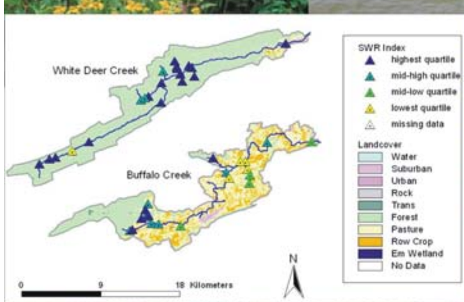
INTEGRATION OF ECOLOGICAL AND SOCIOECONOMIC INDICATORS FOR ESTUARIES AND WATERSHEDS OF THE ATLANTIC SLOPE







18 FEBRUARY 2006

ATLANTIC SLOPE CONSORTIUM

FOREWORD

The Atlantic Slope Consortium (ASC) was conceived to bring together a multidisciplinary team of natural scientists, social scientists, and managers to explore innovative and practical ways to assess and improve the condition of aquatic resources along the Atlantic Slope. Toward that end, we brought together nearly 40 investigators from six institutions:

Pennsylvania State University
Virginia Institute of Marine Science
Smithsonian Environmental Research Center
East Carolina University
Environmental Law Institute
FTN Associates, Ltd.

To accomplish our goals, we convened a dozen intensive “all-hands” meetings in different ecoregions across the Atlantic Slope. Many other meetings involving subsets of our team were held as were numerous conference calls and email communications. Members of the ASC participated in a wide array of conferences, workshops, and outreach activities reporting on the progress of our collective work over the 5-year project period. We joined similar groups funded through U.S. EPA’s STAR Program – the EaGLes – Estuarine and Great Lakes Environmental Indicators Program, to collaborate on complementary projects and to compare notes on administering large, multi-institutional research projects.

Throughout this venture, the levels of creativity, diligence, and camaraderie displayed were truly astounding. The many participants of the ASC’s first project, from research scientists to academic faculty and graduate students, from agency scientists and managers to technicians and clerical staff, should acknowledge to themselves that they have created a body of work that will influence the way environmental resources are assessed, managed, and conserved for decades to come. We give special thought to a colleague who we regret is no longer with us, Charles Taillie. As the ASC’s Director, it has been both a privilege and a pleasure to guide this project to its conclusion. My sincere appreciation goes out to each and every one who contributed to our collective success.

Although there are many individuals from the member institutions and from amongst our collaborating organizations to thank, two colleagues stand out and should be named to acknowledge their essential contributions. First, this project would not have been initiated without the foresight and persuasion of Tom DeMoss of U.S. EPA Region 3 and the MAIA team. He had the vision and provided the encouragement to propel us forward and keep us relevant which has been, and is, a continuing MAIA theme. He, and MAIA Team members, provided us with mid-course corrections when we might have veered from the logical path to completion. Lastly, our Project Officer from USEPA, Barbara Levinson, deserves our deepest gratitude for adeptly keeping us within the administrative and fiscal boundaries while always encouraging us to do our most capable work. I know the ASC Team and the other EaGLe

Directors will join me in thanking Barbara for her guidance, insight, and humor. It was a wonderful journey made much better by her enthusiastic participation in all phases of the project.

This research has been supported by a grant from the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) Estuarine and Great Lakes (EaGLe) program through funding to the Atlantic Slope Consortium, U.S. EPA agreement R-82868401. Although the research described in this report has been funded wholly or in part by the United States Environmental Protection Agency, it has not been subjected to the Agency's required peer and policy review and, therefore, does not reflect the view of the Agency and no official endorsement should be inferred.

Robert P. Brooks, Director, Atlantic Slope Consortium
February 2006

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MESSAGE 2

The Estuarine Segment Approach

Numerous studies have demonstrated that human activities on land can have negative impacts on estuarine ecosystems (Nixon 1995; National Research Council 2000; Bosch et al. 2001, 2003). Few studies, however, have quantified the direct linkages between particular land-use patterns and estuarine responses. One reason that it has been difficult to quantify linkages between specific land use patterns and estuarine responses is that most monitoring studies have focused on large open water systems (e.g., the mainstream of Chesapeake Bay or the large rivers that flow into it). Large-scale monitoring studies of this type are useful in tracking temporal changes for indicators of estuarine health. The Chesapeake Bay Program, for example, has developed a diverse array of indicators for monitoring the Bay (http://www.chesapeakebay.net/indicat.htm). The Chesapeake Bay Foundation uses a wide range of indicators to produce an annual scorecard of the health of Chesapeake Bay (http://www.cbf.org/site/PageServer?pagename =sotb_2004_index).

Monitoring programs and large-scale models such as those developed by the Chesapeake Bay Program (http://www.chesapeakebay.net/pubs/iannewsletter11.pdf) have been used to develop management plans, but they have limited use in guiding small scale land-use decisions because they do not have the sensitivity to quantify the relationships between specific land-use patterns and estuarine indicators at a scale that is appropriate for making management decisions.

The objective of this part of the ASC project was to identify linkages between patterns of land-use and environmental indicators in shallow estuarine habitats. To accomplish this objective we used existing data and also sampled estuarine segments of Chesapeake Bay that were linked to a watershed that was large enough to support at least one perennial stream but small enough for field teams to sample the several habitats within the subestuary in a reasonable period of time (i.e., one or two days).

Estuarine Segment Selection and Characterization

Smithsonian Environmental Research Center (SERC) and Virginia Institute of Marine Science (VIMS) scientists selected estuarine segments based primarily on land-use patterns. But they differed in the selection criteria.

SERC Estuarine Segments - SERC scientists selected estuarine segments independent of watershed size, except for the criteria (described in more detail below) that the watershed was large enough to support at least one perennial stream that flowed into the estuarine portion of the segment. They initially screened more than 75 potential estuarine segments based on salinity regime. An initial goal was to minimize the complicating effects of salinity on estuarine biota by selecting estuarine segments that were in the mesohaline portion (i.e., intermediate salinity - between freshwater and seawater) of Chesapeake Bay. To be included as an estuarine segment, the watershed portion had to: (1) be dominated by one of the land-use types described in Table 3; (2) discharge directly into Chesapeake Bay or into the mesohaline portion of one of the large river systems; and (3) be large enough to have at least one perennial stream that flowed into the subestuary. In addition to shallow subtidal habitats, each estuarine segment included a small (< 2 ha or 5 ac), medium (2–7 ha or 5-18 ac) and large (> 7 ha or 18 ac) brackish tidal wetland. The 32 estuarine segments that were chosen for study were distributed along a north-south axis of Chesapeake Bay (Figure 11) and, with the exceptions of portions of the Back River, Bird River, Gwynns Falls, Jones Falls, Bird River watersheds, were within the Coastal Plain province. Topography of the Coastal Plain varies from rolling hills on the western shore to flat terrain on the central and southern portions on the eastern shore. Land-use patterns on the watersheds of each segment were used as surrogates for human disturbance levels.

Table 3. Land-use categories used to characterize the watershed portions of estuarine segments.

Land Use Category	Criteria
Forested	Greater than 65% total forest covers (forest, mixed, forest wetland) and <10% urban
Agricultural	Greater than 50% total agricultural covers (pasture, crop)
Developed	Greater than 50% total urban covers (low and high residential and industrial areas)
Mixed Developed	20-50% total urban covers
Mixed Agricultural	20-50% total agricultural covers

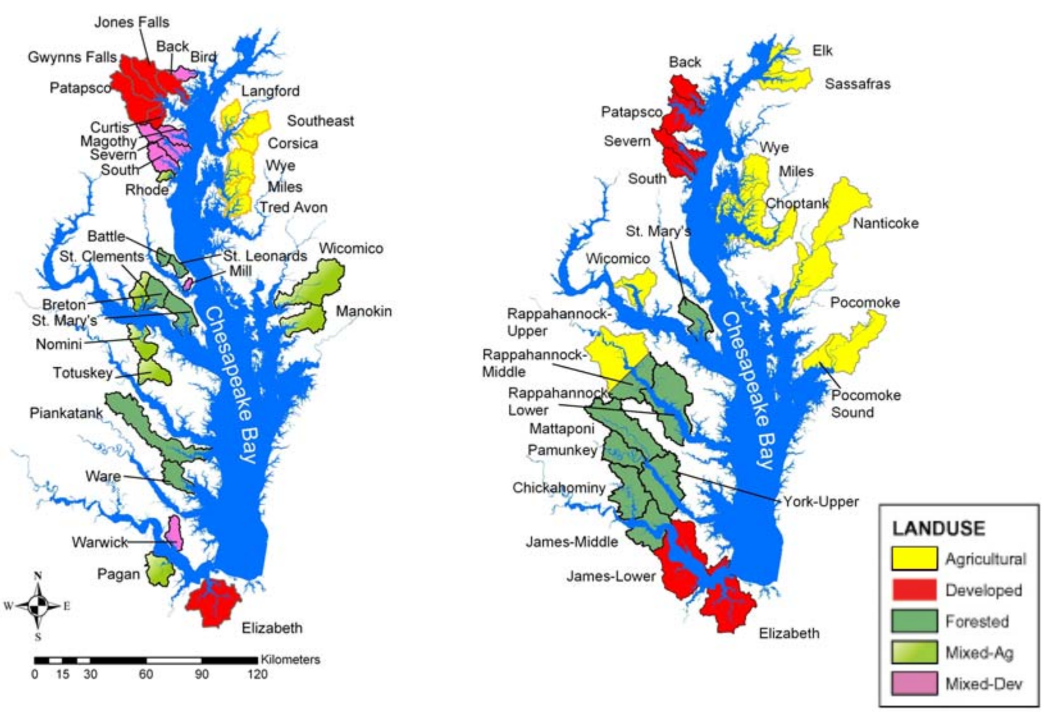

Figure 11. SERC (left) and VIMS (right) estuarine segments.

VIMS Estuarine Segments – VIMS scientists selected 23 estuarine segments in the oligo-to-mesohaline (i.e., low to intermediate salinity) portions of Chesapeake Bay based on: watershed land use classification, salinity regime, and accessibility. United States Geological Survey (USGS) designated 14-digit hydrologic unit codes (HUC) were used to select watershed sampling units and watershed land-use classification was based on principal land use percentages derived from the National Land Cover Database (NLCD, 30 m raster coverage). Because of the sizes of 14-digit HUCs, the number of available watersheds in each land use category was limited, the VIMS estuarine segments, therefore, only included three land-use categories: forested, agricultural (including the mixed-agriculture category in the SERC classification), and developed (including the mixed-developed category in the SERC classification) (See Table 3). Similar to SERC estuarine segments, the VIMS watersheds were distributed along a north-south axis of Chesapeake Bay (Figure 11) and, with the exceptions of portions of the Back, Patapsco, Severn, and Elk river watersheds, were within the Coastal Plain province.

General Description of Sampling Methods

Data collection in each subestuary was tailored to each project (projects described in more detail below) and the reader is referred to the published articles for details.

In general, water quality parameters (e.g., temperature, salinity, dissolved oxygen, pH) were measured in the field at several sites in each subestuary. Field collected water samples were returned to the laboratory for further analyses (e.g., total suspended solids, nitrate-nitrogen (NO_3-N), total nitrogen (Total N) and total phosphorus (Total P)).

Subtidal habitats were sampled in several projects. Benthic samples were collected using coring devices (e.g., Ekman Grab) and habitat assessments (e.g., amount of woody debris, presence of submersed aquatic vegetation, characteristics of adjacent shoreline) were conducted. Fish and crabs were sampled using Fyke nets and nearshore seining and samples of White Perch (*Morone americana*) were retained and analyzed for PCB concentration.

Foraging waterbirds and birds that nested in brackish wetlands were sampled in the field as was wetland vegetation. Samples of Common Reed (*Phragmites australis*), an invasive wetland plant species, were collected in the field and analyzed in the laboratory for nitrogen content.

Results

Table 4 provides a summary of the estuarine indicators that could be related to land-use patterns. In some instances, the indicators responded to land-use patterns only at the watershed scale. In other instances, the indicators responded to land-use patterns at the scale of the entire watershed and at the local scale, especially conditions close to the subestuary. One indicator (wetland breeding birds) only responded to local land-use patterns. In two instances (PCBs in White Perch and abundance of Common Reed), we were able to determine that indicators responded to conditions at the watershed scale, but more strongly to the relationship between land-use conditions and proximity to the estuary.

In the next section we report results for selected indicators. Detailed information on these indicators can be found in journal publications on these indicators. The publications are cited in the Reference chapter.

Table 4. Estuarine indicators identified for estuarine segments of Chesapeake Bay.

Indicator	*Watershed*	*Local Land Use*
Macrobenthos Indices	X	X
Fish Community Index	X	X
Abundance and leaf nitrogen content of Common Reed (*Phragmites australis*)	X	X
Blue crab and bivalve abundance	X	X
PCBs in White Perch (*Morone Americana*)	X	
Waterbird Community Integrity	X	X
Marsh Bird Community Integrity		X
SAV Abundance	X	

BLUE CRAB AND BIVALVE ABUNDANCE

Background

The goal of this project was to explore relationships between regional (e.g., salinity), watershed (e.g., land use), and local (e.g., land use, water quality, habitat) factors on the abundance of blue crabs and species of *Macoma*, common clams that are blue crab prey.

A number of socioeconomic and ecological attributes make blue crabs (*Callinectes sapidus*) potentially ideal indicators of environmental conditions in estuarine ecosystems. Blue crabs are distributed throughout Chesapeake Bay and other estuaries of the East and Gulf coasts of North America and disperse across a wide range of salinities following settlement in the relatively high salinity zone. Blue crabs are also highly prized by humans for food and are the most important commercial fishery in the Mid-Atlantic region. As the dominant benthic predator and as prey for some larger predators, they also play a critical role in energy transfer in estuaries. Blue crabs feed intensively on bottom organisms living in the sediment, particularly clams, suggesting that the spatial distribution of blue crabs might be tied to natural and anthropogenic factors that affect the distribution and abundance of bivalve prey. In addition, blue crabs may be sensitive to anthropogenic shoreline modifications because natural nearshore habitats such as woody debris and marsh creeks are important for both juveniles and molting crabs as refugia from predation. Finally, blue crabs are sensitive to hypoxia (low dissolved oxygen concentrations), thus, their distribution may be directly influenced by cultural eutrophication commonly associated with developed and agricultural land use in watersheds.

Findings

Classification And Regression Tree (CART) analysis, a type of statistical analysis, indicated that 46% of the variance in blue crab abundance was explained by salinity (9%), watershed land use (17%) and shoreline marsh habitat (19%) (Figure 12). Crab abundance was greatest at intermediate and higher salinities (>16 ppt), but in lower salinities crabs were most abundant along wetland shorelines in forested and mixed land use watersheds. Juvenile crabs <85 mm (~3 in) were more strongly associated with wetland shorelines, particularly in estuarine segments with forested and mixed land use watersheds.

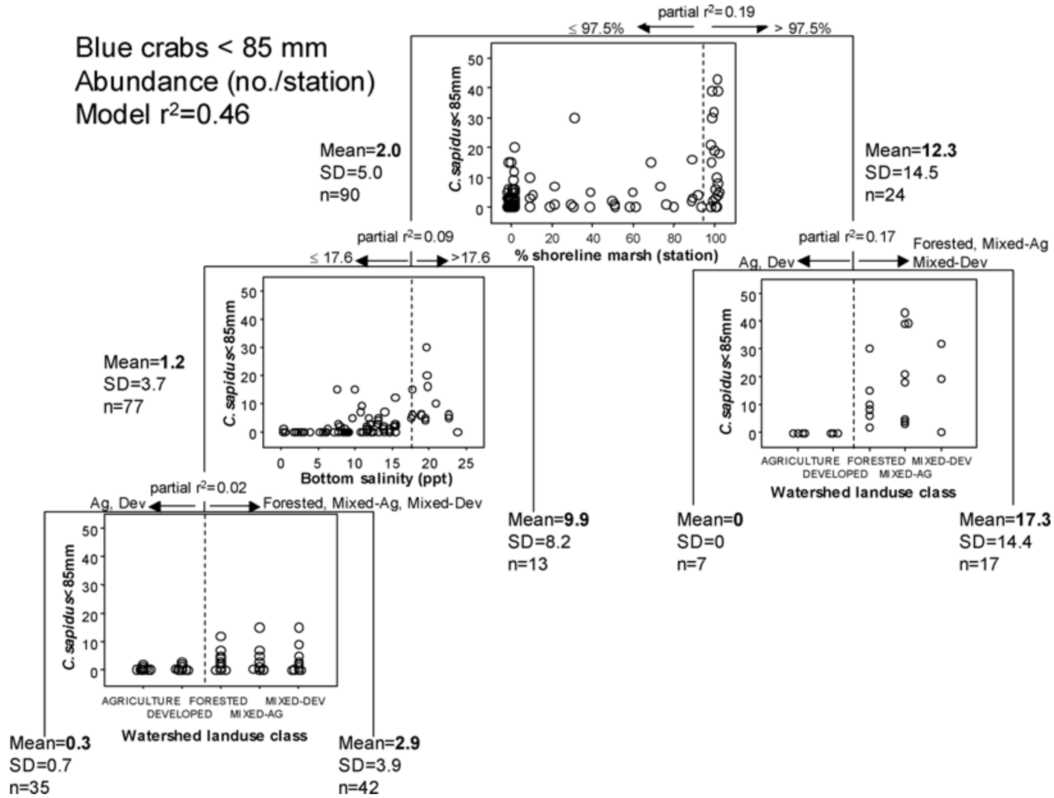

Figure 12. Results from CART analysis of juvenile blue crabs < 85 mm (no. station^{-1}). Scatter plots illustrate the response of juvenile blue crab abundance at each level of the tree. The vertical line in each plot identifies the value of the predictor (x) that best explained variation in juvenile blue crabs. Values of predictors are shown to the left and right of each split above each scatter plot. Variance explained (r^2) for each predictor is shown above each split. Means, standard deviations (SD), and number of stations (n) summarize properties of the data to the left and right of splits in each scatter plot.

Clams (*Macoma*) were similarly associated with wetland shorelines, but mainly in muddy bottoms at moderate-to-high salinities; however, the best CART model only explained 25% of variance in bivalve abundance. These results were consistent with predictions that shoreline wetlands and watershed land use may have important effects on these taxa along the estuarine salinity gradient, and are consistent with hypotheses based on previous descriptive and experimental research linking blue crabs and deposit-feeding clams to habitats rich in particles of plant leaf pods, broken stems, and other organic matter worked in from the watershed. These findings are described in detail in King et al. (2005).

Implications

Within habitat characteristics (salinity, shoreline condition, substrate type, abundance of wetlands) are important factors influencing the abundance of blue crabs and clams. Land-use at the scale of the entire watershed is also important and the lowest abundances of both organisms occur in estuarine segments that are downstream of watersheds dominated by development and agriculture. Land-use, therefore, can be used as an indicator of estuarine conditions but the target organisms (blue crabs and clams) could also be monitored to track conditions within subestuarine habitats. The application of blue crabs and clams within the framework of ASC indicators can be found in Appendix A.

ABUNDANCE AND LEAF NITROGEN CONTENT OF COMMON REED (*Phragmites australis*)

Background

We hypothesized that the distribution and abundance of *Phragmites* may be linked to land use through pathways at both local scales (e.g., disturbance, nitrogen enrichment, and salinity reductions caused by adjacent land use) and watershed scales (e.g., enhanced nitrogen availability in surface water linked to agricultural and developed land uses in adjacent watersheds). To test this hypothesis, we examined the relationship between *Phragmites* distribution and abundance data collected from 90 tidal wetlands located within 30 estuarine segments spanning over 250 km of Chesapeake Bay to digital land-cover data summarized at both local and watershed scales. We also explored the potential linkage between land use and increased nitrogen availability at the watershed scale and *Phragmites* leaf-tissue nitrogen, an indicator of enrichment (Bertness et al. 2002).

Phragmites australis is an invasive species in North America, particularly in the Mid-Atlantic region (Chambers et al. 1999, Sillman and Bertness 2003) and an introduced species appears to be responsible for the recent spread (Saltonstall 2002). *Phragmites* impacts on wetlands ecosystems are considered to be negative so control or eradication management practices are often used (e.g., Philipp and Field 2005 and references therein). What factors are responsible for *Phragmites* invasion and spread? Development of nearshore areas and within-wetland disturbances and increased nitrogen are associated with an increased abundance, cover and spread of *Phragmites* in New England tidal wetlands (Minchinton and Bertness 2003, Sillman and Bertness 2003). Tidal wetlands of Chesapeake Bay have also seen marked increases in the occurrence and abundance of *Phragmites* (reviewed by Rice et al. 2000). However, less is known about the process of invasion and spread in Chesapeake Bay compared to the more comprehensively studied New England salt marshes.

The Chesapeake Bay watershed is rapidly urbanizing and is the fastest growing and culturally enriched coastal region in North America (e.g., Culliton et al. 1990, Boesch and Greer 2003). Cultural eutrophication has been related to point and non-point source nitrogen inputs from agricultural and urban (developed) lands (e.g., Jordan et al. 1997a, Boesch and Greer 2003, Jordan et al. 2003a). Thus, given the mechanistic relationships reported elsewhere, the increase in anthropogenic nitrogen and shoreline disturbances caused by agricultural and developed land uses may be at least partially responsible for the expansion of

Phragmites in Chesapeake Bay. However, no previous study has empirically examined such relationships in this estuarine ecosystem and no study in any region has examined linkages between land use and *Phragmites* among many wetlands spanning a geographical extent as great as that of Chesapeake Bay.

Findings

For wetlands that had *Phragmites*, abundance was best explained by the following factors, in order of importance, by percent inverse distance weighted (% IDW) development (see Sidebar), % IDW forested land, and northing or longitude (Figure 13). If % IDW development was >15%, *Phragmites* abundance increased dramatically (Figure 13 – top diagram). When % IDW development was ≤15%, wetlands in estuarine segments with ≤34% IDW forested land tended to have higher *Phragmites* abundance (Figure 13 – bottom left diagram). Wetlands in the middle and northern regions of Chesapeake Bay also had more *Phragmites* (Figure 13 – bottom right diagram).

Examination of data for all 90 sites showed that *Phragmites* was almost always present when the watershed associated with the subestuary had <39% forested land cover. When watershed forest cover was >39%, abundance was higher in estuarine segments that had higher percentages of development near the subestuary.

Nitrogen concentration in leaves was also highest when % IDW developed land exceeded 14% (Figure 14). In 2002, a drought year with lower runoff into the estuaries, %N in estuarine segments with agricultural watersheds (Figure 14 - bold bubbles in left diagram) were not consistently higher compared to forested systems and were much lower compared to developed watersheds. In 2003, a wet year with higher runoff from agricultural fields, we found the same relationship between % IDW and %N but leaf nitrogen concentration tended to be higher at sites with agricultural watersheds (i.e., higher values for bold bubbles in right diagram in Figure 14 compared to same in left diagram). Additional information will be available in King et al. (in prep.).

Inverse Distance Weighting

Activities on land closest to water bodies generally have the greatest effects on the quality or condition of a water body and its biological organisms. If the runoff from two parking lots is identical, and one of these parking lots is 1 yd from the receiving water body, while the other is 1,000 yds from the same water body, the pollutants from the parking lot only 1 yd from the water body would affect the water body more than pollutants from the parking lot 1,000 yds away. If distance from a stream, wetland, or estuary was used to weight the importance of the land use, the parking lot 1,000 yds away would be weighted higher than the lot 1 yd away, but this is the opposite of which parking lot's pollutant runoff is more important. Therefore, the inverse of this distance is used for weighting, so the land use closest to the water body is weighted as being more important to the quality or condition of the aquatic ecosystem.

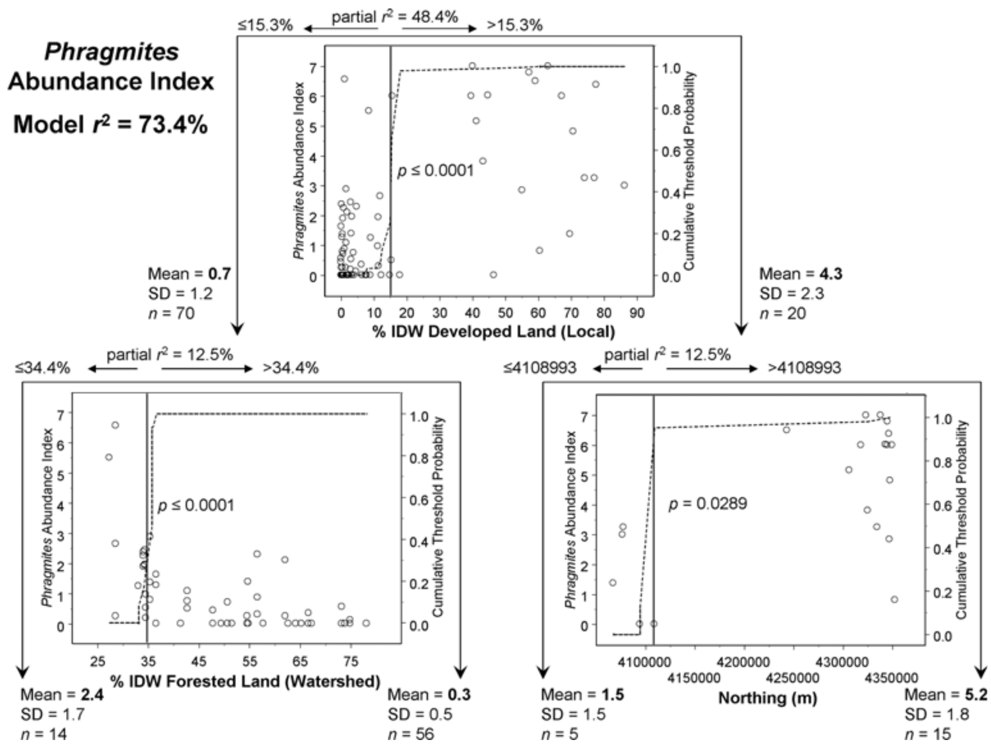

Figure 13. Results from CART analysis of *Phragmites* abundance. Scatter plots illustrate the abundance of *Phragmites* at each level of the tree. The vertical line in each plot identifies the value of the predictor (x) that best explained variation in *Phragmites* abundance. Values of predictors are shown to the left and right of each split above each scatter plot. Variance explained (r^2) for each predictor is shown above each split. Means, standard deviations (SD), and number of stations (n) summarize properties of the data to the left and right of splits in each scatter plot.

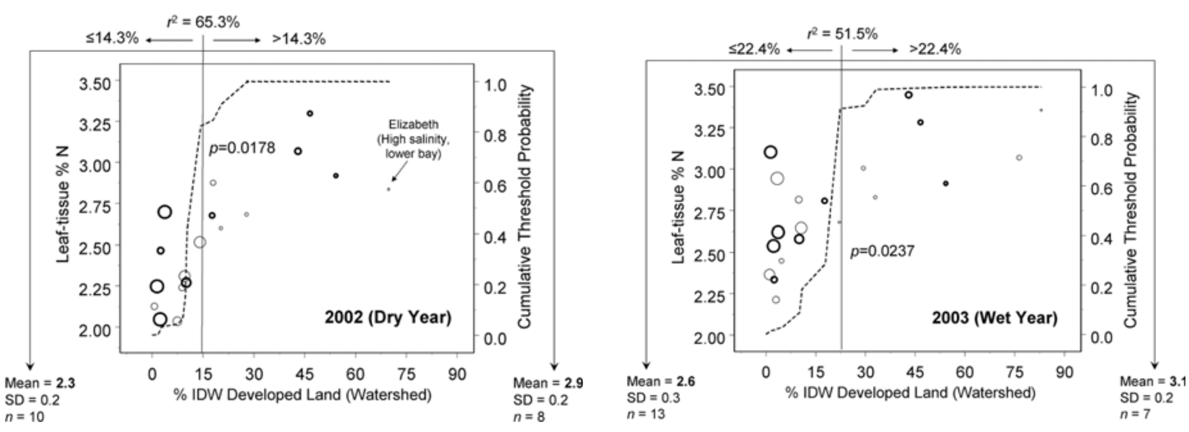

Figure 14. Scatter plots of the relationship between nitrogen in *Phragmites* leaves and the inverse-distance weighted (IDW) percentage of the watershed area that is developed. The left diagram is for 2002 the driest year on record in the region and the right diagram is for 2003, the wettest year in the region. Bold circles are estuarine segments sampled in both years. The size of the circles indicates the relative amount of IDW agircultural land in the watershed. The vertical line in each plot identifies the value of the predictor (x) that best explained N in leaves of *Phragmites*. Values of predictors are shown to the left and right of each split above each scatter plot. Variance explained (r^2) for each predictor is shown above each split. Means, standard deviations (SD), and number of stations (n) summarize properties of the data to the left and right of splits in each scatter plot.

Implications

Land-use, especially the amount of development at the watershed and local scale, are important factors contributing to the abundance of *Phragmites* and the nitrogen content of leaves. Land-use, therefore, can be used as an indicator of estuarine conditions but the target species (*Phragmites*) could also be monitored to track conditions within subestuarine habitats.

MACROBENTHOS INDICES

Background

Our objective was to examine the influence of shoreline alteration and watershed land use on nearshore macrobenthic (organisms, visible without magnification, living on or in the sediment) communities using established indices for related estuarine environments.

Human modification within watersheds arguably has the strongest impact on aquatic condition at the land-water interface. Biotic multimetric indices have been used extensively as measures of condition in a variety of systems, most recently estuaries. The characterization of ecosystem condition using integrative indices was initially developed for, and applied in, freshwater systems. Multimetric biological indices such as benthic indices of integrity, however, have shown promise as methods for assessing condition in estuaries due to their predictable and integrative response to stressors.

Benthic macroinvertebrates have a long history as indicator organisms due to the ease of collection, their immediate and measurable response to impairment, and the fact that they are mostly sedentary, consequently reflecting local conditions. Macrobenthic community indices have been successfully applied in estuarine systems and may be useful as condition or diagnostic indicators in the critical nearshore ecosystem.

Shallow-water tidal habitats provide essential nursery and spawning areas, protection from predators, and foraging opportunities for numerous fish, shellfish and crustacean species. This critical resource area is under intense and increasing pressure from a variety of uses and users and the impact of shoreline and watershed land use on nearshore biotic communities is a fundamental ecosystem management question. Evaluation of the ability of macrobenthic community indices to characterize the influence of shoreline alteration and watershed land use in nearshore estuarine environments could lead to the development of viable management tools.

Findings

Biotic responses were correlated with habitat condition along the shoreline and in the watershed, with the highest scores (i.e., best condition) associated with forested watersheds. Nonparametric changepoint (statistical) analyses indicated that ecological thresholds existed in response to developed land use at the site and watershed scale. There was a significant reduction in Benthic Biotic Index scores at the site and watershed levels when the amount of developed shoreline exceeded 10% and developed watershed exceeded 12%, respectively (Figure 15, left diagram).

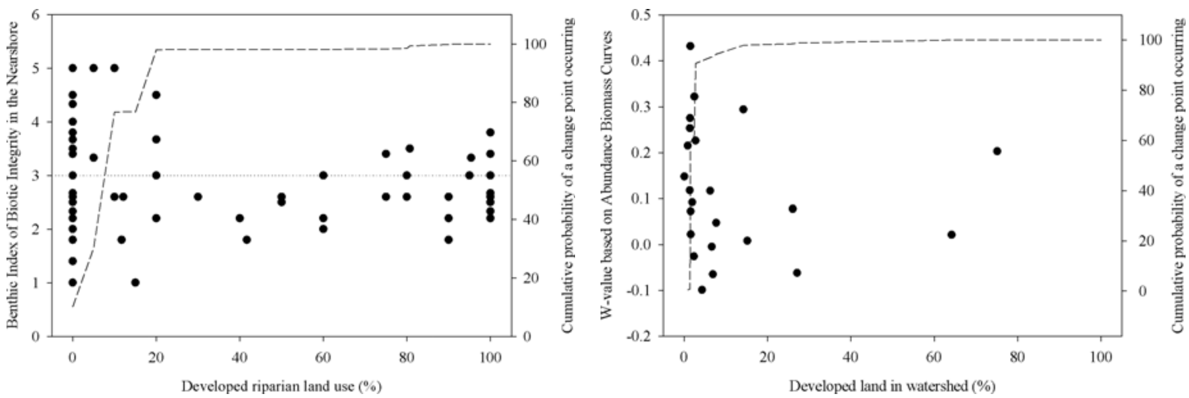

Figure 15. Results of non-parametric changepoint analyses for a) percent development of the shoreline (150 m of water's edge) of study sites and the benthic index of biotic integrity in the nearshore (B-IBI$_N$) (left diagram); and b) percent development within the watershed and W-value (right diagram). The W-value, a statistical measure of abundance biomass curves, interprets high values as indicative of a less-disturbed or reference system. The B-IBI$_N$ is scaled from one to five, with scores less than three indicative of stressed conditions (dashed horizontal line). The cumulative probability curve represents the cumulative probability that a changepoint occurred at various levels of development. Significant macrobenthic community responses ($p = 0.05$) were measured with the B-IBI$_N$ and W-value when developed lands were 10 and 12%, respectively. There was a 95% cumulative probability of an ecological threshold occurring at 20 and 14% developed lands for the BIBI$_N$ and W-value, respectively.

The addition of shoreline land use information enhanced the discriminatory ability of the indices in a given landscape. In particular, the site scale Benthic Biotic Index shows promise for elucidating gradients of condition within landscapes with varying degrees of shoreline alterations. Since shoreline forests and wetlands may diminish the effects of urban land use in localized areas, the inclusion of detailed site-specific information may be indispensable for defining condition. Additional details can be found in Bilkovic et al. (in review).

Implications

Nearshore macrobenthic communities responded to land use conditions at local (site) and watershed scales. Index scores decreased with anthropogenic alterations to the landscape (e.g., developed watersheds), and thresholds were identified for shoreline and watershed developed land use (10% to 12%) beyond which a negative response in macrobenthic communities occurred. Watershed and shoreline land use may be effective integrative measures of stress that are able to infer the state of degradation in a system. The integration of shoreline and watershed land use measures with macrobenthos indices can lead to practical management tools with particular application on small watershed scales.

Ecosystem approaches to condition assessment should incorporate a variety of indicators that measure different scales or types of stressors. The measure of prey community (e.g. macrobenthic) responses to habitat condition adds a layer of information about the nearshore system that will aid managers in prioritizing and targeting sites or watersheds for restoration or protection.

FISH COMMUNITY INDEX (FCI)

Background

The goal of this subproject was to develop and test fish community metrics in the nearshore Chesapeake Bay and evaluate relationships among fish communities and habitat condition assessed at multiple spatial scales (subtidal habitat, shoreline condition and watershed land use).

Fish community characteristics have been used since the early 1900s to measure relative ecosystem health. Within the last 20 years, advances have stemmed from the development of integrative measures of ecological condition, such as the Index of Biotic Integrity (IBI), which relates fish communities to abiotic and biotic conditions of the ecosystem. Fish community IBIs were first developed for use in freshwater, Midwestern streams, and subsequently modified for application in Great Lakes bays, reservoirs, streams and large rivers throughout the United States and other countries. The common thread that connects the various IBIs is a multimetric approach, which describes biotic community structure and function and relates it to the ecosystem or habitat. The use of fish community-level response as an indicator affords many advantages: (1) high public interest; (2) multi-trophic response that integrates aquatic condition; (3) assessment of both habitat and biotic condition as well as cumulative effects; (4) assessment of large-scale regional effects due to their mobility; (5) ease of identification on-site; and (6) availability of long-term monitoring data.

Estuarine systems are arguably some of the most complex aquatic systems. Their natural variability compounds the problems of detecting anthropogenic impacts. Until now, use of fish community IBIs in estuarine systems has been limited, with varying degrees of success. With growing recognition that effective management of estuarine systems can only occur at ecosystem levels, the need for further development of these metrics is widely accepted.

Within estuaries, nearshore habitat provides essential nursery and spawning areas, protection from predators, and foraging opportunities for numerous fish species. This critical resource area is under intense and increasing pressure from a variety of uses and users and generally exists without an operative comprehensive management plan. For instance, the cumulative impact of shoreline armoring has been demonstrated to drastically reduce available shallow-water habitat structure and associated fish communities. Evaluation of nearshore habitat and shoreline condition in conjunction with descriptions of biological communities may establish links between landscape and the biota lending guidance to managers. This association may provide the basis for development of a diagnostic indicator of estuarine condition.

Findings

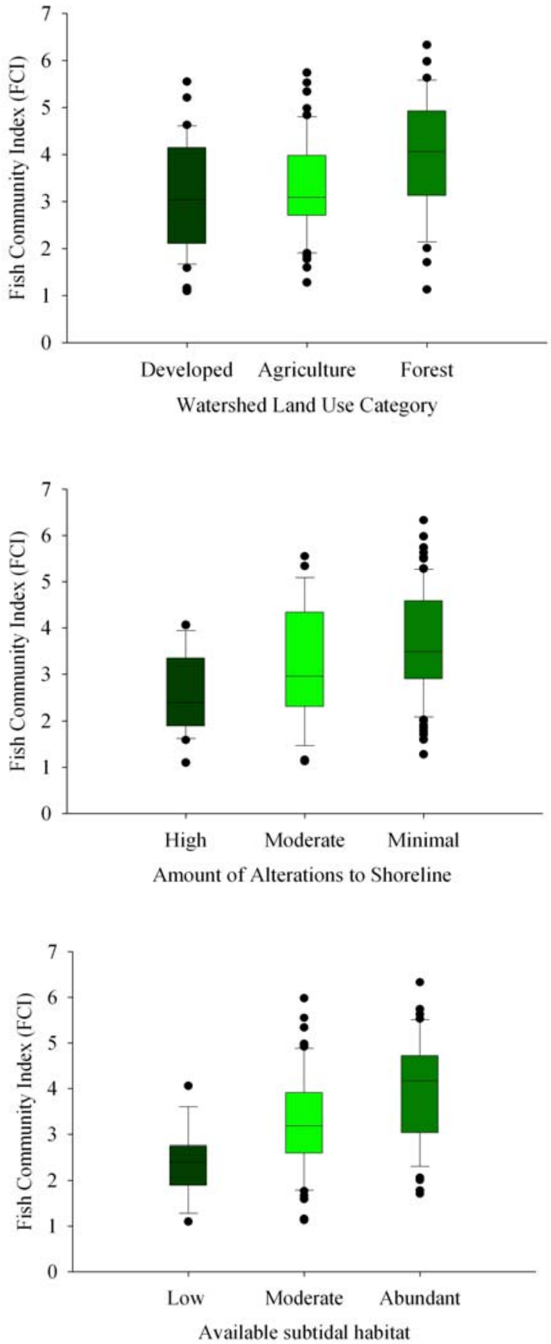

Figure 16. Fish Community Responses (FCI) in relation to habitat condition states assessed at various spatial scales: watershed land use (top), shoreline condition (middle), and subtidal habitat (bottom).

Biotic responses were correlated with habitat condition in the nearshore, shoreline and watershed. Fish Community Index (FCI) scores were significantly lower in developed and agriculture watersheds than in watersheds dominated by forests (Figure 16, top), and there were also negative impacts associated with local land use patterns and nearshore habitat conditions. The lowest average FCI scores were found in areas with highly altered shoreline conditions and minimal subtidal habitat (Figure 16, middle and bottom). This is intuitive, since the direct biotic response may be due to changes in nearshore habitat, with indirect impacts due to watershed land use. These results are supported by recent studies describing the relationship between shoreline alteration and nearshore/littoral habitat condition.

Links among habitat conditions were substantiated in the relationships between subtidal habitat and shoreline condition, as well as shoreline and adjacent watershed land use. Shoreline condition and subtidal habitat measures were significantly correlated indicating a negative association between shoreline alterations and

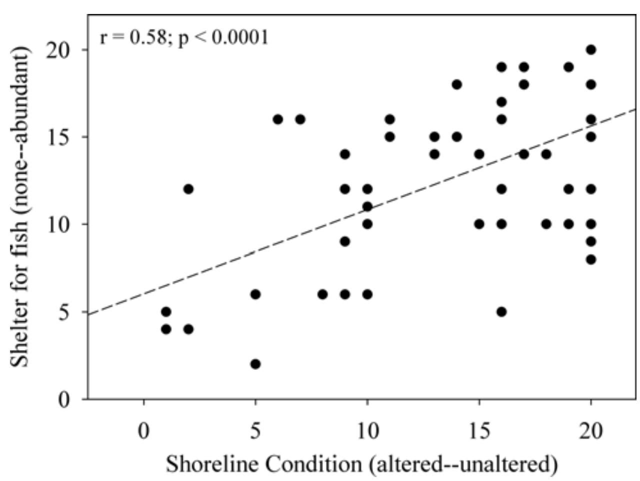

Figure 17. Comparison between available subtidal habitat (scaled from none to abundant habitat) and shoreline condition (scaled from highly altered to unaltered states) per site.

available subtidal structural habitat (Figure 17). Dominant watershed land use was reflected in shoreline land use conditions for all three of the categories (developed, agricultural, forested) (Figure 18). More detailed information can be found in Bilkovic et al. (2005).

Implications

Habitat conditions at multiple spatial scales (subtidal habitat, shoreline condition and watershed land use) are correlated with the Fish Community Index scores. These measures may be used as indicators of estuarine condition in addition to the biological functional response as reflected in the FCI. For instance, since correlations between habitat and biota were noted, if mechanistic processes can be determined and thresholds of response established, then shoreline condition surveys become an essential diagnostic management tool.

MARSH BIRD COMMUNITY INTEGRITY

Background

Our objective was to construct a community index based on marsh birds designed to estimate the integrity of the marsh bird community as well as to provide insight into the integrity of the entire marsh ecosystem. We used basic ecological principles to develop the index of marsh bird community integrity (IMBCI) and then subsequently tested the sensitivity of marsh bird community integrity to independently quantified land-use disturbances.

Birds are considered ideal for use in a community index because they are easy to survey and their life histories are relatively well

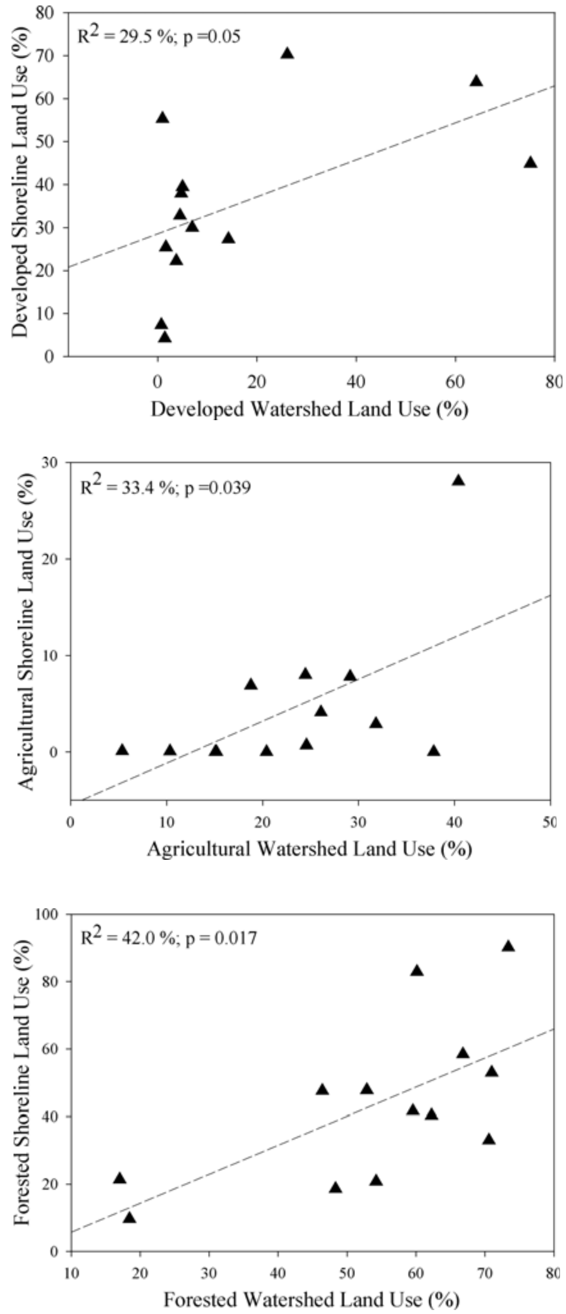

Figure 18. Comparison between percentages of each land use type in a watershed, and the corresponding riparian land use category: Developed (top), Agricultural (middle), or Forested (bottom). VIMS-Center for Coastal Resources Management (CCRM) Shoreline Condition Survey and NLCD land use data were extracted from a subset of thirteen watersheds in the Chesapeake Bay: Back, Battle, Breton Bay, Chickahominy, Elizabeth, Lower Rappahannock, Lower James, Pagan, Piankatank, Severn, St. Clements, St. Mary's, and Totuskey.

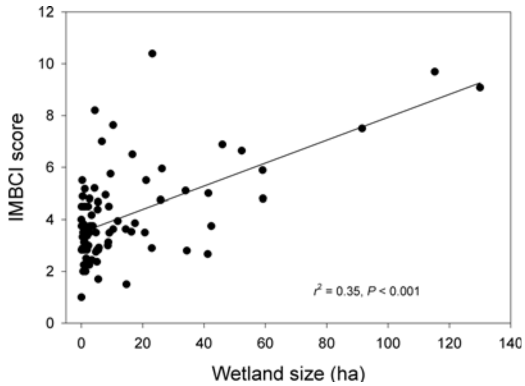

Figure 19. Results of a regression analysis showing the relationship between the index of marsh bird community integrity (IMBCI) and wetland size for 91 wetlands in the Chesapeake Bay, USA. IMBCI scores are calculated by scoring species attributes on a generalist to specialist gradient.

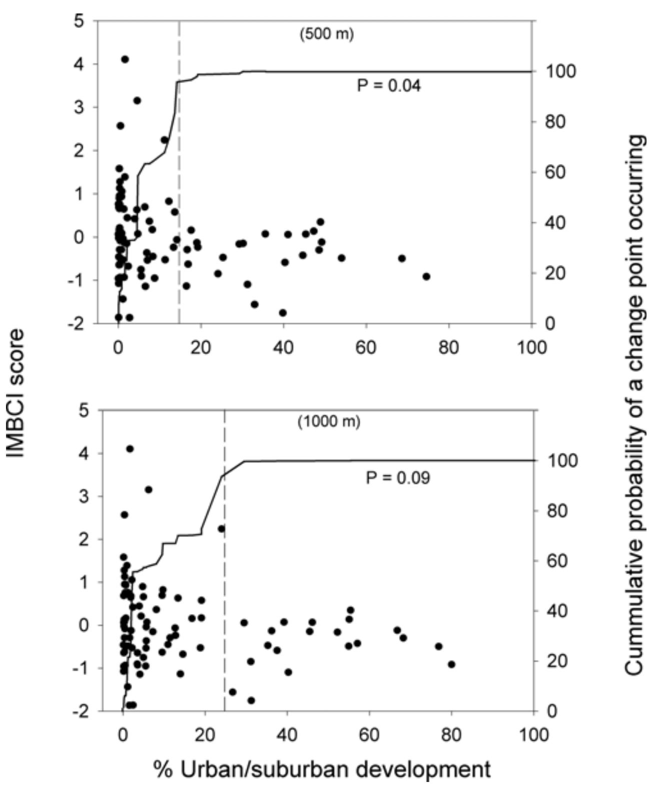

Figure 20. Results of non-parametric changepoint analyses for percent development within 500 m and 1000 m of wetland study sites and index of marsh bird community integrity (IMBCI) scores controlled for wetland size using standardized residuals from Figure 19. The cumulative probability curve represents the cumulative probability that a changepoint occurred at various levels of development. IMBCI scores are calculated by scoring species' attributes on a generalist to specialist gradient. Dashed lines indicate the percent of development within a wetland buffer required to produce a 95% cumulative probability of an ecological threshold occurring.

defined. Previous research has shown that birds are linked to the overall ecological integrity of their respective ecosystem. This is true primarily because birds are sensitive to habitat fragmentation, landscape composition, and changes in habitat structure. Birds may also be particularly good indicators because species at higher trophic levels can be sensitive to disturbances at lower levels. Therefore, it is unlikely that a marsh with low ecological integrity can support a high-integrity marsh bird community.

Findings

Wetland size had a significant influence on IMBCI scores (Figure 19). Changepoint (statistical) analysis revealed a changepoint or threshold occurred when >14% of the area within 500 m of the marsh was developed. IMBCI scores decreased significantly as the percent of developed area increased beyond 14%. In fact, there was 95% probability that IMBCI scores would decline when >14% of the area was developed and a 60% probability of a change occurring when as little as 6% of the land within 500 m of a wetland was developed (Figure 20, top). However, changepoints were not significantly detected when agriculture or forest land use were tested against IMBCI scores at the 500 m scale.

Changepoint analysis also revealed a 95% probability of a changepoint occurring with ≥ 25% development within 1000 m with a 60% chance of a changepoint occurring when 8.5% of the 1000-m buffer was developed (Figure 20, bottom). Again, changepoints were not detected for agriculture or forest land use at the 1000-m scale. In addition, changepoints in IMBCI scores were not detected for percent development, agriculture, or forest at the watershed scale. More detailed information can be obtained from Deluca et al. (2004).

Implications

Changepoints identified in this study represent ecological thresholds, beyond which the ecological integrity of the marsh bird community and potentially the entire marsh ecosystem becomes significantly compromised. These relationships were only identified at relatively local scales (500-m and 1000-m buffers), so it appears that local land cover is the best predictor of marsh ecosystem integrity. Furthermore, our results indicate that developed land use is the primary stressor to marsh bird communities of the Chesapeake Bay.

We demonstrated that the IMBCI is a reliable indicator of marsh bird community integrity that may assist in the assessment of the integrity of the entire marsh ecosystem. IMBCI scores, combined with the identification of a land-use threshold, are easily interpreted and provide rapid assessment approaches for communicating complex ecological data to natural resource managers and conservation planners. By helping to bridge the gap between scientists and regional conservation decision makers, the IMBCI could become a valuable tool to the ongoing efforts of restoring and maintaining the ecological integrity of coastal wetlands.

WATERBIRD COMMUNITY INTEGRITY

Background

We developed an index of waterbird community integrity (IWCI) to provide insight into estuarine ecosystem integrity and used it as a tool to: (1) determine land-cover types that influence waterbird community integrity; (2) identify relevant geographic scales at which land cover influences IWCI scores; and (3) test if ecological thresholds exist in the amount of land-cover disturbance that causes significant declines in IWCI scores.

We modified the IMBCI (DeLuca et al. 2004) to develop the index of waterbird community integrity (IWCI). We defined waterbirds as all species that forage exclusively or opportunistically on aquatic estuarine organisms (i.e., gulls, terns, waders, raptors, kingfishers, and waterfowl). Theoretically, the waterbird community is an ideal indicator because it is at the top of the estuarine food web. Therefore, this indicator is potentially sensitive to stressors influencing the system at multiple trophic levels. Furthermore, as a community that is closely tied to a functioning subestuarine ecosystem, it has high potential as an indicator to be sensitive to stressors at both the watershed and local scales (DeLuca et al. 2004, Hale et al. 2004).

Findings

In 2002 and 2003, one single-predictor model, which included developed land cover, was a significant predictor of IWCI scores (Table 5). Depending on the year, this model was between 13 and 26 times more likely to describe variation in IWCI scores than any of the seven remaining candidate models (Table 5). Because development was the only predictor with strong support in both years, we focused subsequent analyses on this land use.

Table 5. Relative ranking of models using land cover variables to describe variation in index of water bird community integrity (IWCI) scores. Columns give model notation, number of estimable parameters (*K*), second-order Akaike's information criterion values (AIC$_c$), AIC$_c$ differences (ÄAIC$_c$), and AIC$_c$ weights (w_i).

Model	*K*	AIC$_c$	ÄAIC$_c$	w_i
2002				
development	3	68.5	0.0	0.752
null	2	73.7	5.2	0.056
dev + forest	4	74.1	5.6	0.046
dev + agriculture	4	74.1	5.6	0.046
agriculture	3	74.3	5.8	0.041
ag + forest	4	74.8	6.3	0.032
dev + ag + forest	5	76.5	8.0	0.014
forest	3	76.6	8.1	0.013
2003				
development	3	52.1	0.0	0.903
null	2	58.6	6.5	0.035
dev + forest	4	59.7	7.6	0.020
dev + agriculture	4	59.7	7.6	0.020
dev + ag + forest	5	61.9	9.8	0.001
agriculture	3	62.3	10.2	0.001
ag + forest	4	62.6	10.5	0.001
forest	3	62.8	10.7	0.000

As total development increased, IWCI scores decreased significantly at the watershed, IDW, and 500 m scales in 2002 and 2003 (Table 6). Suburban development also had a significant negative impact on IWCI scores at the watershed, IDW, and 500 m scales for both years (Table 6). The relationship between total development and IWCI scores was consistently stronger than the relationship between suburban land cover and IWCI scores (Table 6). In addition, more variation was explained in IWCI scores when the two geographic scales emphasizing local land cover (IDW and 500 m) were used as predictors (Table 6). Increasing urban land cover also lead to lower IWCI scores in 2002 and 2003 at the watershed scale, however, the relationship between IWCI scores and the IDW and 500 m scales were not linear.

Table 6. Results of linear regressions for IWCI scores and three land-cover types at three different geographic extents in a dry (2002) and wet (2003) year. Results are summarized as r^2 and *P* value.

	Geographic Extent					
	Watershed		Watershed (IDW)		500-m buffer	
Land Cover	**2003**	**2003**	**2002**	**2003**	**2002**	**2003**
Development	0.51, 0.001	0.54, <0.001	0.57, <0.001	0.60, <0.001	0.54, 0.001	0.57, <0.001
Suburban/rural	0.43, 0.004	0.47, <0.001	0.54, 0.001	0.57, <0.001	0.55, 0.001	0.54, <0.001
Urban	0.40, 0.007	0.51, <0.001	NL*	NL*	NL*	NL*

**Relationships between urban land cover and IWCI scores were not linear and were therefore analyzed with a changepoint analysis to test for the presence of an ecological threshold (see Figure 21).*

Changepoint analysis indicated that in 2002, when as little as 4% of the IDW land cover within a watershed was urbanized, there was a 94% probability of a threshold response in waterbird community integrity (Figure 21a). When testing the 500 m buffer scale in 2002, we found that when 4% of land cover was urbanized within 500 m of the subestuary there was an 85% probability of a threshold response in waterbird community integrity (Figure 21b). In 2003, when 5% of IDW land cover was urban it lead to a 99.9% probability of a threshold (Figure 21c). Finally, in 2003 we found that when there was as little as 5% urbanization within 500 m of the shoreline it resulted in a 99.9% probability of a threshold occurring (Figure 21d). Additional detailed findings can be found in Deluca et al. (in prep).

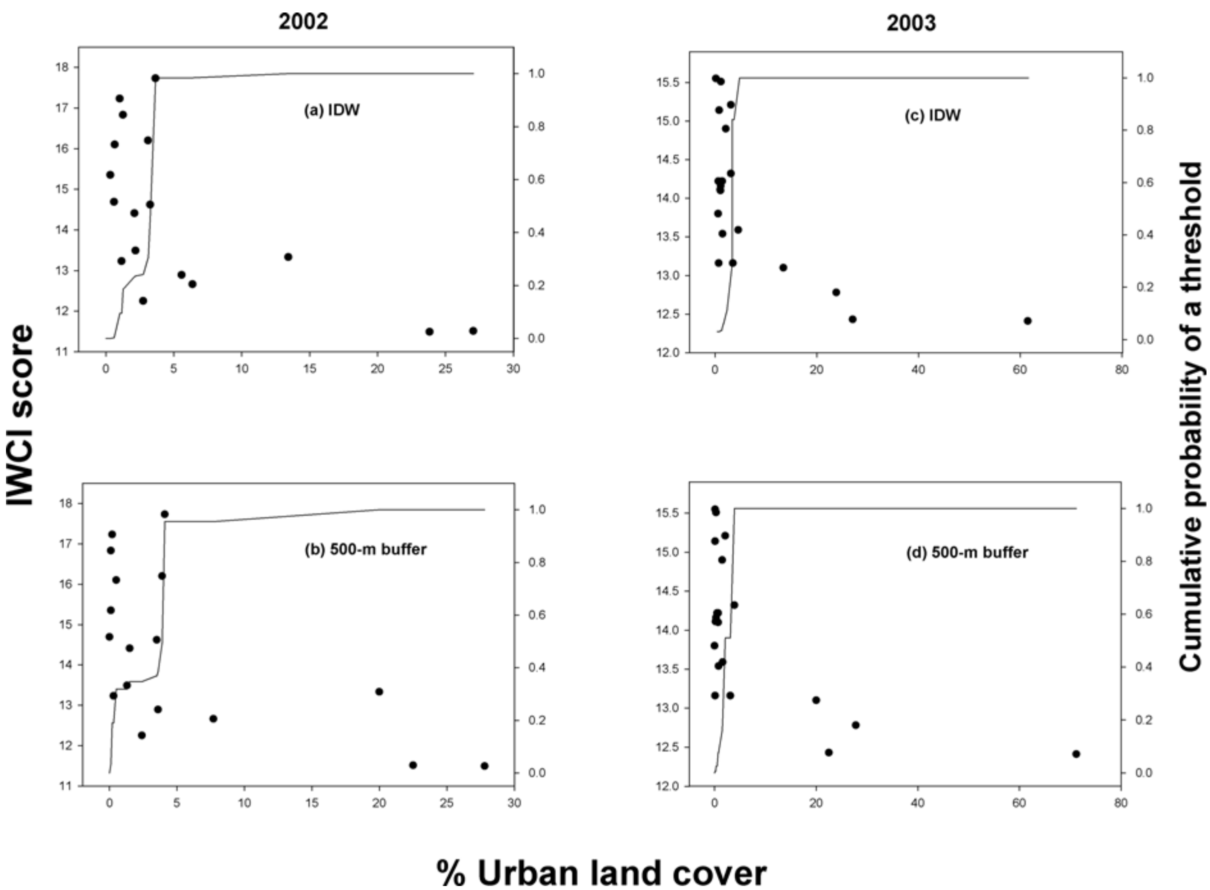

Figure 21. Results of changepoint analyses for percent urban development and index of waterbird community integrity scores (IWCI) in 2002 (a, b) and 2003 (c, d) for two different spatial scales; inverse distance weighted (IDW) land cover within the watershed (a, c) and a 500-m buffer around the subestuary (b, d). The solid lines depict the cumulative probability that an ecological threshold will occur with increasing urban development.

Implications

The IWCI clearly identified developed land cover as the primary stressor influencing waterbird community integrity (Table 6). The waterbird community is particularly sensitive to urban development, as it exhibits a threshold response to alarmingly low levels of disturbance near the shoreline. From a management perspective, the threshold response to urban development at the IDW and 500 m buffer scales, offer clear management guidelines of how much coastal development estuarine ecosystems can tolerate before a collapse in ecological integrity can be expected. A compromised waterbird community, at the top of the estuarine food web, may have significant implications on the entire ecosystem through altered top-down food web relationships and controls (Baird et al. 2004).

PCBS IN WHITE PERCH (*MORONE AMERICANA*)

Background

The goal of this project was to develop statistical models that predict total PCBs (t-PCBs) in an economically and ecologically valuable fish species in Chesapeake Bay using different types of urban land use from estuarine watersheds.

Polychlorinated biphenyls (PCBs) are a group of organochlorine compounds that resist degradation in the environment and are widely distributed in aquatic ecosystems. PCBs accumulate in fat-rich tissues of biota. Because of their toxicity, PCBs present a health risk to both humans and a variety of other organisms. Although banned in the U. S. in 1979, PCB levels in many aquatic ecosystems remain sufficiently high to contaminate food webs and cause consumption advisories for a wide range of valuable fish and shellfish species.

Major sources of PCBs in estuaries are thought to be legacy pools of past point-source releases by manufacturing and from nonpoint sources associated with the general use, storage, and disposal of these persistent compounds. However, the sources, spatial extent, and magnitude of PCB contamination are not well characterized and have proven difficult to predict, presumably because estuaries are hydrologically open systems affected by long-distance transport of contaminants from upstream and downstream areas. However, some recent studies have successfully linked land use data from small estuarine watersheds to various sediment contaminants. Given that PCBs are known to be associated with industrial or other urban land uses, these previous findings suggested to us that quantification of land-use patterns in watersheds may be useful for predicting PCB contamination in downstream estuarine ecosystems.

We tested the hypothesis that the amount and spatial proximity of urban land in watersheds would be significantly linked to concentrations of total PCBs (t-PCBs) in biota from estuarine segments of Chesapeake Bay. We examined: (1) the strength of correlations between different measures of developed (urban) land in the watershed and t-PCBs; and (2) the relative improvement in our predictions of t-PCBs afforded by weighting urban land by its inverse distance from the shoreline to account for proximity to the estuarine segments. We focused on t-PCBs in White Perch (*Morone americana*), a widely distributed estuarine fish that supports a valuable commercial and recreational fishery throughout Chesapeake Bay. White perch are an ideal indicator species for detecting watershed linkages to PCBs because they spend most of their lives within or near specific estuarine segments. White perch also prey upon small fish and bottom-dwelling invertebrates, which are consumers of fine organic particles running off the land and accumulating in sediments. Moreover, White Perch are semi-anadromous, moving into freshwater tributaries to spawn with the young moving back down into the estuarine segments to find a nursery and feeding habitat, so their life cycle spans a zone that continuously exposes them to runoff from the watershed. Finally, because PCB-related consumption advisories have recently been posted for several estuarine segments and many other locations have yet to be assessed, there is great interest in developing geographical indicators of PCBs in this region.

Findings

All unweighted developed land-use measures were significant predictors of t-PCBs in White Perch, explaining 51% to 69% of the variance among the 14 estuarine segments. Percent high residential/commercial land was the best predictor of t-PCBs among the unweighted developed-land-use classes (Figure 22, top).

Inverse-distance-weighting markedly improved the linear fit of each land-use predictor and t-PCBs in White Perch among the 14 estuarine segments (Figure 22, bottom). Inverse-distance weighted percent commercial land, was the best predictor of t-PCBs of any of models considered and accounted for nearly all the variance (r^2 = 99%).

Two estuarine segments had distinctly higher levels of t-PCBs than the other estuarine segments and may have had disproportionately strong effects on the regressions; so the effect of removing these two observations from the analysis was evaluated. All land-use classes remained significant predictors of t-PCBs using the reduced (n=12) set of observations. In particular, inverse-distance-weighted models for % high-residential/commercial and % commercial land exhibited large improvements in explain-

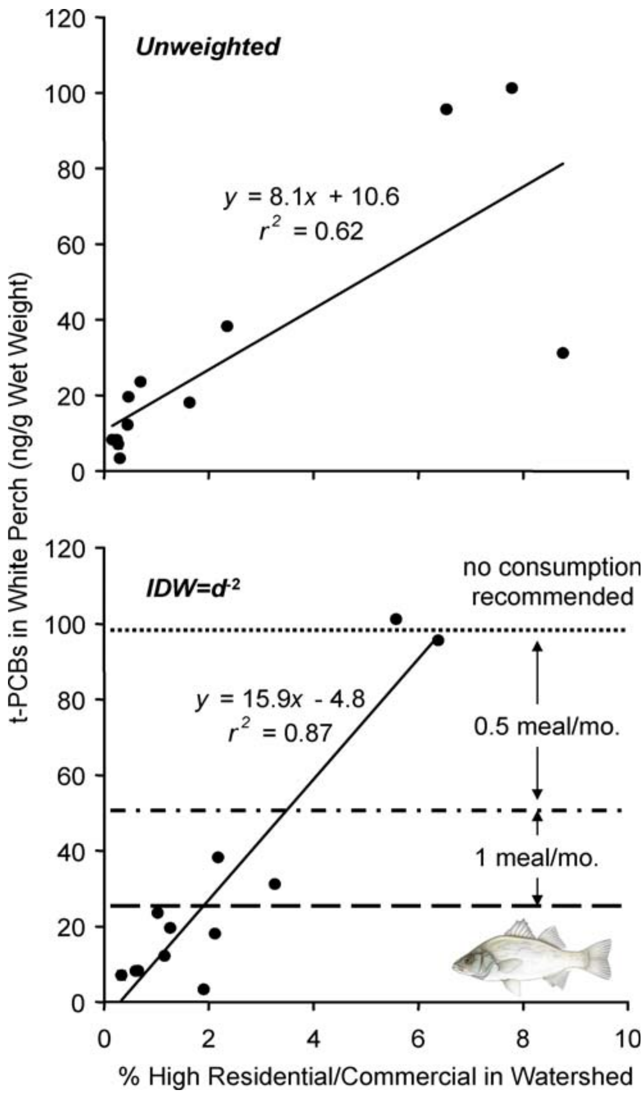

Figure 22. Regressions of unweighted (top) and inverse-distance weighted (IDW) % high-intensity residential/commercial (bottom) in watersheds on t-PCBs in white perch across 12 subestuaries, excluding the two locations with the hightest levels of developed land and t-PCBs. Dashed lines illustrate levels of t-PCBs that correspond to U.S. EPA (1999) consumption advisories for cancer health endpoints.

ing variance over unweighted models. Percent high-res/comm and % commercial land explained 87% and 86% of the variance in White Perch t-PCB concentrations, respectively among all predictors in the reduced data set. Additional information can be found in King et al. (2004).

Implications

Our study is novel because we demonstrated a remarkably strong relationship between the amount of developed land in watersheds, weighted by its proximity to the water, and PCBs in White Perch across many tributaries of Chesapeake Bay. No previous study has demonstrated such a relationship between watershed land use and contaminants in fish, particularly among multiple watersheds. Perhaps more importantly, we also showed that very little watershed development, particularly near shorelines, corresponded to levels of PCBs that were unsafe for human consumption. Thus, these findings were not just limited to highly urban areas where we already know the water is badly polluted. Although PCBs have been banned since 1979, new consumption advisories for several fish species have been posted across many Chesapeake Bay tributaries because of PCBs, and these advisories have been big news for communities previously unaware of this problem. Our study suggests that PCBs historically produced and used in this region are persisting in the environment at the scale of these watersheds, and urban runoff may still be acting as a source of legacy PCBs to downstream aquatic habitats.

The relationships we discovered will be very important to managers because they may be used as tools for predicting areas that have a high probability of PCB contamination. Moreover, because many other contaminants are associated with development, these models will likely be very useful for identifying other types of contamination in estuaries. Many new contaminants are still in production and use, including flame retardants (PBDEs), metals, and emerging contaminants such as pharmaceuticals, and may well be related in a similar way to the amount and spatial proximity of development in watersheds.

The study also helped confirm that White Perch may be an ideal species for assessing bioaccumulation of estuarine contaminants associated with watershed runoff because of its small home range on an individual level but broad distribution across a wide range of salinities that span the length of Chesapeake Bay.

On a broader front, this study points to the importance of better understanding the impacts of development on estuaries. Our study highlights the implications of development on the health of aquatic ecosystems. It links environmental and ecological conditions in estuaries to land use in their associated watersheds. There may be other contaminants at unsafe levels in estuaries that we have yet to discover that are related to urbanization.

BIO-OPTICAL INDICATORS

Background:

Communities of submersed aquatic vegetation (SAV) are highly valued habitats because of the functions they perform in coastal systems. These functions include, among others, provision of refuge and nursery habitat for juvenile fish, shellfish and crabs, sediment stabilization, and food for certain waterfowl. Loss of valuable SAV habitat has been one of the most deleterious effects of pollution in numerous coastal systems along the Atlantic slope. Presence or absence of SAV is, therefore, a powerful indicator of estuarine water quality. Efforts to preserve and restore seagrasses have focused mainly on factors affecting water clarity, because of the inherently high light requirement of seagrasses. The attenuation of light in water is controlled by the concentrations of three parameters: suspended particulate matter (SPM), phytoplankton chlorophyll (Chl), and colored dissolved organic matter (CDOM). The goal was to develop an optically based indicator of habitat suitability for SAV, and explore its variation with land use in the local watershed.

Findings

Concentrations of chlorophyll were higher in estuarine segments with developed watersheds, while CDOM was higher in segments with developed and mixed agricultural watersheds. Concentrations of TSS were remarkably independent of land use in the local watershed, including the reference site. Specific-absorption coefficients were significantly higher in segments with developed and mixed-developed watersheds. Specific-scattering coefficients were also elevated somewhat in these land uses. Using these specific-absorption and –scattering coefficients in bio-optical modeling routines, we determined water quality thresholds (diagonal lines in Figure 23) that delineate conditions that will support SAV (low concentrations, points near the origin) from those that will not (concentrations falling outside the thresholds. The green shaded area represents the approximate contribution of phytoplankton to TSS, and is an area that should have few or no points).

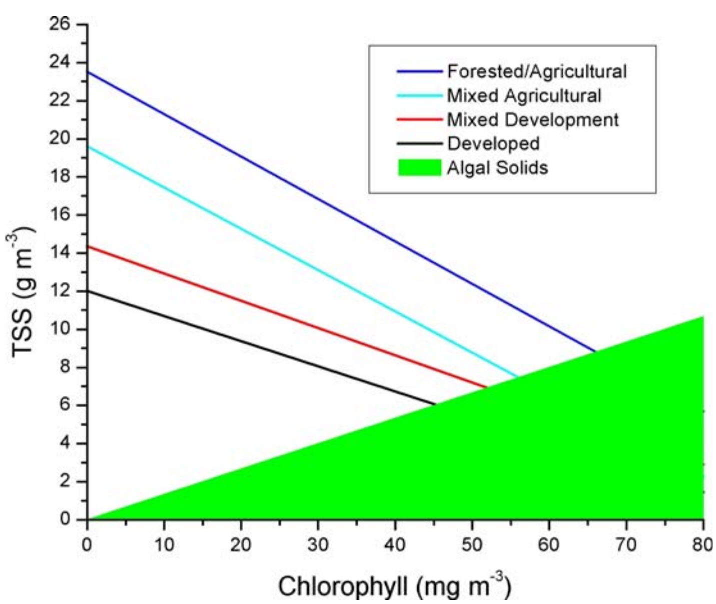

Figure 23. Water quality thresholds for SAV growth in estuarine segments of Chesapeake Bay with differing land use in their watersheds. Differences as development increased were due to higher concentrations of CDOM as well as higher specific-absorption and -scattering coefficients of suspended particulate matter.

Implications

Not only did estuarine segments with developed watersheds have higher concentrations of optically significant water quality constituents (especially chlorophyll), but the water quality requirements for segments with developed watersheds were considerably more stringent than less developed watersheds. The results imply that greater management effort is expected to be required to restore SAV in developed watersheds. Optical properties of the particulate matter and bio-optical modeling offer improved insight into mechanisms responsible for loss of SAV.