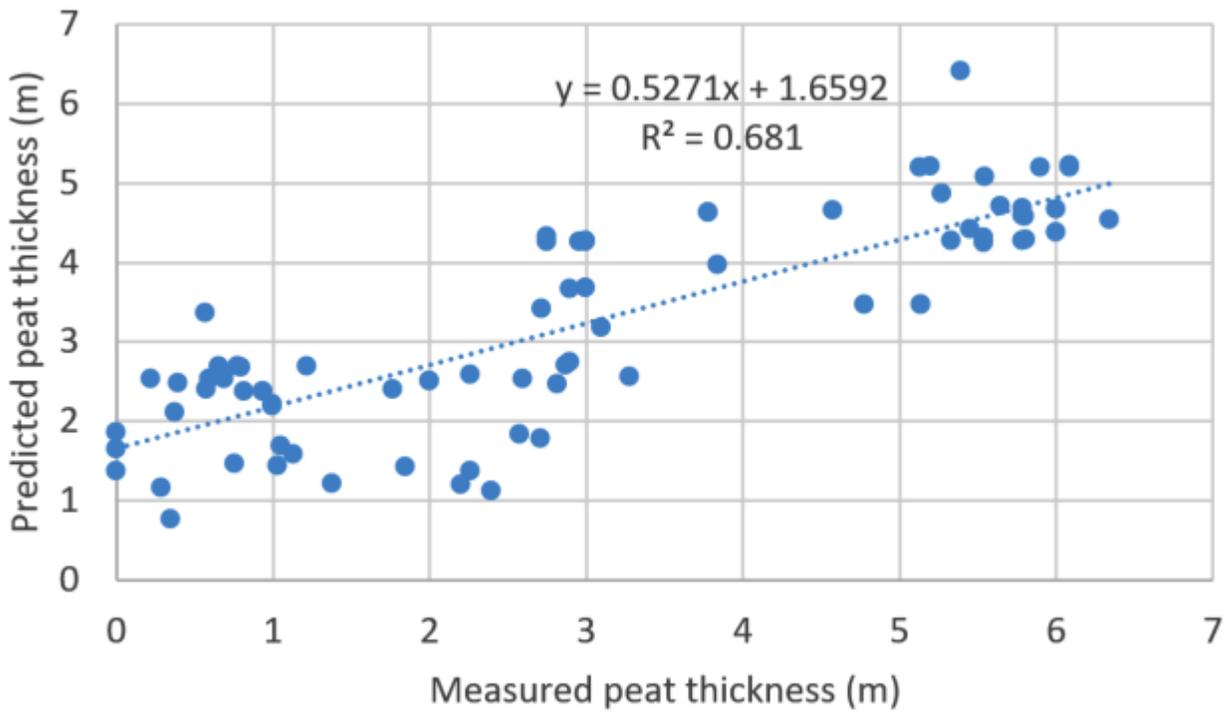


Figure 3

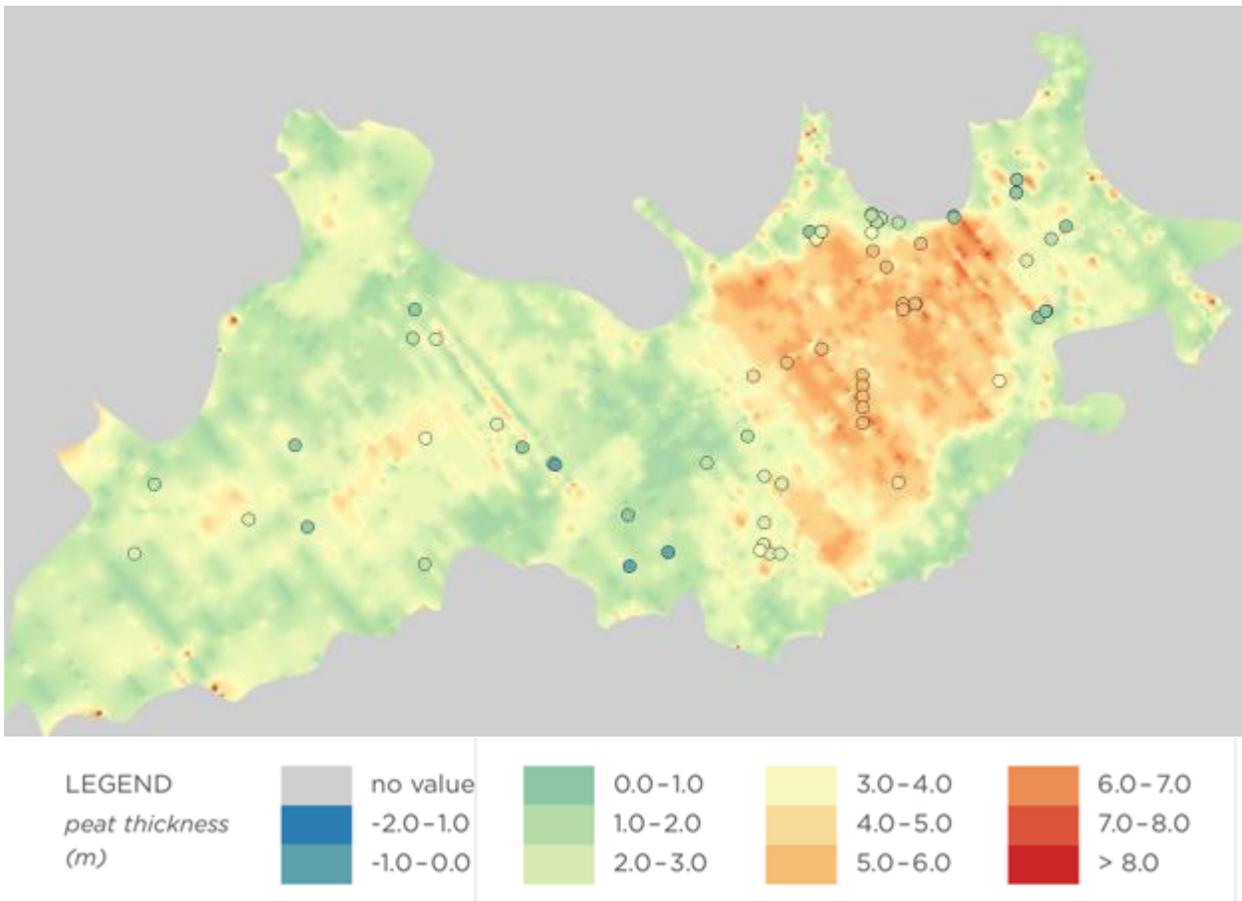


Figure 4



Sources, Transport, and Fate of Nitrogen and Phosphorus in the Upper Falls Lake Watershed, NC

2014-2018

Mark River, NSOE Ph.D. 2018, studied the sources, transport, and fate of nitrogen and phosphorus in the Upper Falls Lake Watershed in North Carolina. The Falls Lake Watershed supplies all drinking water for Durham, along with half for the city of Raleigh. The Falls Lake Watershed also receives half of Durham's wastewater, along with all of Hillsborough's and Butner's wastewater. The rapid population growth and changing land use in the watershed raises concerns about the potential for eutrophication of water resources.

His field work and lab analysis investigated the stormflow delivery of nutrients; the relationship between phosphorus and suspended sediment; the ultimate fate of nitrogen and phosphorus that reaches wetlands/reservoirs; and how wetland restoration and/or BMPs can reduce N & P transport in the watershed. His approach to the particulate transport of phosphorus will be useful in the development of best management practices.

River, M., and C.J. Richardson. 2018. Particle size distribution predicts particulate phosphorus removal. *Ambio* 47 (Suppl. 1):S124-S133. DOI 10.1007/213280-017-0981-z

River, M., and C.J. Richardson. 2018. Stream transport of iron and phosphorus by authigenic nanoparticles in the Southern Piedmont of the U.S. *Water Research* 130 (2018) 312-321. <https://doi.org/10.1016/j.watres.2017.12.004>



Lower left. Mark River collects sediment cores from Falls Lake. **Right.** Collected core samples awaiting analysis. **Lower left.** River collects a sample of the stormwater runoff that will eventually find its way to Falls Lake.





The primary objective of this EPA-funded study was to assess how predicted climate and land-use driven changes in hydrologic flux and temperature regimes of floodplain ecosystems affect plant communities in terms of their vulnerability to the establishment and spread of invasive species, and in turn ecosystem functions and services. Future climate scenarios for the southeastern U.S. predict that surface water temperatures will warm (in concert with air temperature) and that stream flows will likely decrease, with a greater proportion of annual watershed hydrologic yield occurring during major storm events. Land-use changes (urban vs. forested, etc.) have been shown to also raise water temperature and increased pulsed water releases during storms. We analyzed a series of riparian wetland sites along existing gradients of temperature and hydrology produced on dammed and undammed rivers to find the relative importance of a suite of environmental variables describing temperature, hydrology, soil characteristics, and watershed land use composition.

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The Relationship Between Waterfowl Herbivory and Wetland Methane Emission

2012-2017

Waterfowl are among the longest-recognized values provided by wetlands, with enthusiasts catalyzing the first widespread wetland conservation efforts in America during 1920s. But ducks and their ilk may play an underappreciated role in the regulation of greenhouse gas emission from wetlands and in the Earth's climate system.

DUWC researcher Scott Winton studied waterfowl and greenhouse gas emissions at Lake Mattamuskeet, North Carolina's largest natural fresh water body and home to hundreds of thousands of wintering ducks, geese, and swans.

All those birds migrate south from their northern breeding grounds to escape the harsh winters and are attracted to Lake Mattamuskeet's open water and abundant aquatic vegetation. Many emergent wetland plants have hollow stems, which studies have shown greatly enhance the emission rates of methane, an important greenhouse gas produced in oxygen-depleted wetland sediments. When water birds arrive at Lake Mattamuskeet for winter to gobble up plant matter, reducing stem densities, they may be attenuating the release of methane and helping to mitigate climate change.

To look for evidence of this phenomenon Winton set up plots bordered by deer fencing to keep waterfowl out. He compared methane efflux rates in these areas protected from herbivores to those of control plots, into which birds can freely enter. Winton's project was sponsored by a generous research grant from the Carolina Bird Club that allowed him to purchase weatherproof cameras to monitor bird activity at his study sites and procure materials to construct the plots as well as large custom-built transparent chambers that Winton designed for collecting gas samples.

Few studies outside Europe have attempted to link herbivore-plant interactions and methane emission rates. Given that milder winters are allowing waterfowl to shorten their southerly migrations along the east coast, Southeastern wetlands may be left with an herbivore shortage and enhanced methane emission. This scenario, if true, would represent a novel positive climate feedback, with milder weather allowing waterfowl to shift their wintering grounds northward, lowering their populations in southern lakes and impoundments, and resulting in less herbivory and more methane escape through the stems of denser stands of wetland plants.

Winton, S.R., and C.J. Richardson. 2017. Top-down control of methane emission and nitrogen cycling by waterfowl. *Ecology* 98 (1):265-277. DOI: 10.1002/ecy.1640

Winton, R.S., M. Moorman, and C.J. Richardson. 2016. Waterfowl impoundments as sources of nitrogen pollution. *Water, Air, & Soil Pollution* 227:390. doi:10.1007/s11270-016-3082-x



Left. Sunset finds thousands of birds over and on Lake Mattamuskeet, a major wintering ground for northern waterfowl, including Tundra Swans, Snow Geese, and many duck species. DUWC researcher Scott Winton selected several sites on the lake to study possible relationships between bird herbivory and GHGs. Right top. An automatic camera captured a group of foraging birds in one of the research plots. Right bottom. The red dot indicates the location of the Lake Mattamuskeet National Wildlife Refuge in eastern North Carolina.





Differential Nutrient Limitation

2008-2013

The structure and function of ecosystems is governed by the patterns of nutrient limitation of the primary producers (e.g., plants) and heterotrophs (e.g., soil microbes). Often, these groups of organisms are limited by the same nutrient. However, an increasing body of evidence indicates that different nutrients can limit primary producers and heterotrophs in some ecosystems; this is known as differential nutrient limitation (DNL). This study funded in the fall of 2008 examined why DNL occurs in some ecosystems (but not others), and what the consequences of DNL are with respect to the utilization vs. storage of carbon. Our project addressed these questions in four wetlands ranging from Georgia to Rhode Island, including both freshwater and saline systems, which were projected to have either N or P limitations based on traditional N: P ratio methods.

[THE FINAL REPORT](#)





Using part of the results from their larger, multi-year study of the Everglades, Duke University Wetland Center researchers Curtis J. Richardson and Song S. Qian won an EPA Science to Achieve Results (STAR) grant in 2005 to develop a Bayesian hierarchical modeling approach for estimating ecological thresholds. The hierarchical modeling approach is built on the Bayesian change point methods of Qian et al. (2003, 2004) for single species/metric. Single metric methods have been successfully used in the Everglades research (as described in a 2007 article by Richardson et al. in *Environmental Science and Technology*). Richardson and Qian's STAR research focused on the interaction among multiple metrics within the ecosystem of interest.

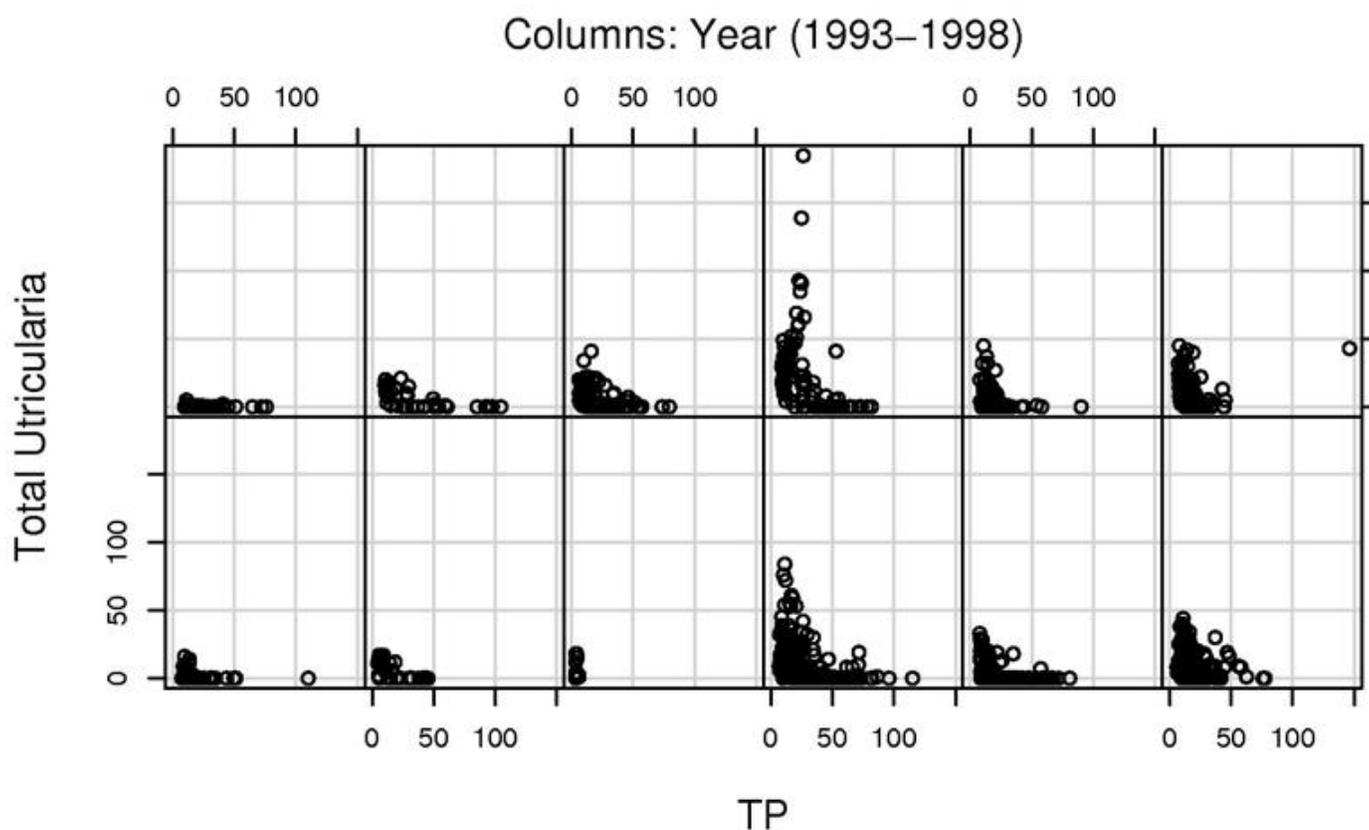


Figure 1: Observed total *Utricularia* stem counts are plotted against the previous 6 month average total phosphorus concentrations. The stem counts vary greatly by year and season. The stem counts also respond to the changes in phosphorus concentration, and the count is generally small when phosphorus concentration is high. A threshold is apparent in most year-seasons.

Initially, DUWC researchers discovered that the TP threshold for the Everglades varies by metrics. Even for a single metric, the estimated threshold varies over time. For example, Figure 1 shows how the bladderwort (*Utricularia purpurea*) stem density drops suddenly when TP concentration exceeds a certain

value (the threshold) and that the threshold changes over time and season. To understand the factors affecting the changes in TP threshold, conventional mathematical and statistical methods are insufficient and the Bayesian hierarchical modeling approach is necessary. This is because traditional methods can only analyze the threshold response using data specifically for a single metric observed from a single sampling event. There is no easy way to combine data from multiple metric and dates without some ecologically unrealistic assumptions. As part of the effort, Qian studied the application of the hierarchical (or multilevel) analysis of variance in ecological data analysis, publishing his results in a paper in the journal *Ecology* (Qian 2007). This effort led to a new statistical method for analyzing combined threshold data from multiple metrics and multiple sampling events. The new method preserves individual (metric, sampling event) specific features and can be used to study their interaction. Using this method, Qian and Richardson re-analyzed the bladderwort stem count data from all sampling events. They found that the varying threshold value is slowly converging to a stable value (Figure 2).

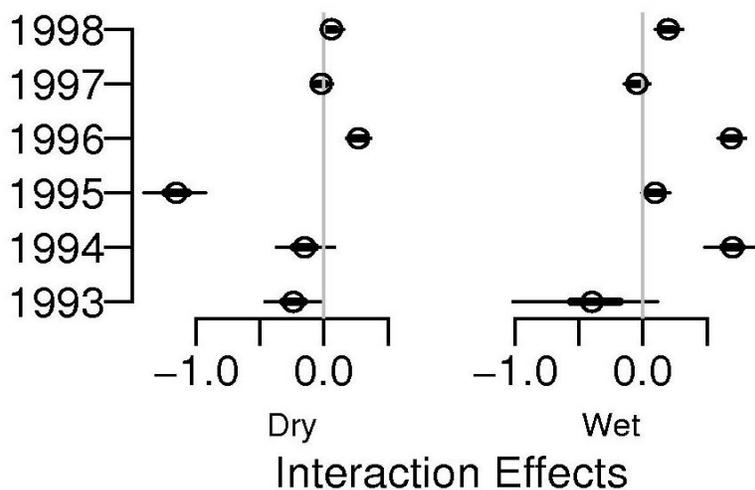


Figure 2: Estimated year-season interaction effects on TP threshold of total *Utricularia* stem count show the differences of year/season-specific thresholds from the overall average. The figure shows that the estimated year/season-specific threshold are gradually converging towards the overall mean, suggesting that the dosing system was gradually mature after initial dose of phosphorus.

The STAR project allowed the researchers to summarize several important findings:

- 1) The use of Bayesian hierarchical change point method for detecting and quantifying ecological threshold is feasible. This finding is an important contribution to the field in that it provides a series of quantitative methods

for combining data from multiple sources to understand ecological responses at both individual metrics and ecosystem levels.

2) The Bayesian hierarchical method can also be used to account for interactions among species.

3) The hierarchical modeling approach also introduces an ecosystem-level response that can be easily integrated into a decision-making process.

[Related Articles](#)

Qian, S.S., and Z. Shen. 2007. Ecological applications of multilevel analysis of variants. *Ecology* 88 (10):2489-2495.

Richardson , C.J., R.S. King, S.S. Qian, P. Vaithyanathan, R.G. Qualls, and C.A. Stow . 2007. Estimating ecological thresholds for phosphorus in the Everglades . *Environmental Science and Technology* 41 (23):8084-8091.

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A Comparison of Wetland Functions and Services on Restored Wetlands of the Piedmont: Carbon and Nitrogen Storage and Gaseous Release Estimates

2008-2013

Billions of dollars are spent on wetland restoration to compensate for functions and values lost when wetlands have been destroyed by development in the United States. One important value that wetlands provide is the long-term storage of carbon in sediments, which helps mitigate anthropogenic global warming. Yet wetlands are also capable of emitting significant amounts of methane, a potent and important greenhouse gas. Any accounting of how much climate mitigation (or exacerbation) a given wetland restoration project might provide must consider both the potential of the wetland as a sink for carbon and as a source for methane.

One restoration practice that has been widely utilized is the amendment of soil with a source of organic matter (i.e., compost) to increase the soil carbon content and decrease soil bulk density, thus facilitating the establishment of desired wetland soil conditions. The Duke University Wetland Center investigated the effects of soil organic matter amendments on emissions of greenhouse gases. Wetland restoration sites in Virginia and North Carolina were used as research sites for assessing greenhouse gas emissions dynamics in response to experimental carbon additions and carbon accumulation over time.

The restoration sites were studied to determine changes in soil carbon flux in response to the experimental carbon additions. Analysis of bulk density, total carbon and total nitrogen were consistent with earlier studies at the site, although lower amounts of soil organic matter (OM) were found. However, plots that received greater OM amendment loads have higher total carbon and nitrogen and lower bulk density. There is concern that widespread restoration and/or creation of wetlands may present a radiative forcing hazard because of the potential for high rates of methane (CH₄) emissions. Yet data on greenhouse gas (GHG) emissions from restored wetlands remains relatively sparse and there has been little investigation into the GHG effects of amending wetlands with soil organic matter (OM), a practice used to improve function in mitigation wetlands in the Eastern United States. In this study we evaluate the effect of added OM on GHG across an organic matter gradient at the Charles City Wetland (CCW) in Charles City County, Virginia, ten years post original OM additions. Our data suggest that soils heavily loaded with OM are emitting significantly more CO₂ than those that have received little or no OM amendment. Emissions of CH₄ are low compared to those of other forested wetlands in the region and show no relationship with the loading rate of added OM or total soil carbon. We conclude that adding moderate amounts of OM to the CCW does not greatly increase GHG emissions, while the addition of high OM loading rates produces additional CO₂, but not CH₄.

This research was supported by funding from the Peterson Family Foundation.

Winton, R.S., and C.J. Richardson. 2015. The Effects of Organic Matter Amendments on Greenhouse Gas Emissions from a Mitigation Wetland in Virginia's Coastal Plain. *Wetlands* 35:969-979. DOI 10.1007/s13157-015-0674-y



The Duke Wetland Center has completed a five-year cooperative project with the City of Charlotte and Mecklenburg County in the restoration of Little Sugar Creek located off North Tryon St. in Charlotte. The city and county bought property adjacent to the creek and restored the stream and wetlands in a 2-block section. Sections of the restored marsh received one of three soil treatments: 1) topsoil only, 2) topsoil plus organic matter in a 4:1 ratio, and 3) topsoil plus organic matter in a 2:1 ratio. The Duke Wetland Center monitored the water quality, the geomorphic and physical changes in the stream channel, as well as the vegetation and soils of these marsh treatment areas. Faculty and graduate students performed on-site sampling and ran laboratory analyses. The Duke Wetland Center reported to Mecklenburg County how these soil amendment treatments affected the soil nutrient and moisture levels and in turn how these soil properties affected the survival and growth of the vegetation.



Role of Sediment Processes in Controlling Water Quality in the Cape Fear River

2002-2003

Sediment loading and sediment processes were evaluated for their role in regulating water quality conditions at three lock and dam (LD) structures on the Cape Fear River (CFR) in North Carolina in fall of 2001. In comparison to the upstream site LD 3, surface waters at downstream sites LD 2 and LD 1 generally had higher concentration of dissolved reactive phosphorus during the May to December 2001 study period. ^{137}Cs dating of sediment cores from the floodplains at the three LD locations reveal that the sedimentation rates vary from 0.5 cm/yr at LD 3 to 1.5 cm/yr and 1.3 cm/yr at LD 2 and LD 1, respectively. The sedimentation rates correspond well to the total sediment phosphorus concentrations, indicating that sediment deposition during the recent decades (≈ 40 years) has caused an increase in nutrient loading to the CFR. The floodplain sediments at LD 2 had the greatest phosphorus binding capacity, while the most downstream site, LD 1, had the lowest. However, the intra-site variability in phosphorus sorption capacity and mineral element composition increases downstream, most likely in response to differential sorting of the riverine sediment. ^{31}P Nuclear Magnetic Resonance (NMR) analyses of concentrated river water and floodplain sediments reveal that phosphorus loading in this river occurs in diverse chemical forms. Although the surface water concentration of these forms of phosphorus may be very low, over time the phosphorus binding properties of the deposited sediments may concentrate these forms of phosphorus in the floodplain of the CFR. Importantly, increasing variability downstream in the mineral element composition and the P-binding capacity of riverbank sediments suggests that moving seaward, sediment sorting will lead to creation of "hot spots" for efficient P-sorption and release along the riverbank of the CFR, and this could pose a considerable challenge with regard to water quality management. We further show that converting natural wetland forests to agricultural land leads to the loss of "chemical diversity" in nutrient speciation. However, wetland restoration promotes the re-establishment of this diversity in chemical speciation of phosphorus. Thus ^{31}P NMR spectrometry can be used as a tool to track the progress of wetland restoration actions. These findings have important implications for water quality management in this largest river system in North Carolina.

Sundareshwar, P.V., and C.J. Richardson. 2003. Role of Sediment Processes in Controlling Water Quality in the Cape Fear River. Final Report for Water Resources Research Institute Project No. 70191.



Inadequately sized channels passing under superhighways can seriously disrupt roadside wetland ecosystems by interfering with the natural flow of water, a Duke University Wetland Center Study has shown.

The first phase of a study funded by the North Carolina State University-based Center for Transportation and the Environment investigated the effect of highway construction on wetlands. DUWC researchers found that trees, plants, and soils in two wetland systems were significantly changed by the way underlying culverts altered water levels on either side of a stretch of Interstate 40 in eastern North Carolina.

The extension of I-40 from Raleigh to Wilmington in the late 1980s meant cutting through miles of wetlands. The highway's effects on drainage, water flow, and species habitats posed many important questions. According to Duke Wetland Center Director Curtis J. Richardson, state and federal transportation officials now recognize a vital need for new construction standards in wetlands. "But they really don't have the data to say how they should design when crossing wetland areas," he added. "So that is what we are trying to provide."

Dr. Richardson and fellow investigator Kevin Nunnery, now a Nicholas School post-doctoral researcher, faced an immediate hurdle when they began their study in 1995. They had to assess construction impacts of a highway that had been built seven years before their study began.

They chose two adjacent wetland corridors, Beaverdam Swamp and Kill Swamp, which cross Interstate 40 about 1.5 miles apart near the Sampson County town of Newton Grove in North Carolina's coastal plain. Both swampy creeks had similar water flow rates and kindred upstream and downstream environments. Their upstream land use patterns—agriculture and livestock production—were also similar. And both passed under I-40 through the same type of conduit systems—a central box-shaped culvert and two smaller stream overflow pipes. The locations were deemed the best sites available in North Carolina for studying a recently constructed highway crossing's effects on wetlands.

In a move to mimic how the affected wetlands might have appeared before the superhighway's construction, Dr. Richardson and Dr. Nunnery selected an undisturbed "reference area" about 320 yards upstream from the Beaverdam Swamp study site. They also obtained highway department pre-construction aerial photos of the wetland crossing sites to gauge what the tree cover was like before I-40 was completed.



DOT Highway Study "reference area."



DOT Highway Study "impacted site."

Their study showed that the box culvert systems ended up acting more like bottlenecks than conduits, especially at the Beaverdam Swamp crossing. "During the wet periods water backed upstream significantly," Richardson said in a recent interview. "That significantly changed the areas that were wet, and it quite often killed upstream vegetation there.

More than that, we found after a period of time that a lot of the wetlands were converted into new types of wetland. And some uplands also were converted into wetlands."

In a final report on the 18-month field study, conducted from March 1995 until October 1996, the researchers said the culvert bottleneck raised Beaverdam Swamp's mean surface elevation more than 7 inches upstream of the highway crossing. Resulting ponding extended more than 100 yards upstream. And the soil decomposition rate was significantly lower upstream as well, "suggesting that ponding was inhibiting decomposition there," the report said.

While Kill Swamp's water levels were altered less dramatically, there were significant changes in vegetation within both wetlands. Plants downstream of both crossings were 30 percent to 50 percent thicker below the crossing than in upstream sections. Trees also grew 10 percent to 40 percent less prolifically upstream than downstream.

The reference area, which had escaped any impact from I-40, contained "several less flood tolerant species" than the affected areas, "suggesting that stream hydrology had been disturbed near the highway," the report said. Trees in the reference area were also significantly leafier than in the affected areas.

The report described a general "paucity of information on what effects highways may have on wetland ecological functions, and how severe and geographically far-reaching those effects are." There is also "no accepted, reliable procedure for quantifying and assessing" those impacts, it added.

In the study's second phase the center studied how a new U.S. 17 bypass project near the Camp Lejeune Marine Corps base in the vicinity of New Bern will affect coastal wetlands in the adjacent New River Estuary. This time the scientists weren able to begin their work before construction began.

Nunnery, K.T. November 1997. An assessment of highway impacts on ecological function in palustrine forested wetlands in the upper coastal plains of North Carolina. Report to the Center for Transportation and the Environment, Raleigh, NC. Duke Wetland Center publication 97-04. Nicholas School of the Environment, Duke University, Durham, NC. 124 pp.



Effects of Highway Construction on Wetlands, Phase 2

1998-2003

A major objective of research at the Duke Wetland Center is to develop methods to assess and minimize human impacts on wetland systems. As part of the NC DOT study, we refined a functional assessment framework for wetlands using carefully chosen parameters as "key indicators" of ecosystem level functions. For wetland systems we have grouped these functions into five categories including hydrologic flux and storage, biological productivity, biogeochemical cycling and storage, decomposition, and community/wildlife habitat. In our studies these key indicators were measured simultaneously in the impact wetland and several reference wetlands.

In the first phase of our study, we assessed the impacts of highway operation upon two Cypress/hardwood swamps located in the coastal plain region of North Carolina. Alterations of hydrology in these wetlands have resulted in reductions in woody plant cover and in changes in the aquatic invertebrate community. These changes in hydrology are largely related to the elevation of drainage culverts that pass through highway fill. The culvert bottoms are positioned at higher elevations than the sediment surface in the surrounding wetlands. As a result, ponding occurs upstream of the highway during periods of low flow and this has resulted in a shift from a forested wetland community to an open water or emergent plant community. Simple changes in highway design such as the number and placement of culverts could reduce the impact of highways upon similar wetland systems.

In our second phase we are assessed the impact of highway construction on brackish wetlands located adjacent to the New River Estuary near Jacksonville, NC. The assessment framework developed in the previous phase was being refined and modified for brackish wetlands. We collected baseline data for a full field season prior to the beginning of highway construction in both an impact wetland and two reference wetlands. We monitored these wetlands through the construction phase and through any recovery phase.

Our results clearly demonstrate that biological indicators like macrophytes, macroinvertebrates, and fish communities should be an integral component of a highway impact assessment program. Biota

are excellent integrators of a variety of potential stressors imposed upon wetland systems by highway construction. Results from this study and our previous study have shown that wetland biota are sensitive to disturbances associated with construction and operation of highways and are better indicators of environmental impacts than conventional water chemistry or habitat surveys (*e.g.*, HGM). Although most attributes of biotic assemblages are not direct measures of wetland ecosystem processes *per se*, changes in biotic assemblages in response to human activities are indicative of both structural and functional changes in a wetland, and thus are linked to wetland ecosystem processes (Richardson 1994). Moreover, §101(a) of the Clean Water Act mandates the restoration and maintenance of biological integrity of the USA's streams, lakes, and wetlands, an unduly neglected aspect of wetland assessment. Thus, biotic attributes are indeed functional indicators, and should be included in a functional assessment system for wetlands. Importantly, our BACI approach allowed for a clear test of the effects of the highway construction on biotic response and we were also able to eliminate the affect of environmental variation by the use of reference systems as well as before and after data collection comparisons.

One potential criticism of bioassessment is that it is laborious relative to rapid procedures like HGM. While our assessments were relatively intensive, use of the USEPA's Rapid Bioassessment Protocol for macroinvertebrates produced results that were equally, if not more informative than the laborious quantitative coring technique used to sample benthic macroinvertebrates. It is our recommendation that this rapid assessment procedure be considered over more quantitative sampling approaches, possibly using a composite sample from all available habitats as commonly done in many state biomonitoring programs (*e.g.*, FDEP 1996, Maxted *et al.* 2000). Since most of the useful information lies within species composition rather than in density estimates, rapid approaches like RBP are cost-effective techniques for generating species lists and semi-quantitative abundance estimates that serve well in assigning an impact rating to a site.

Highway construction in environmentally dynamic habitats like coastal wetlands may pose the most significant threat to biota through the loss of connectivity between areas upstream and downstream of highway crossings. While we do not have long-term post-construction data to evaluate recovery of the impacted site, short-term disturbance from construction caused significant alteration to species composition of both macroinvertebrates and fish as well as macrophytes and water chemistry. This is particularly important considering that water quality at all sites was considered poor prior to construction, as indicated by water-chemistry monitoring and the Estuarine Biotic Index. Thus, it should not be assumed that impaired sites like Edwards Creek are not susceptible to further impact, as our results have demonstrated that they can be. Our data suggest that the culverts installed in the extension pads and the temporary causeway were insufficient for allowing adequate flushing of tidal water upstream of the crossing. Our recommendation is that greater attention be directed toward minimizing the obstruction of tidal creeks (*i.e.* changes in salinity) during the construction phase, which may help reduce short-term impacts to the biota and associated ecosystem processes of coastal wetlands.

Finally, post-construction phase data are needed to assess long-term impacts at this highway construction site and future studies at this site should utilize the existing reference sites and BACI comparison approach.





"Digging a hole and putting cattails around it does not restore a wetland," said Duke University Wetland Center director Curtis Richardson. "Wetland restoration is one of the highest environmental priorities in the entire country right now, but no one knows exactly how to do it and there's lots of missing science."

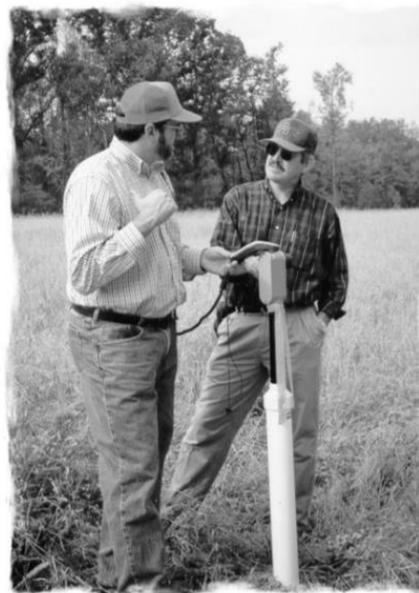
Richardson's center, based at Duke's Nicholas School of the Environment and Earth Sciences, aimed to address those pressing questions with a new \$551,000 federal grant. The goal was to identify scientific and socioeconomic factors that contribute to successful wetlands restoration in North Carolina.

Funded by the US Department of Agriculture, this Water and Water-sheds project worked in tandem the state North Carolina Wetlands Restoration Program developing remediation plans for 17 different river basins.

Duke's Wetland Center focused its ecological investigations on a Johnston County Community College pilot project to restore a drained wetland adjacent to Hannah Creek, near Smithfield, N.C., within the Neuse River Basin. It also did a larger study of farmer willingness to participate in such restorations in the Neuse as well as in other state watersheds.

The Neuse has been designated as nutrient sensitive, in part due to runoff from agricultural operations as well as from fertilized lawns in the upstream urbanized Raleigh, Durham, and Chapel Hill area, known regionally as the Triangle. Animal wastes and manufactured fertilizers both contribute excess amounts of nitrogen and phosphorus, which lower water quality and encourage explosive growths of algae.

Right. Mac Haupt, MEM '93, Environmental Specialist for the North Carolina Department of Environment and Natural Resources' Wetlands Restoration Program, and DUWC Director Curtis J. Richardson upload water level data from an automated recording unit at the Johnston County community college restoration site.



Previous studies have shown that the presence of a wetland can dramatically improve water quality by filtering out nitrogen and phosphorus before those nutrients ever reach major rivers. Nevertheless, "In a given river it might not be easy to see the changes in water quality because those restoration sites are so scattered," said Neal Flanagan, a Duke Wetland Center research associate.

Using the Johnston County site as a test site, the Duke study will examine how the ecologies of entire watershed areas factor into the filtering effectiveness of individual wetlands. "Our ultimate objective is to help the state wetland restoration program design and place wetlands in a manner that optimizes improvements in water quality," Flanagan said.

"Generally state regulators and people who are involved in water quality issues are more interested in the watershed scale trends," Flanagan added. "For instance, how do land use practices on a watershed scale affect water quality?"

In the second thrust of the Duke project, Nicholas School professor of environmental economics Randall Kramer interviewed about 500 farmers in a number of different watersheds to assess their attitudes towards wetland restoration.

"The state offers payments to farmers who agree to restore their wetlands by taking them out of agricultural production," said Kramer, who has previously done similar conservation analyses at sites as far away as Indonesia. "Because this wetlands restoration program is voluntary, you somehow have to entice the farmers to enter into the program."

From data collected in the farmer surveys, Kramer and associate-in-research Jon Eisen-Hecht planned to "develop a statistical model to predict farmer enrollment under different payment levels," he added. That economic model was then combined with information from the ecological and water quality studies to help guide restoration planners.

"We really worked to make this an integrated research approach," Kramer said. "There's a distinct ecological component to the study, and a distinct economic component. But then we propose to bring those together."

Flanagan, Kramer, and Richardson are all principal investigators for the project.

Kramer, R.A., J. Huber, and J.I. Eisen-Hecht. 2005. *Toward an Improved Understanding of Wetland Restoration Choice Behavior of Landowners: A Hierarchical Bayes Approach*, Final report submitted to the US Department of Agriculture, National Research Initiative, CSRES.



SUMMARY AND CONCLUSIONS

A two year study of sediment cores collected from the Pamlico and Neuse River estuaries has been completed. The purpose of this paleoecological study was to begin to re-create the history of water quality in these estuaries by dating sediment core samples and analyzing indicators of water quality, nutrient and trace metal flux, and diatom assemblages through time. We also analyzed the stratigraphic record of pollen found in the sediments for dating purposes. The results indicate that this type of study is not only feasible in these estuarine systems but also very useful. Sediment chronologies have been developed for the sediment cores collected, and the resolution of each 2-cm increment of each core varies from less than 1 year in recent sediments to 36 years in older sediments. Average sedimentation rate in the past 50 years is 0.65 cm yr⁻¹. Sedimentation rates have generally increased three to 10-fold in the past 50 years over previous sedimentation rates based on the data and the models used.

Results show that nutrient, metal and sulfur flux to the sediments has increased over the past 50 years. Trace element analyses show that surface sediments often contain heavy metal concentrations that exceed "Threshold Effects Levels" (TEL) as reported by the U. S. Environmental Protection Agency. Cadmium shows highest levels in the Pamlico estuary at the core collection site nearest the phosphate mining operations. Most other metals show higher concentrations in the Neuse River estuary.

Diatom valves and pollen grains are well preserved in the sediments of the Neuse and Pamlico. For example, samples analyzed to date from the Pamlico River estuary contain diatom valves in abundances of about 1 to 5 million valves per cubic cm of wet sediment, and pollen grains are present in abundances of about 50,000 to 500,000 per cubic cm of wet sediment. Over 430 diatom species have been identified from subsampled intervals of the Pamlico and Neuse sediment cores to date.

Diatom and pollen assemblages have changed through time. The most dramatic assemblage changes in the diatoms appear to have occurred in the past 30-50 years in the Pamlico and Neuse estuaries, possibly associated with industrial activity, increasing population, and land-use changes. Recent assemblages are composed of higher abundances of small planktonic taxa that are often found in large blooms in higher nutrient waters. These samples exhibit relatively low species richness and diversity compared to older (pre-1950) samples. Older diatom assemblages are composed of more benthic and epiphytic taxa. Changes likely reflect eutrophication, increased turbidity and sedimentation, and increased freshwater flow to the estuaries, as well as an increase in industrial activities. They may also reflect declines in submerged aquatic vegetation in these estuaries. Overall trends are similar to those found in the Chesapeake Bay, although the time frame of major changes is different. Similar changes began to occur much earlier in the Chesapeake. Pollen assemblage changes include an increase in ragweed pollen over the past several hundred years signifying increased land disturbance by humans. Pollen count results also show an increase in nut tree pollen (walnut and pecan) over the last several hundred years and an increase in sweetgum tree pollen in the past 50 years.

The biogenic silica (BSi) results and the determination of diatom valve flux to the sediments both show that more diatom frustules are being deposited to the sediments in recent years. BSi is primarily a measure of diatom frustules, which are composed of biologically

deposited silica. These results indicate higher diatom production, most likely due to increased nutrient inputs to the estuaries. As production increases, dissolved silica in the waters may become limiting, especially if diatoms frustules are preserved in the sediments and not recycled. As silica becomes limiting in the water column, diatoms may be out-competed by other algal species, including dinoflagellates. Diatoms are generally better food sources in the estuarine food web than other algal species, so this change could potentially cause problems in higher trophic levels.

Understanding the historical processes of water quality problems is important for managing the continuing impacts of growing populations in North Carolina. These data are useful for providing information on historical changes in estuarine water quality and realistic goals for management.

RECOMMENDATIONS

- Human impacts on estuarine water quality are evident, especially over the past 30-50 years, and should continue to be addressed.
- Sedimentation rates and nutrient and trace metal flux to both the Pamlico and Neuse estuaries appear to have increased in the past 30-50 years. Trace metal levels in surface sediments exceed “Threshold Effects Levels” as reported by EPA at several sites. Efforts should continue to be made to reduce sediment, nutrient and metal inputs to the estuaries.
- Industrial sources are apparently responsible for some of the increase in nutrient and trace metal accumulations in estuarine sediments. This influence appears to be substantial, and should continue to be monitored.
- Population trends and land clearance also appear to have influenced sedimentation and water quality in the estuaries and appear to be more significant for the Neuse. Careful planning and management of development should be a priority for local and state government.
- Preliminary results indicate that hypoxic and anoxic bottom waters can most likely be reduced in the Pamlico with proper management of nutrients and sedimentation.
- Diatom assemblages have changed significantly in the past 10-50 years. These changes may be related to eutrophication, increased turbidity, loss of submerged aquatic vegetation, and increased freshwater flow to the estuaries. Continued monitoring of water quality and algal species would increase our understanding of linkages and aid in management.
- The time frame of water quality changes seen in the Pamlico and Neuse estuaries occurs more recently than similar changes in the Chesapeake Bay. These differences may be due to several factors, including slower population growth, different land use near the estuaries, and the geomorphology of the estuaries. This may indicate that proper management could reverse trends in water quality changes more quickly for these estuaries than for the Chesapeake Bay.

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