

ECOSYSTEM VARIABILITY AND ESTUARINE FISHERIES: A SYNTHESIS

COP Project Final Report

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II. Abstract

We developed a suite of forecasting tools that sought to predict patterns and distribution of estuarine production at intra-annual, inter-annual and decadal time scales. At intra- and inter-annual time scales, we developed and employed an approach to analyzing patterns of synoptic climatology to understand the effect of low frequency, long term variation in climatological patterns on the abundance, distribution, structure and production of estuarine plankton communities and on fish recruitments. We quantified the impact of environmental parameters on fish recruitment with a focus on bay anchovy, Atlantic menhaden and striped bass. We applied general additive models to forecast the within-seasonal distribution of fish and blue crabs. At longer time scales, we developed a multispecies surplus production model that quantified patterns in relative biomass and exploitation. We explored the impact of historical changes in nutrient loading on the ratio of pelagic and benthic fish yield in the Chesapeake Bay. Finally, we developed models of the trophic interactions within estuarine ecosystems that quantified how the distribution of production at different trophic levels should respond to restoration efforts to reduce the impacts of human perturbation.

III. Executive Summary

We conducted analyses to develop forecasting tools to predict responses of estuarine production, community composition and trophic structure at intra-annual, inter-annual and decadal time scales. These tools provide a platform to forecast the impact of both natural low frequency climatic variability and anthropogenic changes on estuarine dynamics.

We demonstrated that the main stem of Chesapeake Bay is a diatom-dominated system wherein seasonal variability of temperature and Susquehanna River flow (SRF) explains most of the annual variability of floral composition (Adolf *et al.*, 2004). Specific combinations of floral composition, *chl-a* biomass, and PP characterize the ‘seasons’. Our analysis of a six-year dataset showed that each season was characterized by regional blooms of recurring taxa related to trophic gradients in the main stem of the Bay. Inter-annual variability of phytoplankton dynamics in spring and summer was driven primarily by freshwater input that stimulated diatoms. Thus, diatoms were highly responsive to large-scale nutrient inputs such as those associated with freshwater inputs. These responses were most pronounced in the lower Bay in summer where high SRF precipitated a floral shift from picoplanktonic (<3 μm) cyanobacteria to larger diatoms.

We developed several predictive relationships between Chesapeake Bay hydrologic conditions and zooplankton dynamics. Kimmel and Roman (2004) described the local environmental processes that force zooplankton dynamics. They found freshwater input into Chesapeake Bay to be a major driver of zooplankton dynamics, particularly during the spring. This period is critical for anadromous fish which spawn during the spring and their larvae which rely on zooplankton as a primary food source. Dominant year classes of striped bass and white perch are tightly linked to years of high freshwater input and high zooplankton biomass in the spring.

On seasonal to inter-annual time scales, much of the environmental variability responsible for patterns in the distribution and characteristics of estuarine phytoplankton and zooplankton communities is related to differences in regional-scale weather patterns. A synoptic climatology provided a mechanism to classify and quantify weather variability on smaller spatial and temporal scales than basin-scale climate indices such as NAO or ENSO that do not have a proximate influence on the Chesapeake Bay region. Several climatological patterns were identified that have a relatively consistent set of weather conditions in terms of cloud cover, temperature, wind speed and direction, and precipitation. We developed a model to predict spring freshwater input and its subsequent impacts on multiple trophic levels (phytoplankton and zooplankton) using a winter synoptic climatology. Miller *et al.* (2006) found that a winter synoptic climatology model could predict 54% of the variance in spring freshwater input into Chesapeake Bay. This prediction of flow also allowed prediction of ecosystem response, including the size and location of the spring phytoplankton bloom and the abundance and species composition of zooplankton. These analyses were carried further by Kimmel *et al.* (2006) who showed that climate patterns are linked to zooplankton dynamics in the upper Chesapeake Bay. This work included some analysis of fish variability as well, showing how winter climate is related to spring abundances of anadromous fish and zooplankton.

We developed statistical predictions of the distribution of young-of-year fish in estuarine systems. These forecasting tools utilize a suite of environmental parameters to predict the probability of occurrence and abundance separately. Cross validation analysis indicated that transferability of models developed on data for individual years was not consistent. Some models performed well in cross validation, whereas distributions in some years appeared to be determined by unique suites of parameters.

We developed a range of tools to forecast recruitments in bay anchovy, Atlantic menhaden and striped bass. These tools utilize environmental and population specific parameters to improve traditional stock-recruitment relationships for modeled species. These modified stock recruitment relationships explain between 60-90% of the variability in the recruitment time series. Analyses indicated that they appeared to perform well as forecasting tools and not simply in hindcasting mode.

We reconstructed patterns of historical nutrient loadings to the Chesapeake Bay and the Potomac River. These data were used to quantify whether the ratio of pelagic to demersal fish species in the Chesapeake ecosystem changed with anthropogenic nutrient additions as predicted from a comparative analysis of other estuaries. The Chesapeake Bay system is likely the only system in the world that has sufficient data to determine whether the inferences from inter-system comparison predict within system responses. Using nutrient loading and fisheries landing data for the full Chesapeake Bay system Kemp et al (2005) reported a small but distinct increase in the P:D ratio that was caused by both increases in pelagic catch and decreases in demersal catch. This pattern was accompanied by increasing nutrient loads, declining SAV communities, increasing algal stocks, intensification of hypoxic duration and extent and declines in the efficiency in the transfer of primary production to higher trophic levels. In contrast, the P:D there was a relatively large range in both chlorophyll concentrations and P:D ratio in the Potomac River estuary, in part because this data set spans a longer period of time during which several management actions took place. In this case, the P:D ratio was quite low (~1.8) during the earliest period of the record when chlorophyll concentrations were highest, increased as chlorophyll levels declined (2.3 – 3.3) and declined further when chlorophyll levels fell below 20 mg/l (1985 – 2000). It is clear that both algal biomass and fisheries composition changed substantially during this 30 year period.

IV. Purpose

A. *Detailed description of any problems or impediments of research project that were addressed*

The purpose of the proposal that was funded was to develop a series of forecasting tools that would make forecasts at different levels of temporal resolution, from intra-annual to decadal. We successfully met the majority of project goals and objectives. Our successes are detailed below in Sections V and VI of this report. These achievements lead to the publication of 33 papers in peer-reviewed journals, books or conference proceedings and 50 presentations at national or international meetings. The project also fully or partially supported the completion of 1 PhD dissertations and 5 MS theses.

However, it is also inevitable that in a project as ambitious and broad ranging as that proposed, that some aspects of the proposed work were not completed. The principal area of deficiency relates to the coupling of individual forecasts. In the proposal it was envisaged that these forecasting tools would be hierarchically nested to a large extent, so that the consequences of forecasts at shorter temporal scales should inform forecasts at larger temporal scales. While we have been successful in coupling forecasts within the same level of temporal resolution, we have been largely unsuccessful in exploring the consequences of forecasts at one temporal resolution on forecasts at the higher resolution.

B. *Objectives of the project.*

We sought to build, from a comprehensive empirical platform of available data detailing spatial and temporal patterns in estuarine production derived from federally- and state-funded research, a suite of forecasts at three distinct temporal resolutions: intra-annual, inter-annual and decadal. We sought to make the following forecasts

1. Intra-annual time scales
 - a. Patterns of oxygen depletion
 - b. Patterns in the timing, distribution and magnitude of primary production
 - c. Patterns in the distribution of fish and their forage
2. Inter-annual time scales
 - a. Variability in fish abundance, growth and distribution
 - b. Variability in fish stock- recruit relationships
 - c. Patterns in multispecies fish production
3. Decadal time scales
 - a. Changes in the fish community structure
 - b. Changes in ecosystem structure and function.

To present our results, we report our findings with respect to seven distinct tasks: (1) Patterns in timing and distribution of primary production, (2) Regulation of zooplankton distributions, (3) Distribution of fishes, (4) Variation in fish recruitments and production, (5) Development of multispecies surplus production, (6) Changes in fish community structure, and (7) forecasts of ecosystem responses.

V. Approach

A. Detailed description of the work that was performed

Data sources

The platform for our forecasts include a diverse range of historical information on water quality parameters from state and federal monitoring sources. We also made extensive use of the large USEPA Chesapeake Bay Program Monitoring Database, that is available online at www.chesapeakebay.net. However, at the core of our forecasting ability are two large, multidisciplinary research programs conducted by project PIs prior to this COP award. The first of these programs was an NSF-Funded project that sought to determine “Trophic Interactions In Estuarine Ecosystems” (TIES). This program sampled the variability and distribution of estuarine production at primary and secondary levels. Sampling was conducted from a diverse array of sampling platforms including satellites, aircraft overflights and shipboard sampling. The data are available for 1995-2000 at www.chesapeake.org/TIES. The second program was a fishery independent, multispecies monitoring program funded by the NOAA Chesapeake Bay Office. Data for this sampling program are available for 2001-2005 at hjort.cbl.umces.edu/CHESFIMS.

TASK 1: Patterns of timing and distribution of primary production

Data to support the analyses conducted for this task come from observations from SAS III obtained on flights over the main stem of Chesapeake to measure *chl-a* and sea surface temperature (SST) distributions. The Chesapeake Bay Remote Sensing Program consists of >20 flights per year, and a companion program has conducted 8-12 flights per year on two tributaries of focus, the Choptank and Patuxent Rivers River (<http://www.cisnet-choptank.org>). A NASA-supported component of the ACE INC program in which we participate currently supports these flights, maintaining a 15-year time series that has generated data of high spatial and temporal resolution for key ecosystem properties such as *chl-a* and PP.

Our methods have entailed retrospective analyses and new observations in the Bay and two tributaries. Results from the NSF-sponsored Land Margin Ecosystem Research (LMER) program, entitled Trophic Interactions in Estuarine Systems (TIES) are the basis for much of the retrospective analysis of biomass as *chl-a* and PP. These data have been used to develop depth-integrated models (DIMs) and artificial neural network models (ANNs) that estimate PP from relatively simple input terms (Harding Jr. et al. 2002, Harding Jr. and Scardi In prep). We used data from a number of research cruises to characterize phytoplankton dynamics and bio-optical parameters of the water column. Three cruises (April, July, and October, 2003) were conducted on the Choptank and Patuxent Rivers in association with ACE INC. Four cruises (April, August, October, November, 2003) were conducted on the main stem Chesapeake Bay in conjunction with related projects, including NSF Biocomplexity in collaboration with Bess Ward, NSF MOVE with Eric Wommack and Wayne Coats, and NSF Small Grants Emergency Response (SGER) that supported a post- Hurricane Isabel cruise. The first set provided coverage of the main stem Bay and adjacent coastal waters; the second set gave coverage of the Choptank and Patuxent Rivers concurrent with surveys of physical properties (Boicourt), zooplankton sampling (Roman), and fish trawls (Houde); a third set sampled the Bay before and after passage of Hurricane Isabel in fall 2003 to measure changes in plankton and fish communities associated with this strong storm. Bio-optical measurements on all cruises supported the remote sensing

efforts and included: (a) *chl-a*, (b) particulate absorption, (c) CDOM absorption and fluorescence; (d) seston; (e) HPLC pigment determinations; (f) in-water profiles of downwelling irradiance and upwelling radiance from a suite of instruments to recover remote sensing reflectance; (g) sun photometer measurements for atmospheric turbidity. The optical instruments for profiles included a Satlantic hyperspectral tethered radiometer buoy (TSRB) and two profilers, a Biospherical Instruments MER-2040 and a Satlantic MicroPro. Deployment of these instruments is supporting QA/QC of radiometry and comparisons with satellite and aircraft recoveries of key ecosystem properties.

TASK 2: Regulation of zooplankton distributions

Forecasts were based on analysis of zooplankton abundance and distribution data collected during the TIES program and during other related sampling programs, including the Chesapeake Bay programs zooplankton monitoring database. In order to predict shifts in zooplankton abundance in the upper Chesapeake Bay, we chose to quantify climate using synoptic climatology methods. The result was a series of sea level pressure maps that classified the dominant modes of weather over the Chesapeake Bay region. Particular weather patterns impacted the Chesapeake Bay region differently, causing variations in temperature, precipitation, cloud cover, etc.. The critical period affecting peak freshwater input (spring) was identified as winter.

We developed multiple regression models to predict spring cumulative freshwater discharge of the Susquehanna River from winter weather pattern frequency. Winter climate frequency proved to be an adequate predictor of spring Susquehanna River discharge. Specifically, an increase in the frequency of low pressure systems, e.g. nor'easter storms and a decrease in the frequency of high pressure systems, e.g. the Bermuda high, were the most critical weather patterns. The multiple regression model could not predict extreme high or low flow conditions based on winter climate pattern frequency. This is because the magnitude of precipitation cannot be determined from the weather pattern's *frequency*. For example, an increase in low pressure storms over the winter typically results in higher freshwater discharge in the spring; however a year of normal frequency of low pressure systems may include one large storm. Several years in our data set showed this pattern, in particular 1993 and 1996, both years with extremely powerful blizzards during the winter period. We feel this short-coming of the model is to be expected as it is difficult to predict rainfall amounts and locations from sea level pressure maps due to the patchy nature of rainfall. However, the approach is useful in predicting spring discharge of the Susquehanna River and, in concert with our previous work, a predictor of *E. affinis* abundance in the upper Chesapeake Bay.

TASK 3: Distribution of fish.

General linear models are a flexible statistical modeling approach to predicting the distribution of fish based on environmental and water quality parameters. It is difficult to apply traditional regression-based approaches to such questions as survey data are often characterized by a large proportion of tows in which none of the target species were caught (so-called zero-inflation), and accordingly the distribution of observations are highly non-normal and usually do not respond to transformations. The general linear model approach separates the forecasting problem into two stages. In the first stage, one seeks to forecast presence /absence of the target species. In the second stage, one seeks to forecast abundance given presence. Model choice in one stage does not limit model choice in the other phase – thus making the approach highly flexible. We applied this approach to forecasting the distribution of fishes and blue crabs from TIES, CHESFIMS and the blue crab winter dredge survey databases (Sharov et al. 2003).

GAMs are now commonly applied to estimate distributions of fish and shellfish. Most studies validate their models by reserving a portion of the data used to develop the model. However, given the size of our forecasting platform, we were able to undertake a formal cross-validation by assessing the ability of models developed in one year to predict distributions in other years. We used the models developed on the training data in a single year to predict distribution and abundance for the test data for that year, and for the entire data sets for alternative years.

Task 4: Variation in fish recruitments and production

We developed models to predict recruitment in a number of fish, but paid particular attention to bay anchovy, Atlantic menhaden and striped bass. For bay anchovy we used data from the TIES and CHESFIMS programs, together with results from a single NSF-funded research cruise in 2003 to quantify the effects of Hurricane Isabel on the Chesapeake Bay ecosystem. We explored the potential for environmental parameters, population characteristics and community composition to explain residual variation remaining from Ricker-style stock recruitment relationships. Specifically, we quantified the additional predictive power of freshwater runoff, salinity, shifts in the distribution of the anchovy spawning stock, and the abundance of potential predators to modify stock-recruitment relationships. For Atlantic menhaden, we conducted a multivariate analysis of synoptic atmospheric pressure patterns throughout the mid-Atlantic Bight to identify characteristic patterns in pressure. These pressure patterns were then regressed on the residuals of a Ricker-style stock and recruitment relationship. For striped bass, we analyzed data from fishery-independent surveys of juvenile striped bass conducted by the Maryland Department of Natural Resources. We approached these data in a similar way to that described above for bay anchovy.

In addition to stock-recruitment modeling, we also analyzed the production dynamics of bay anchovy, the most abundant fish in the Chesapeake Bay. We combined abundance estimates from the TIES and CHESFIMS programs with size-dependent growth and mortality models to estimate the biomass dynamics of annual cohorts of bay anchovy from 1995-2004.

Task 5: Development of multispecies surplus production

A priori, we categorized the Chesapeake Bay fish community into three guilds, based largely on trophic level and habitat: pelagic piscivores, benthivores, and plantivores. We included several species in each guild, making sure to include those that had high value either from an economic or ecological perspective. Pelagic piscivores included striped bass, bluefish, weakfish, and white perch. Benthivores included blue crab, Atlantic croaker, spot, summer flounder, channel catfish, and white catfish. Planktivores included menhaden and bay anchovy. From 1995 – 1999, these species comprised 94% of the commercial harvest in the Chesapeake Bay, with menhaden representing 76% alone. Bay anchovy are not commercially important but are a critical prey fish for many benthivores and pelagic piscivores (Hartman and Brandt 1995). Several fishery-independent surveys occur in the Chesapeake Bay that provide time series of CPE for several species. Even though estimates of the survey catchabilities were not accurate, model results still represent time series of relative biomass estimates (B/B_{msy}) or relative fishing mortality estimates (F/F_{msy}) that reveal important trends within the population. Catch data equaled the sum of commercial and recreational catches. Annual commercial catches in the Chesapeake Bay were provided by the NOAA Chesapeake Bay Office in Annapolis, Maryland. Annual recreational catches were downloaded from the MRFFS internet website.

For any species or guild i at time t , its change in biomass without considering ecological interactions (e.g., competition, predation) is represented as

$$\frac{dB_{it}}{dt} = (r_i - F_{it})B_{it} - \frac{r_i}{K_i} B_{it}^2 \quad (1)$$

where B_{it} represents the biomass, F_{it} represents the fishing mortality rate, r_i represents the intrinsic rate of population increase, and K_i is the carrying capacity. Integrating equation 1 with respect to t over a specific time period provides estimates of B_{t+1} for species or guild i given its estimates of B_t . To include ecological interactions, we add an interaction term to equation 1 to describe the effect of species or guild j on species or guild i so that:

$$\frac{dB_{Pt}}{dt} = (r_P - F_{Pt})B_{Pt} - \frac{r_P}{K_P} B_{Pt}^2 - gB_{Pt}B_{Bt} \quad (2)$$

where g represents the competition coefficient that reveals the negative interaction between guild P (pelagic piscivores) and guild B (benthivores). A corresponding differential equation occurs for the change in benthivore biomass with respect to time.

Task 6: Changes in fish community structure:

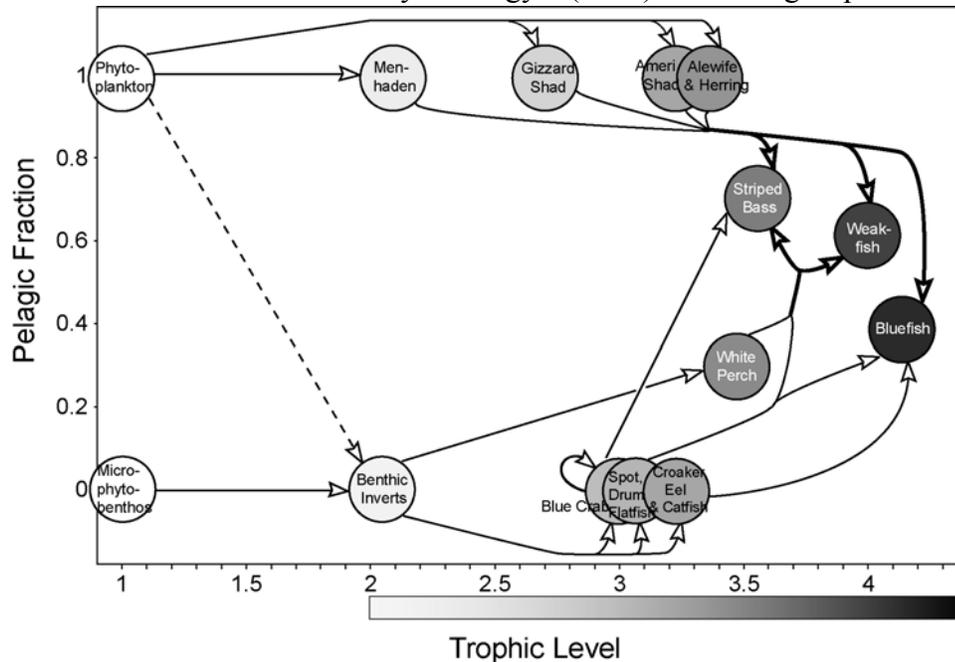
A major objective of this portion of the NOAA-COP research effort was to develop analyses of historical data relating temporal trends in fisheries yield and pelagic/demersal partitioning of fisheries yields to nutrient loading rates, degree of nutrient enrichment, phytoplanktonic primary production and water quality (algal abundance as indicated by chlorophyll-a concentrations and hypoxia/anoxia) in Chesapeake Bay and the Potomac River estuary. We assembled data to conduct these analyses and we strove to develop time series data sets that included data from periods before enrichment was extensive up to the present time when eutrophication is quite severe in the Chesapeake system. We also developed relationships between the composition (pelagic versus demersal species) of fisheries landings for several regions of the Bay system and nutrient loading rates and algal biomass levels. Previous efforts to empirically examine ecosystem level responses to environmental change have often relied on a comparative approach (Nixon 1995). Because comparative analyses include data from a variety of sources, the signal range for variables is increased and the chance of interpretable patterns emerging from admittedly complex interactions also increases (Vollenweider 1976, Nixon 1988, Boynton and Kemp 2000). However, implicit in this approach is the assumption that responses to a particular forcing function evident among sites parallel the responses within a single site. For example, Moreno *et al.* (2000) examined fisheries yield data and algal biomass data for a selection of European estuaries and coastal seas and found that the ratio of pelagic to demersal fish changed in response to changes in chlorophyll concentration. They suggested that as algal biomass increases, so does the propensity for deep-water habitat degradation (e.g., hypoxia and anoxia, shifts in autotrophs) and loss of habitat for demersal fish. In a similar fashion (i.e., using comparative analyses) Nixon and Buckley (2002) found a strong relationship between primary production rates and fishery yields for a variety of coastal and estuarine ecosystems and the relationship indicated an increase in yield with primary production increases. They did not find evidence of a decline in yield as suggested by Caddy (1993) at high levels of enrichment. However, enrichment may well lead to enhancement of pelagic species that can more readily avoid low dissolved oxygen conditions, and thus their abundance might increase relative to benthic species.

We analyzed data for both the mainstem of Chesapeake Bay and the Potomac River estuary, for which we believed fifty-year records of freshwater inputs, nutrient loads, algal biomass, summer hypoxia and species-specific catch and effort records could be readily

assembled. We synthesized the data available to evaluate the functional forms and validity of suggested ecological relationships, mainly by applying general linear models and time series analyses which account for the temporally and spatially autocorrelated nature of these data.

Task 7: Forecasts of changes in ecosystem structure

We extended and analyzed Hagy's (2002) an existing trophic network model, which had

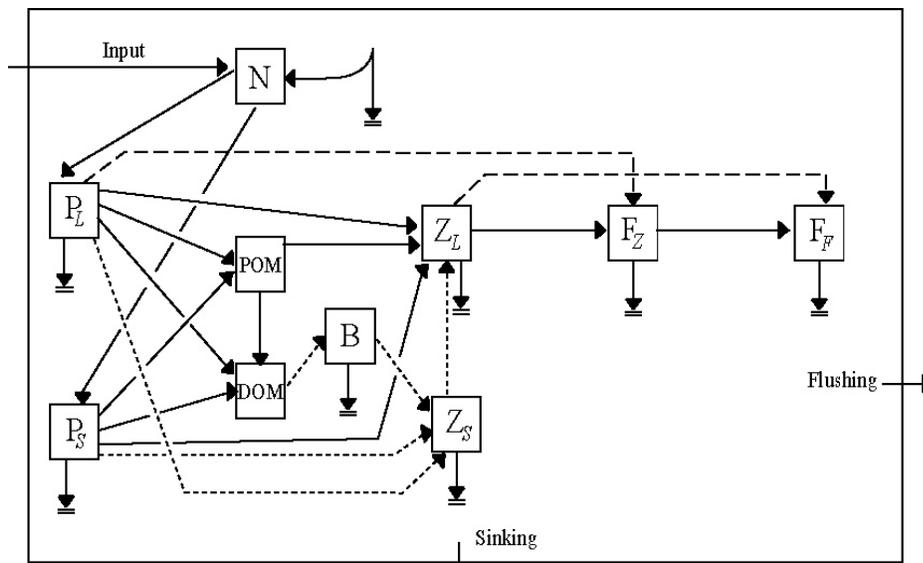


been developed for the main stem of Chesapeake Bay to represent average conditions in the upper, middle and lower estuary during the mid 1990s. Organisms at upper trophic levels were organized by taxonomic and functional groupings. Using the Ecopath software (Christensen and Pauly 1992), we were able to assign an average trophic level for each of the major species harvested in the

Fig. 1. State space describing mean trophic levels and fraction of diet supported by pelagic food webs (passing through planktonic herbivores) for major species and functional groups of organisms harvested in Chesapeake Bay based on data from mid 1990s (based on trophic network model of Hagy 2002).

fisheries (Fig. 1). We used a simple algorithm to compute the percentage of each species' diet originating from either pelagic herbivores or benthic detritivores or herbivores. Thus, we computed mean trophic level and fraction of diet as pelagic for each harvested species and plotted these in a two-dimensional state space (Fig. 1). For this analysis we adopted the conservative assumption that these did not vary over the last fifty years.

In parallel with our analyses of data on trends in estuarine fisheries and water quality, we have continued development and analyses of mechanistic models to simulate ecosystem trophic responses to interacting changes in nutrient loading and fishing pressure. Model structure follows standard formulations used in many estuarine and oceanographic simulations. This model focuses on the pelagic habitat, and includes up to ten state variables, including dissolved inorganic nitrogen, two functional groups of phytoplankton, two herbivorous zooplankton groups, two categories (dissolved and particulate) of organic detritus, bacterioplankton, and two functional groups of fish, planktivores and piscivores (Fig. 2). Specific simulations experiments were conducted with several simpler versions of the model, and an alternative "planktonic food-chain" version was also developed where two groups of gelatinous predators (1st and 2nd carnivores) were added in place of the planktivorous and piscivorous fish. Model simulations experiments were designed to examine decadal-scale responses to interacting changes in both nutrient enrichment and fisheries harvest. The model was calibrated such that steady-state model solutions approximated annual mean values for functional groups of organisms and chemical pools in Chesapeake Bay. The model simulates ecosystem dynamics for a spatially aggregated



estuarine region. External forcing functions were held constant, and simulation experiments were long enough to allow model variables to reach steady state values.

Fig. 2. Schematic of a pelagic ecosystem model, with state variables indicated by boxes and trophic pathways and nutrient fluxes by arrows. State variables = P_L : large phytoplankton; P_S : small phytoplankton; Z_L : herbivorous mesozooplankton; Z_S : protozooplankton; B: bacterioplankton; F_Z : planktivorous fish; F_F : piscivorous fish; N: dissolved inorganic nitrogen; POM: particulate organic matter; DOM: dissolved organic matter. Arrows with double underlining indicate respiration and imply recycling. Solid lines are standard food-chain pathways. Short dash lines indicate microbial loop pathways, while long-dash lines indicate additional trophic complexity or food-web pathways.

B. Project management: List individuals and/or organizations actually performing the work and how it was done.

Climatic Forcing of Phytoplankton Dynamics (Task 1)

L.W. Harding, Jr. (Co-P.I.)	8%
J.E. Adolf (Postdoctoral Scientist)	100%
M.E. Mallonee (Faculty Research Associate)	20%
D.W. Miller (Graduate Student)	Partial support
Miranda Hoover (Undergraduate)	NSF intern program

Patterns in the distribution and dynamics of zooplankton (Task 2)

M. Roman (Co-PI)	15%
Dave Kimmel (Assistant Research Scientist)	50%

Fish distribution and community production tasks (Task 3 and 5)

T. J. Miller (Co-PI)	15%
D. B. Bunnell (2002-2004)	100%
D. Loewensteiner (Faculty research assistant)	33%
O. P Jensen (graduate student)	partial support
K. L. Curti (graduate student)	partial support

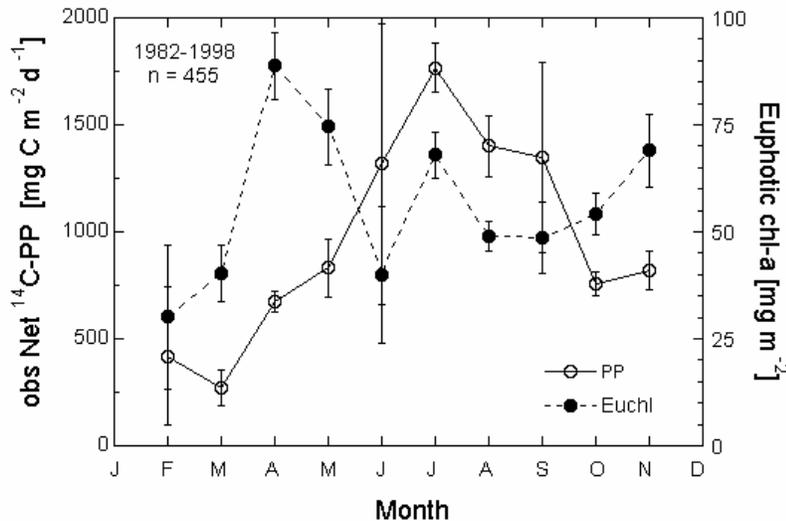
Variability in fish growth and recruitment tasks (Task 4)	
E. D. Houde (Co-P.I.)	15%
Sukgeun Jung (Assistant Research Scientist)	50%
John Bichy (Faculty Research Assistant, 2002-2004)	33%
Adriana Hashinaga (Faculty Research Assistant, 2005)	25%
Edward Martino (graduate student)	partial support
Robert Wood (NOAA Chesapeake Bay Office collaborator)	
Forecasts of fish community structure (Task 6)	
W. R. Boynton (Co-PI)	5%
J. Anderson (Assistant Research Scientist)	50%
Forecasts of ecosystem properties (Task 7)	
W. M. Kemp (Co-PI)	15%
Maureen Brooks (Graduate Student)	100%

VI. Findings

A. Actual accomplishments and findings.

TASK 1: Patterns of timing and distribution of primary production

In the past two years with NOAA CSCOR funding, the phytoplankton component of this ‘synthesis and forecasting research’ project in Chesapeake Bay has addressed the goal of developing predictive capabilities for seasonal and inter-annual variability of phytoplankton composition, biomass, and primary productivity (PP). Our work builds on more than a decade of progress in defining the roles of freshwater flow and nutrient loading on the distribution and



abundance of phytoplankton in the Bay, using shipboard measurements coupled with aircraft and satellite remote sensing.

Figure 3. Annual cycles of euphotic-layer chl-a and net PP for Chesapeake Bay (from Harding *et al.*, 2002).

Coarse seasonal resolution of the annual cycle of phytoplankton productivity is captured in a ‘textbook’ view of PP and euphotic-layer chl-a from Harding *et al.* (2002) depicted in Figure 3, illustrating a spring

biomass peak displaced several months from a summer PP maximum. This view was developed from the compiled data for >70 cruises spanning nearly two decades. Annual integral production (AIP) computed from such input data show a strong relationship to winter-spring loading of total nitrogen (TN) and total phosphorus (TP) that explains over 62% of the variance of AIP (Figure 4).

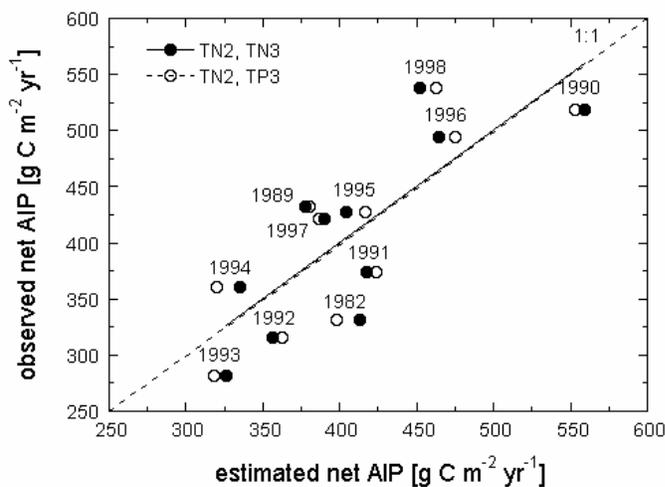
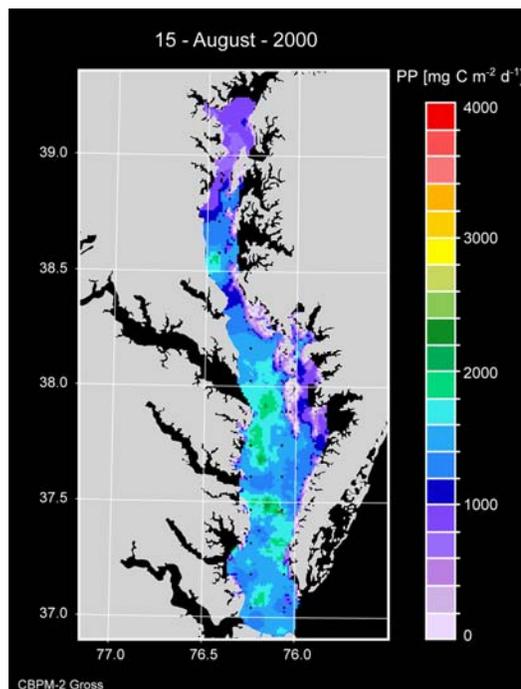


Figure 4. Simple, linear regression of observed AIP for 11 years on estimates from two models of nutrient loading. Closed circles are model outputs for TN loading in February and March of a given year; open circles are model outputs for TN loading for February and TP loading for March (negative sign); $r^2 = 0.62$, $p < 0.001$.

During CSCOR, we have moved to finer resolution than the shipboard data that were used to generate these figures. Our goal was to alleviate the undersampling of the Bay by augmenting inputs with remotely sensed data. DIMs we developed from shipboard data were applied to remotely sensed observations of the Chesapeake Bay Remote Sensing Program (<http://www.cbrsp.org>) for the period 1989-2005. Figure 5 shows an example of a spatially explicit PP output for one airborne ocean color survey on 15 Aug 2000. We have applied the DIMs to a combination of data from >400 flights and cruises and are using the outputs to refine our estimates of seasonal and interannual variability of PP, and to develop a predictive capability. We are also using DIMs in concert with historical data for the post-World War II period, following on our trend analysis for *chl-a* covering the same period.

Figure 5. Bay-wide PP from CBPM-2 applied to airborne ocean color data, 15 Aug 2000

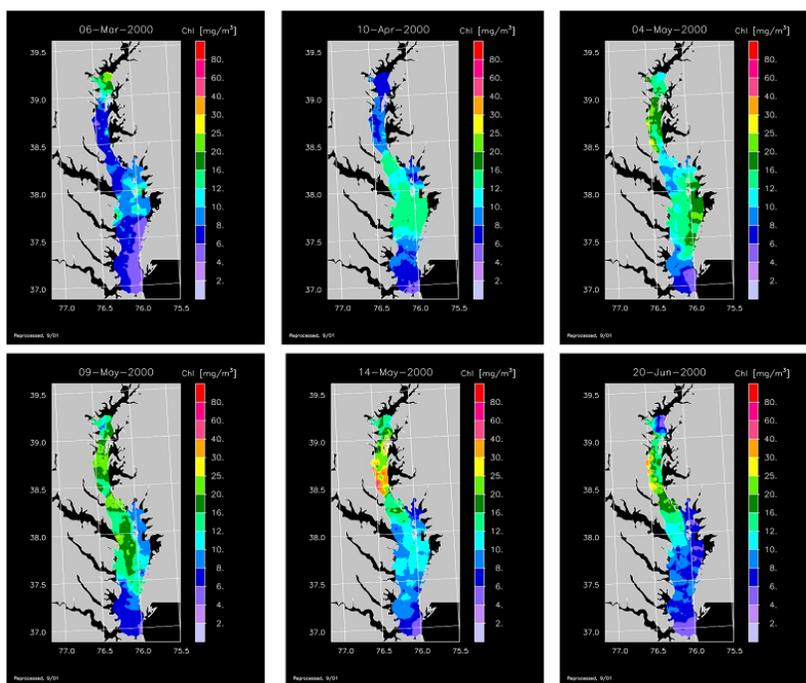


New data to support these analyses have come from aircraft remote sensing using SAS on flights over the main stem of Chesapeake to measure *chl-a* and sea surface temperature (SST). The Chesapeake Bay Remote Sensing Program consists of >20 flights per year and a companion program has conducted 8-12 flights per year on two tributaries of focus, the Choptank and Patuxent Rivers River

(<http://www.cisnet-choptank.org>). A NASA-supported component of the ACE INC program in which we have participated supports these flights, maintaining a now 17-year time series that has generated data of high spatial and temporal resolution for key ecosystem properties such as *chl-a* and PP. Examples of a spring to early summer series of *chl-a* distributions from aircraft remote sensing reveal the development of phytoplankton biomass in a year of moderate flow (Figure 6). Additional panels illustrate spring and summer phytoplankton blooms of diatoms and dinoflagellates (Figure 7), and a compilation of imagery for wet and dry years showing the contrasting *chl-a* distributions accompanying each climatic regime (Figure 8).

We used data from a number of research cruises to characterize phytoplankton dynamics and bio-optical parameters of the water column were conducted on seven occasions in 2003. Three cruises (April, July, and October) were conducted on the Choptank and Patuxent Rivers in association with ACE INC. Four cruises (April, August, October, November) were conducted on the main stem Chesapeake Bay in conjunction with related projects, including NSF Biocomplexity in collaboration with Bess Ward, NSF MOVE with Eric Wommack and Wayne Coats, and NSF Small Grants Emergency Response (SGER) that supported a post- Hurricane Isabel cruise.

Figure 6. Chlorophyll (*chl-a*, mg m^{-3}) distributions in Chesapeake Bay from aircraft remote sensing of ocean color using SAS III for six dates in spring-summer 2000.



The first set provided coverage of the main stem Bay and adjacent coastal waters; the second set gave coverage of the Choptank and Patuxent Rivers concurrent with surveys of physical properties (Boicourt), zooplankton sampling (Roman), and fish trawls (Houde); a third set sampled the Bay before and after passage of Hurricane Isabel in fall 2003 to measure changes in plankton and fish communities associated with this strong storm.

Bio-optical measurements on all cruises supported the remote sensing efforts and included: (a) *chl-a*, (b) particulate absorption, (c) CDOM absorption and fluorescence; (d) seston; (e) HPLC pigment determinations; (f) in-water profiles of downwelling irradiance and upwelling radiance from a suite of instruments to recover remote sensing reflectance; (g) sun photometer measurements for atmospheric turbidity. The optical instruments for profiles included a Satlantic hyperspectral tethered radiometer buoy (TSRB) and two profilers, a Biospherical Instruments MER-2040 and a Satlantic MicroPro. Deployment of these instruments is supporting QA/QC of radiometry and comparisons with satellite and aircraft recoveries of key ecosystem properties.

The Chesapeake Bay group has applied recently published models of PP (Harding *et al.*, 2002) to the complete time-series of remote sensing data to generate spatially explicit outputs of PP for the main Bay. These data are now being analyzed to develop predictive capabilities for this integrative indicator of ecosystem function for the Bay. The specific approach combines data on freshwater input and nutrient loading to the estuary with the >400 time point data set developed from the remotely sensed data and models applied thereto. We reported progress at an international symposium on primary productivity in the oceans in Bangor, Wales in March 2002. Measurements of PP on the main stem Bay and tributary cruises were conducted throughout 2002 to obtain validation data for model outputs and the data are now being processed and analyzed. Progress on this aspect of our work supported presentations at the EaGLes meeting

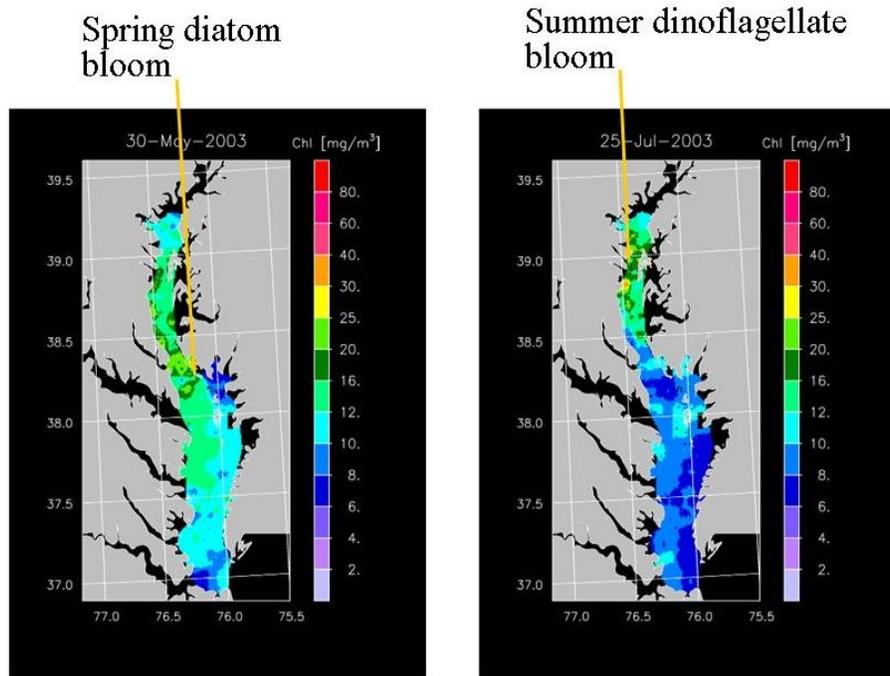


Figure 7. Examples of spring diatom and summer dinoflagellate blooms detected by aircraft remote sensing of ocean color.

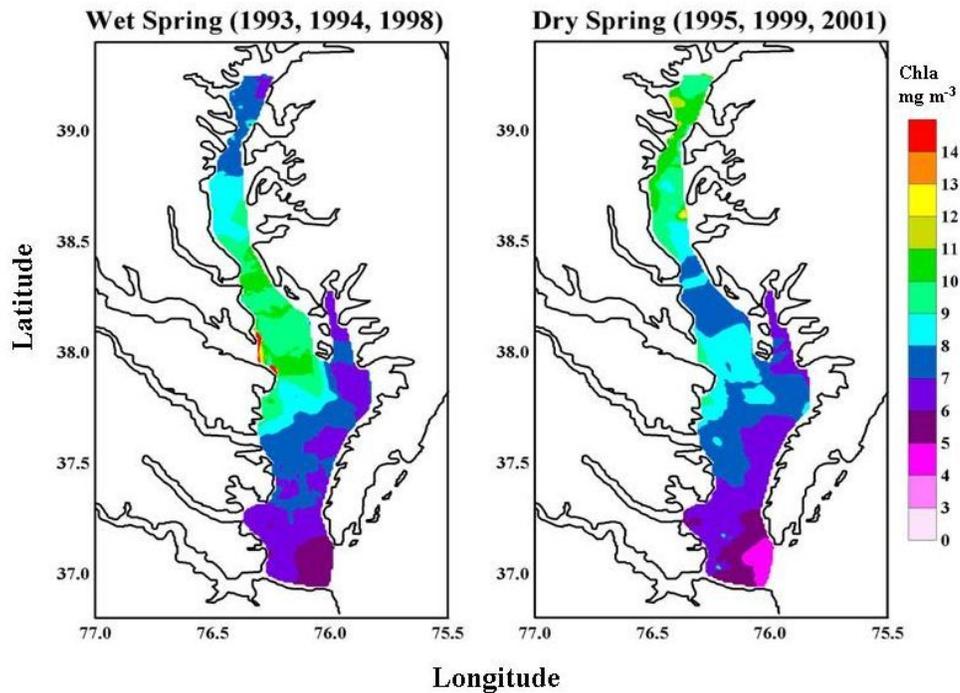


Figure 8. Composites of chl-a for wet and dry springs from aircraft remote sensing data, showing contrasting distributions for distinct climatic conditions.

in Bodega Bay in December, at ASLO/TOS in Honolulu in February, for the IAN and Horn Point Laboratory seminar series in October 2004 and April 2005, a set of presentations at ERF in Norfolk in October, and a number of publications listed here.

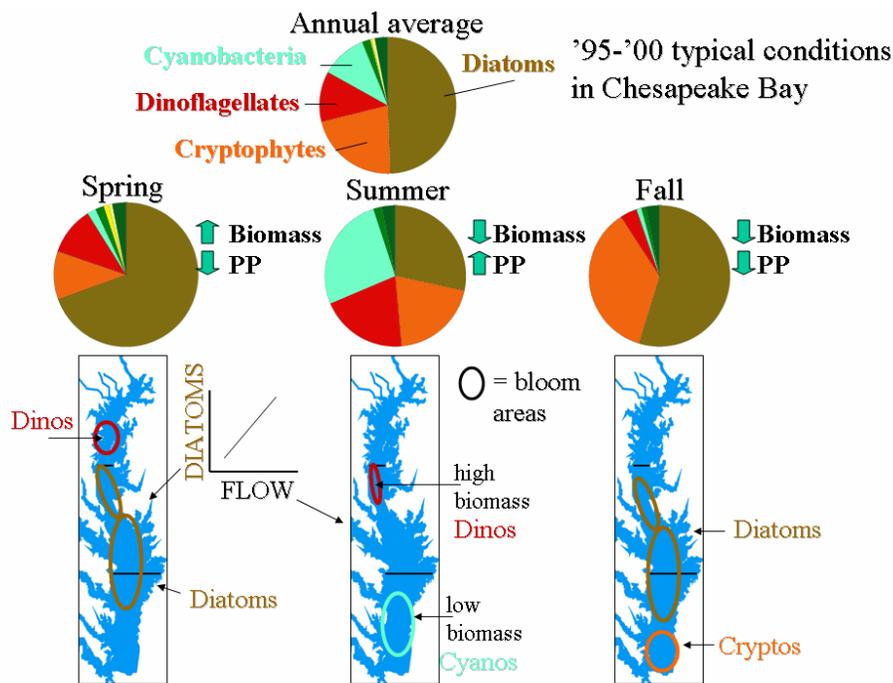


Figure 9. Conceptual diagram showing 'typical' conditions of phytoplankton floral composition, chl-a biomass, and primary productivity in the main stem of Chesapeake Bay. These conditions represent long term averages derived from the LMER TIES dataset (1995-2000).

In the remaining space, we will highlight two publications that were supported in part by CSCOR funding. A paper that will soon appear in *Estuarine, Coastal and Shelf*

Science (Adolf *et al.*, 2006) significantly extends our understanding of physical forcing of Bay phytoplankton. We focused on *chl-a* biomass (mg m^{-3}), floral composition (as fraction of *chl-a* - *f_chl-a* - attributable to specific taxonomic groups), and community size structure as phytoplankton indicators, each of which conveys an independent aspect of phytoplankton dynamics (Figures 9, 10). Major issues addressed include: (1) quantifying the responsiveness of these indicators to environmental variability, focusing on freshwater flow and nutrient loading from the watershed; (2) analyzing the relationships among these indicators, *i.e.*, how floral composition, biomass, cell size distribution, and primary productivity co-vary and are forced by similar environmental drivers; (3) detailing the ramifications for ecosystem function. *Chl-a* biomass is generally regarded as a good indicator of trophic status, as *chl-a* tends to increase as a function of nutrient loading. Floral composition and cell size distribution serve as 'qualitative' descriptors of the phytoplankton biomass captured in *chl-a* measurements, which may impact the fate of phytoplankton biomass captured in our *chl-a* measurements. Further, floral composition and size structure of the phytoplankton can potentially respond to environmental forces that do not affect *chl-a* biomass. Coincident data for *chl-a* biomass, floral composition, and size structure can be used to estimate fates of phytoplankton, such as sedimentation (*i.e.*, high biomass, large diatoms) or HAB formation (*i.e.*, high biomass, high % dinoflagellates).

Adolf *et al.* (2006) used sophisticated statistical approaches to explain variability of floral composition in the Bay. Figure 10 (a, b) presents the results of classification and regression trees (CART) applied to these data. CART sorts the response variable according to splits that can be found in the predictor variables, with the goal of producing terminal nodes within which the deviance of the response variable is minimized. Note that in the upper graph (regions 1, 2, 3), the lowest values of $f_chl-a^{diatoms}$ were to the right of the sea surface temperature (TEMP) split, suggesting that in this portion of the Bay, warmer springs were associated with lower values of

the fraction of *chl-a* comprised by diatoms, $f_chl-a^{diatoms}$. In the lower graph (regions 4, 5, 6), the lowest values of $f_chl-a^{diatoms}$ were to the left of the Susquehanna R. flow (SRF) split, and then to the right of the TEMP split. These findings suggest that low values of $f_chl-a^{diatoms}$ were associated with low SRF and relatively high TEMP. It is important to note that the absolute values chosen for splits in CART analyses should be viewed cautiously, but the nature of the relationships between predictors and response variables nonetheless yields important

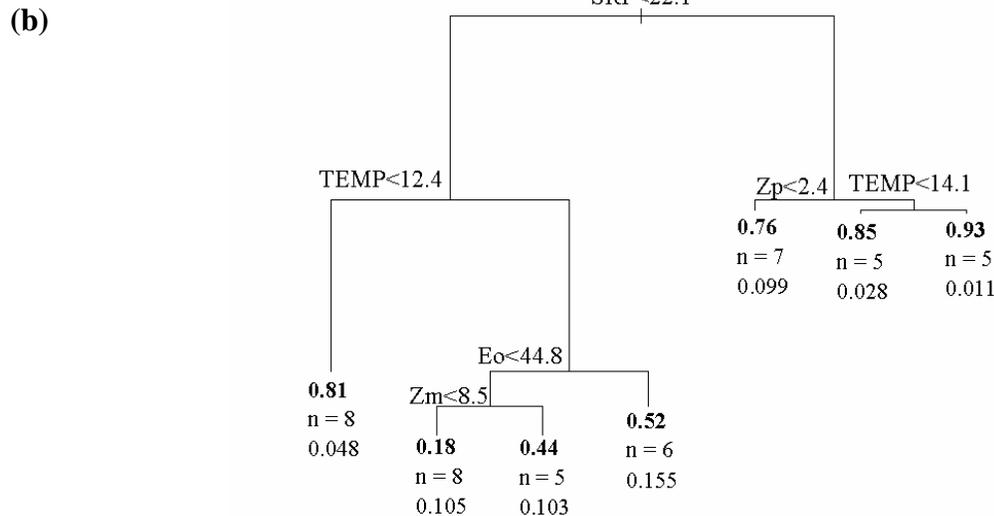
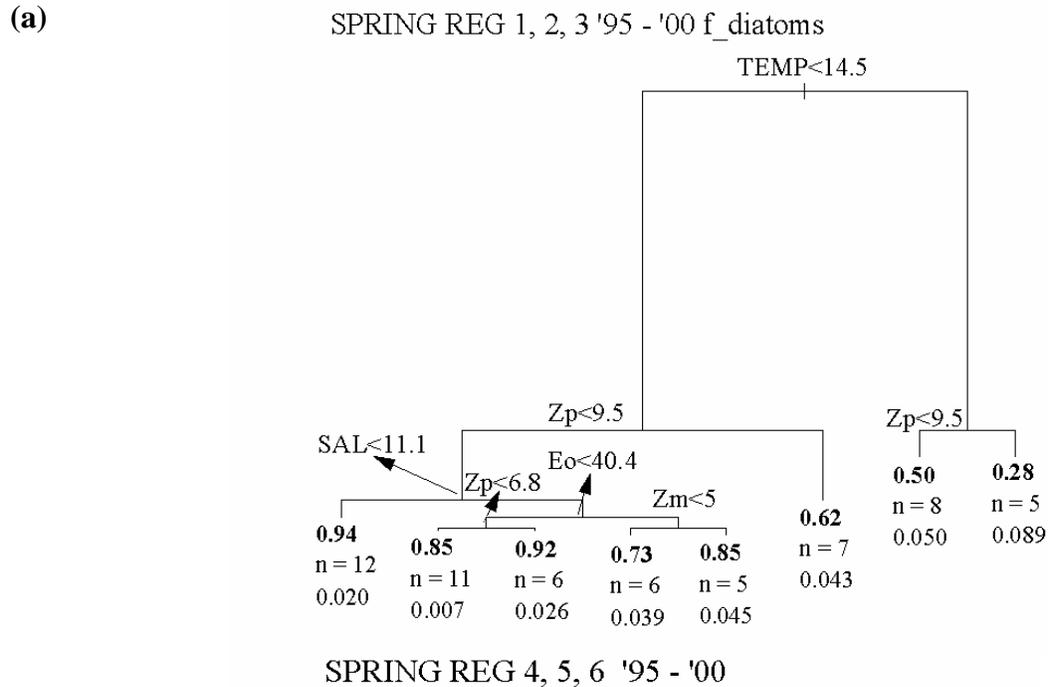


Figure 10 (a, b). Regression tree with $f_chl-a^{diatoms}$ as the response variable and Susquehanna River flow (SRF), Z_m , Z_p , salinity (SAL), and water temperature (TEMP) as predictor variables. The average value, n , and deviance of the response variable are shown at the terminal nodes.

information. Figure 11 (a, b) shows the predicted values of $f_chl-a^{diatoms}$ plotted against the observed values to give an idea of how well the data were classified using this technique.

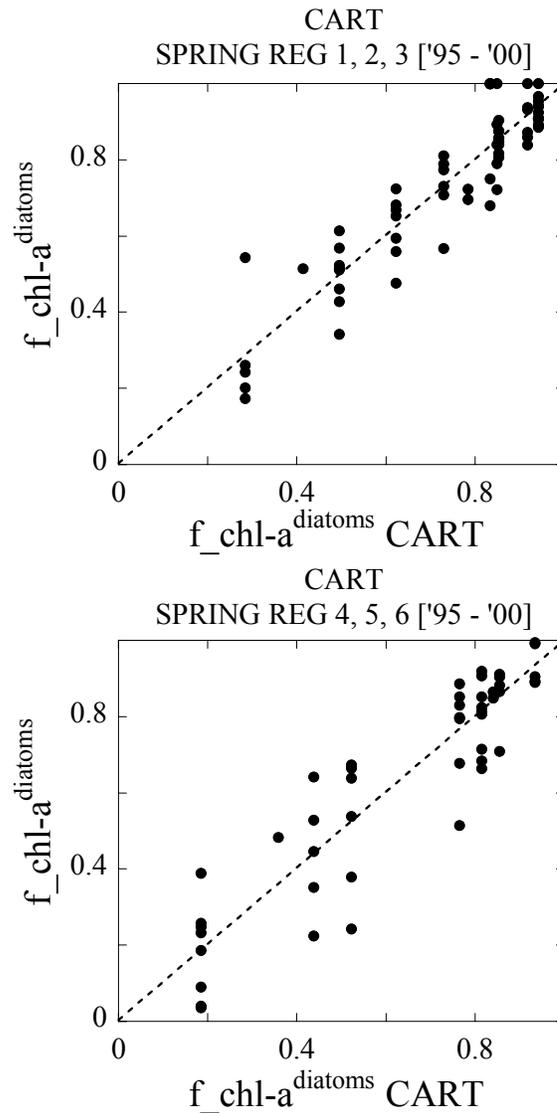
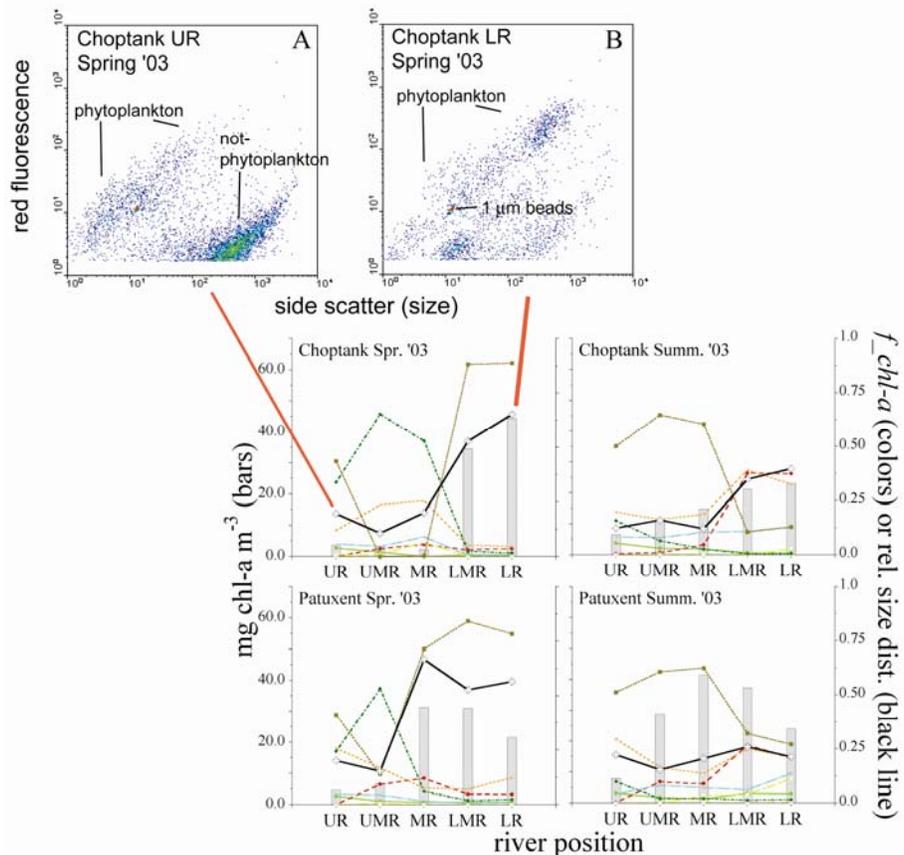


Figure 11 (a, b). Scatter plots of predicted (X-axis) vs. observed (Y-axis) $f_chl-a^{diatoms}$.

The central finding from the CSCOR project leading to this paper is that the main stem of Chesapeake Bay is a diatom-dominated system wherein seasonal variability of temperature and Susquehanna River flow (SRF) explains most of the annual variability of floral composition. Specific combinations of floral composition, *chl-a* biomass, and PP characterize the ‘seasons’. Our analysis of a six-year dataset showed that each season was characterized by regional blooms of recurring taxa related to trophic gradients in the main stem of the Bay. Interannual variability of phytoplankton dynamics in spring and summer was driven primarily by freshwater input that stimulated diatoms. Thus, diatoms were highly responsive to large-scale nutrient inputs such as those associated with freshwater inputs. These responses were most pronounced in the lower Bay

in summer where high SRF precipitated a floral shift from picoplanktonic ($<3 \mu\text{m}$) cyanobacteria to larger diatoms.

Figure 12. Spring and summer chl-*a* biomass (bars, mg m^{-3}), floral composition (colored lines, fraction of chl-*a* - $f_{\text{chl-a}}$), and relative size distribution (heavy black line). Taxa are represented by colors: diatoms (brown), chlorophytes (green), dinoflagellates (red), cryptophytes (orange), cyanobacteria (blue), haptophytes (yellow). Panels A and B show representative 'cytograms' from assemblages dominated by: (A) small and (B) large cells.

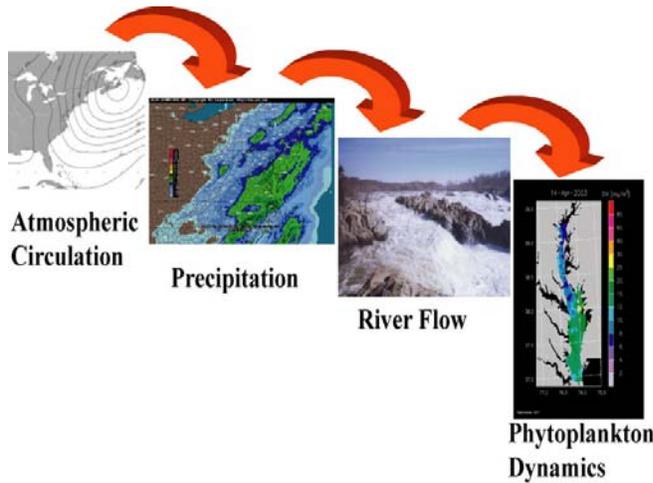


New data were obtained in 2002 and 2003 from a series of cruises on the Choptank and Patuxent Rivers as part of ACE INC. We added flow cytometer measurements of phytoplankton community size distribution to core measurements of biomass and floral composition in 2003. Figure 12 illustrates seasonal relationships among floral composition, *chl-a* biomass, and cell size distribution.

Relative size distribution was measured with a Becton Dickinson FACSCalibur flow cytometer, using an empirical algorithm developed in an REU Fellowship project (Miranda Hoover, Wittenburg University) to relate side-scatter to cell size. Here, the size distribution is scaled between 0 and 1 for presentation. High flow in spring 2003 pushed biomass distributions toward the mouths of each river where phytoplankton were characterized by relatively large diatoms. The average cell size of phytoplankton was smaller in summer than in spring. The advantage of combining these different phytoplankton indicators is that community size distribution associated with diatom assemblages in spring (*i.e.*, large cells) and summer (*i.e.*, small cells) carries different ecological ramifications for the fate of algal biomass. Future studies will attempt to quantify relationships between phytoplankton and higher trophic levels, drawing on biomass, floral composition and size distribution data measured in this study.

A recent focus of our research addresses the role of synoptic-scale weather in determining spatial and temporal variability of phytoplankton biomass in Chesapeake Bay, as shown in the conceptual diagram of Figure 13. On seasonal to interannual time scales, much of the environmental variability is related to differences in regional-scale weather patterns. Surface *chl-a* values collected as part of CBRSP from 1989-2002 have been used to calculate monthly, average *chl-a* for various regions of the Bay that experience similar salinity, nutrient, and light attenuation conditions. *Chl-a* is expressed as anomalies from long-term monthly mean conditions

by region to determine the response of the ecosystem to the various synoptic-scale weather patterns. Figure 14 shows *chl-a* anomalies for the period of record from a region near the mouth of the Bay. A synoptic climatology provides a mechanism to classify and quantify weather



variability on smaller spatial and temporal scales than basin-scale climate indices such as NAO or ENSO that do not have a

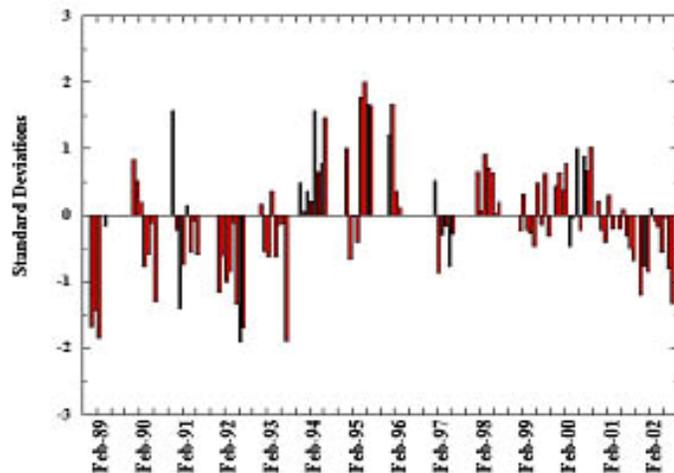
Figure 13. Conceptual links of atmospheric circulation, precipitation, river flow, and phytoplankton dynamics.

proximate influence on the Chesapeake Bay region. Figure 15 shows the output of a synoptic climatology for the region encompassing most of the weather patterns that Chesapeake Bay experiences. Each of these patterns has a relatively consistent set of weather conditions associated with it in

terms of cloud cover, temperature, wind speed and direction, and precipitation. The frequency of occurrence of certain of these weather patterns in a given month, and deviations from the ‘normal’ condition, are being related to the *chl-a* anomalies to detect weather patterns that most influence surface *chl-a* and the quantify magnitude of the response.

Figure 14. Surface *chl-a* deviations from normalized mean monthly values for region 1 (Bay mouth) from 1989-2002.

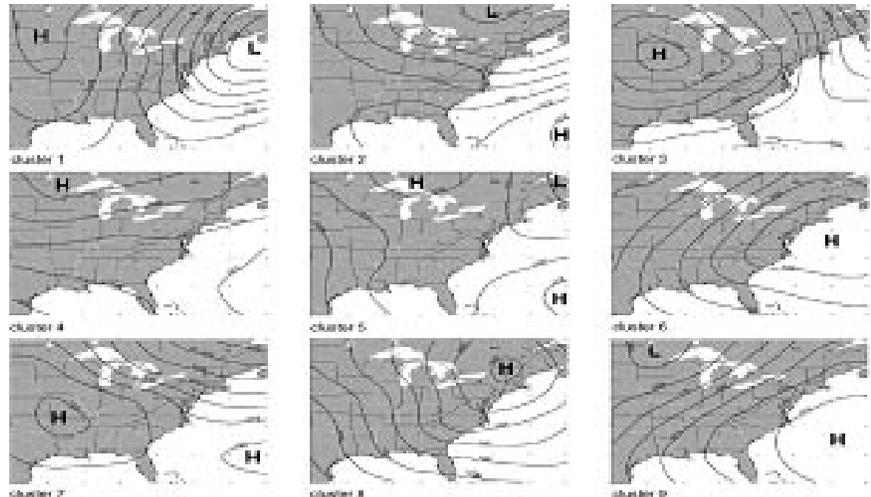
Dave Miller, a graduate student working in our group, has developed a ‘water balance model’ for the Susquehanna River basin, the primary freshwater source for Chesapeake Bay that will appear in *Water Resources Research* (Miller et al. 2006). Variability of freshwater flow from the Susquehanna R. influences phytoplankton biomass, particularly in the spring when nutrients and sediments associated with flow that



largely determine prevailing light and nutrient conditions in the Bay. By developing a water balance model that is forced by synoptic-scale weather patterns, we have been able to identify and quantify the type of weather that most strongly influences phytoplankton dynamics. The synoptic climatology is used as a statistical approach to classify and quantify variability in atmospheric circulation on a regional spatial scale. Each day’s weather is clustered into one of ten dominant patterns. These weather patterns have distinct meteorological conditions associated with them, including probability and amount of precipitation, temperature, and wind speed and direction. These parameters are then used in a water balance model to estimate freshwater flow from the river basin. This approach allows us to predict monthly to seasonal freshwater flow

based on earlier months' atmospheric circulation and thereby predict phytoplankton biomass on seasonal and regional time and space scales.

Figure 15. Results from a synoptic climatology using gridded daily average sea-level pressure data from 1989-2002.



Lastly, we are nearing completion of a paper (Miller and Harding, 2006) that links synoptic climatology to spring bloom dynamics in the Bay.

This is the core chapter in Dave Miller's Ph.D. Dissertation. It will be submitted to Marine Ecology Progress Series within a month.

TASK 2: Regulation of zooplankton distributions

The zooplankton group has developed several relationships between Chesapeake Bay hydrologic conditions and zooplankton dynamics. Kimmel and Roman (2004) describe the local environmental processes that force zooplankton dynamics. They found freshwater input into Chesapeake Bay to be a major driver of zooplankton dynamics, particularly during the spring. This period is critical for anadromous fish which spawn during the spring and their larvae which rely on zooplankton as a primary food source. Dominant year classes of striped bass and white perch are tightly linked to years of high freshwater input and high zooplankton biomass in the spring.

Other studies have determined that winter climate is tightly coupled to spring freshwater discharge into the Chesapeake Bay. We developed a model to predict spring freshwater input and its subsequent impacts on multiple trophic levels (phytoplankton and zooplankton) using a winter synoptic climatology. Miller et al. (2006) reports on this effort and found that a winter synoptic climatology model could predict 54% of the variance in spring freshwater input into Chesapeake Bay. This prediction of flow also allowed prediction of ecosystem response, including the size and location of the spring phytoplankton bloom and the abundance and species composition of zooplankton. These analyses were carried further by Kimmel et al. (2006) who showed that climate patterns are linked to zooplankton dynamics in the upper Chesapeake Bay. This work included some analysis of fish variability as well, showing how winter climate is related to spring abundances of anadromous fish and zooplankton.

TASK 3: Distribution of fish.

We applied GAM to develop forecasts of the distribution of all principal species in the TIES and CHESFIMS database and blue crab. To illustrate the efficacy of the approach, we present the results for predictions of blue crab distributions, together with the results of a cross validation exercise to assess the ability of models developed in one year to forecast predictions in other years.

Significant correlations were present among variables that affected blue crab distributions. Most notably, there was a strong and negative correlation ($r = -0.64$) between

salinity and distance from the Bay mouth. Moderately strong correlations occurred between salinity and temperature ($r = 0.34$), and between depth and bottom slope ($r = 0.28$). Although the correlations among the explanatory variables were often statistically significant, even the two most strongly correlated variables (salinity and distance from the Bay mouth) do not overlap entirely as salinity patterns are strongly influenced by freshwater flow from the western shore tributaries, which, combined with the Coriolis effect, results in a pattern of lower salinities in the western region of the Chesapeake Bay. Colinearity among the explanatory variables was not deemed sufficient to drop variables from the full models, but will be considered in the interpretation of model selection results.

All six explanatory variables were included as either significant main effects or in interaction terms in at least three of the final models; however, no variable occurred in all models. Distance from the Bay mouth and depth were the most commonly included variables. In stage I, distance from the Bay mouth was significant in 9 out of 13 years and depth was significant in all years. Distance from Bay mouth appeared in 10 out of 13 years for stage II models, while depth was included in 5 stage II models. Water temperature also appeared commonly in stage I, occurring in 9 out of 13 years, but was only found to be significant in 2 of the stage II models. Salinity was included in 8 years for stage I and in 2 years for stage II. Importantly, salinity was often included in stage I models when distance from the Bay mouth was not. The remaining two variables, bottom slope and distance from SAV, were not often found to be significant in either model stage.

Penalized regression spline fits of individual environmental factors to blue crab density varied from simple linear functions to highly complex curves. All other response curves are available at: <http://hjort.cbl.umces.edu/crabs/GAM.html>. A detailed description of the pattern in these figures, and the utility of the figures for understanding the distribution of blue crab are given by Jensen et al. (2005). Here, we focus on the validation of these models as this is the true test of the utility of this approach for forecasting.

Our models performed well under validation. Abundance was highly variable and more difficult to predict than distribution. Two-stage GAMs developed using the six habitat variables included in this study explained between 13% and 36% (mean $R^2 = 0.277$ - Table 1) of the variability in blue crab winter densities in the training data set. WDS samples were characterized by a large percentage (80-90%) of observations containing no mature female blue crabs, as well as a small number of very high-density samples. The two-stage models showed no evidence of bias and generally predicted realistic densities but underestimated the observed variability. For example, predicted log densities from the 1998 two-stage model showed a similar mean as the survey observations, with the linear regression of observed vs. predicted falling nearly coincident with the one-to-one line, but showed lower variability, i.e., fewer low- or zero-density predictions and a lower range of predicted values. Because of the relatively short tows (one minute), observed densities show a notable gap between tows with zero catches, and the lowest observed densities.

The mean R^2 for the intra-annual comparison was 0.192. Results for the intra-annual cross-validation showed that there was a significant difference in model performance between test data and training data (paired t-test, $p = 0.002$). The inter-annual cross-validation displayed substantial variation among years and was significantly less accurate than the intra-annual cross-validation (t-test, $p < 0.001$). The cross-validation table (Table 1) represents the ability of a model developed with data from one year (columns) to predict data from other years (rows), and it displays two different but related pieces of information. Examining the patterns within a column evaluates the characteristics of one model. Patterns within a row relate to the

Table 1. *Callinectes sapidus* . Cross-validation where models developed with data from one year (columns) are applied to data from another (rows). Values in (a) represent the cross-validation r-squared. Values on the diagonal (in bold for (a)) represent intra-annual cross-validation where models developed using a training data subset are applied to the test data subset for the same year. The first row of (a) represents the model fit to the training data. Values in (b) represent the z-score, i.e., the number of standard deviations above or below the grand mean Fisher (1915) transformed cross-validation correlation coefficient.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
training	0.299	0.315	0.255	0.296	0.270	0.130	0.314	0.241	0.346	0.232	0.305	0.360	0.239
1990	0.099	0.064	0.016	0.069	0.059	0.091	0.014	0.060	0.081	0.001	0.015	0.069	0.013
1991	0.028	0.219	0.048	0.135	0.174	0.071	0.128	0.071	0.195	0.043	0.148	0.009	0.086
1992	0.003	0.257	0.291	0.191	0.265	0.210	0.146	0.099	0.271	0.235	0.273	0.069	0.221
1993	0.129	0.188	0.128	0.238	0.113	0.089	0.113	0.090	0.165	0.022	0.047	0.031	0.125
1994	0.000	0.194	0.200	0.232	0.244	0.237	0.117	0.056	0.194	0.176	0.222	0.041	0.124
1995	0.010	0.032	0.040	0.063	0.095	0.086	0.016	0.008	0.040	0.023	0.048	0.010	0.014
1996	0.043	0.111	0.088	0.077	0.098	0.042	0.168	0.110	0.152	0.017	0.005	0.062	0.081
1997	0.087	0.165	0.095	0.171	0.097	0.055	0.129	0.197	0.172	0.024	0.097	0.054	0.110
1998	0.035	0.105	0.085	0.109	0.079	0.066	0.084	0.099	0.129	0.008	0.049	0.005	0.044
1999	0.000	0.155	0.236	0.157	0.139	0.174	0.108	0.088	0.176	0.196	0.205	0.080	0.184
2000	0.042	0.206	0.222	0.202	0.183	0.191	0.092	0.077	0.243	0.255	0.311	0.069	0.165
2001	0.078	0.184	0.108	0.080	0.121	0.009	0.129	0.078	0.166	0.036	0.054	0.228	0.087
2002	0.001	0.083	0.075	0.016	0.084	0.021	0.019	0.056	0.084	0.062	0.128	0.061	0.089

a

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1990	0.04	-0.43	-1.38	-0.36	-0.52	-0.06	-1.44	-0.50	-0.20	-2.10	-1.41	-0.37	-1.46
1991	-1.08	1.35	-0.69	0.48	0.89	-0.33	0.39	-0.33	1.11	-0.79	0.62	-1.61	-0.12
1992	-1.91	1.72	2.04	1.07	1.79	1.26	0.60	0.05	1.85	1.51	1.87	-0.37	1.37
1993	0.40	1.04	0.39	1.53	0.21	-0.08	0.22	-0.07	0.80	-1.22	-0.71	-1.03	0.36
1994	-2.16	1.10	1.16	1.47	1.59	1.53	0.26	-0.57	1.10	0.92	1.38	-0.82	0.35
1995	-1.58	-0.99	-0.84	-0.45	-0.01	-0.13	-1.37	-1.66	-0.84	-1.20	-0.70	-1.58	-1.43
1996	-0.78	0.20	-0.09	-0.25	0.03	-0.80	0.83	0.18	0.67	-1.36	-1.78	-0.47	-0.19
1997	-0.11	0.80	0.00	0.86	0.02	-0.58	0.41	1.13	0.87	-1.18	0.02	-0.59	0.18
1998	-0.93	0.12	-0.13	0.17	-0.22	-0.41	-0.15	0.04	0.40	-1.66	-0.68	-1.80	-0.77
1999	-2.28	0.69	1.52	0.71	0.52	0.89	0.15	-0.10	0.92	1.12	1.21	-0.21	1.00
2000	-0.80	1.22	1.38	1.18	0.99	1.07	-0.04	-0.25	1.59	1.70	2.22	-0.36	0.80
2001	-0.24	0.99	0.15	-0.21	0.32	-1.61	0.40	-0.23	0.81	-0.91	-0.60	1.43	-0.11
2002	-2.07	-0.17	-0.28	-1.39	-0.16	-1.25	-1.31	-0.56	-0.15	-0.46	0.39	-0.48	-0.08

characteristics of a particular data set. The column patterns show that apart from 1990 and 2001 all models yielded above average r values for at least four other years of data. This suggests that the models, though they differ in their individual parameters, do capture some general features of the blue crab habitat preference. The 1998 model displayed above average cross-validation r values for all years except 1990, 1995, and 2002. The other striking feature of the column patterns is that the 1990 and 2001 models yield below average r values for nearly all data sets except test data from the same year. The row patterns offer further information about inter-annual differences. The year 1990 is well predicted (i.e., above average r) only by the model from the same year. The data for 1995 is simply difficult to predict with any model. The 1994 data are well predicted by models from any year other than 1990, 1997, or 2001.

Task 4: Variation in fish recruitments and production

We developed statistical models relating bay anchovy recruitments to dissolved oxygen, freshwater input from the Susquehanna River, spatial location of adult stock, and adult stock biomass (Jung and Houde 2004b, a). Recruitment levels from 1995-2004 survey data (TIES, CHESFIMS, and 'Post-ISABEL' programs) varied nine-fold; a peak recruitment of >250 billion anchovies was observed in 1998 (Figure 16). A modified Ricker stock-recruitment

relationship was fit to data from 1995-2004, which demonstrated how the compensatory relationship between adult stock and recruitment also depended on intra-annual up-bay shifts in distribution of

adult anchovy biomass between spring months (before the spawning season) and summer (spawning season) (Figure 17). In years of high freshwater flow in the months preceding the spawning season, adult anchovy stock remains primarily in the lower Bay region during summer and mostly spawns there. Under that condition, recruitments tend to be high, apparently a consequence of successful spawning and high larval production in the lower Bay region.

In a synthesis-modeling framework, daily production of bay anchovy was estimated for years 1995-2004. There was approximately 4-fold variability in peak daily productions (Figure 18) among years (Jung and Houde 2004a). Highest productivities, biomass proliferation, and

Forecasting Bay Anchovy Recruitment

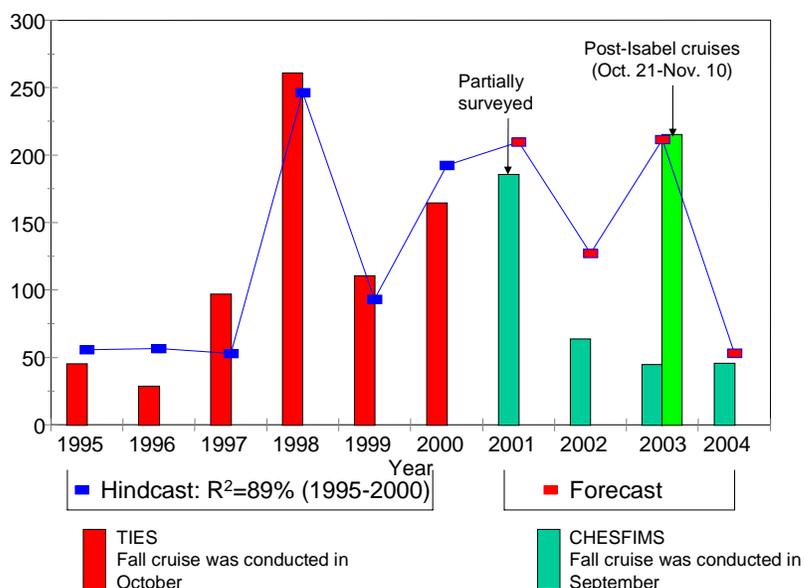


Figure 16. Recruitments of young-of-the-year bay anchovy in Chesapeake Bay from midwater trawl surveys conducted 1995-2004. Observed (bars) and modeled (symbols) recruitments are from baywide trawl surveys and a modified Ricker stock-recruitment model, respectively. The model includes adult stock biomass and ΔL , a measure of adult stock migration and location, as independent variables, which were fit to survey data from 1995-2000. Recruitments for 2001-2004 were forecast from the model. The annual survey cruises in 2001-2004 were conducted in September; cruises in 1995-2000 had

Stock-recruitment model for Bay Anchovy (1995-2003)

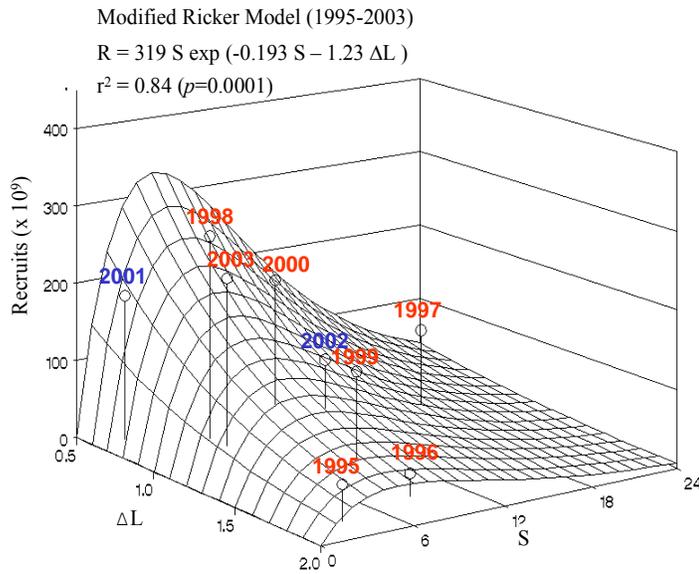
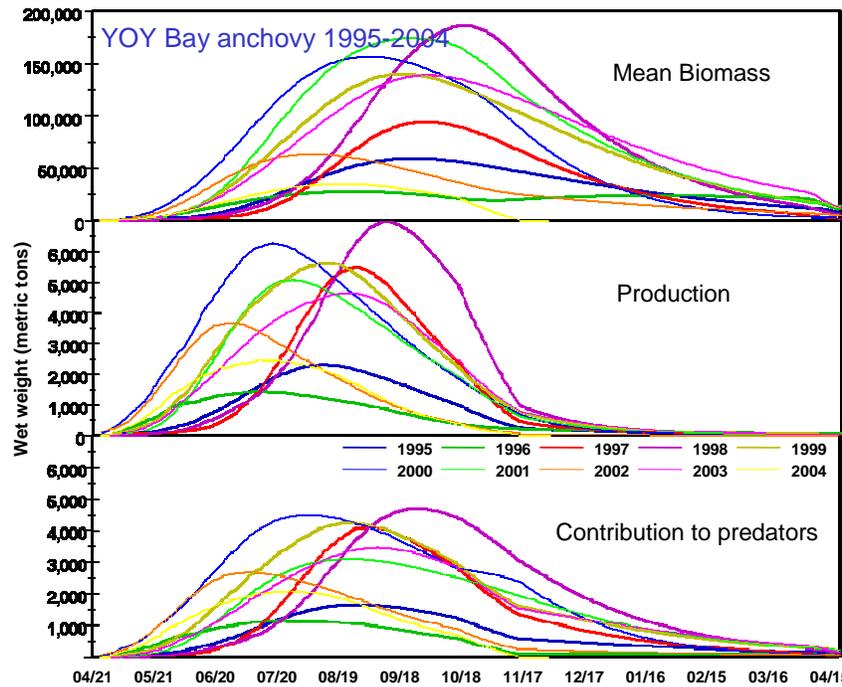


Figure 17. Modified Ricker stock-recruitment model, Chesapeake Bay, 1995-2003. ΔL = upbay migration (expressed as decimal degrees of latitude) of adult stock between spring (pre-spawning) and summer (spawning) period. SSB = adult spawning stock biomass (tons $\times 10^3$). Recruitment data for years 2001 and 2002 are included in the model; however, the survey cruises in these years were conducted in September (before age-0 anchovy are fully recruited to the gear), rather than October (remaining years). Spawning stock biomass and ΔL data are from TIES and CHESFIMS programs.

consumption by predators of pre-recruit (age-0) anchovy occurred in 1998, 1999, and 2000; lowest productivities were observed in 1996 and 1995 (Table 2). The dates of peak production of pre-recruit bay anchovy varied among years, ranging from late June to early September.

Recruitment levels of bay anchovy from 1995 to 2000 were found to be inversely correlated with sub-pycnocline mean dissolved oxygen (DO) levels during summer months.



This non-intuitive

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Figure 18. Estimated daily production of young-of-the-year bay anchovy, years 1995-2004. Estimates derived from observed larval size and abundance data and applied size-based growth and production theory. Modeling and analytical approaches are given in Jung and Houde (2004a).

Table 2. Baywide estimates of annual biomass, production and contribution to predators by young-of-the-year bay anchovy in Chesapeake Bay from 1995 to 2004. Mean standing stock biomass (\bar{B}), production to mean biomass ratio (P/\bar{B}) of YOY bay anchovy including larval stages, and the dates of maximum (= peak) daily standing stock biomass, daily production, and daily contribution to predators (C). In addition, the P/\bar{B} ratio applied only to individuals > 21 mm TL is estimated. The unit of \bar{B} , P and C is wet weight in 10³ metric tons. CV is coefficient of variation (%).

YEAR	April –October				November- April				Total for a year					Peak Date		
	\bar{B}	P	C	P/\bar{B}	\bar{B}	P	C	P/\bar{B}	\bar{B}	P	C	P/\bar{B}	P/\bar{B} (> 21 mm TL)	B	P	C
1995	30	231	179	7.58	26	15	58	0.56	28	246	237	8.64	6.96	09/25	08/14	08/28
1996	17	164	147	9.57	22	17	15	0.78	19	182	162	9.34	6.34	08/27	06/26	07/10
1997	36	441	359	12.14	30	23	99	0.75	34	464	457	13.77	9.68	09/30	08/21	08/28
1998	64	581	393	9.10	67	50	226	0.74	65	631	618	9.68	8.01	10/24	09/11	09/24
1999	76	592	475	7.76	52	42	146	0.82	64	634	621	9.86	7.82	09/19	08/13	08/20
2000	99	676	559	6.84	29	30	144	1.03	64	707	703	10.98	8.49	09/04	07/16	08/05
2001	100	520	363	5.21	56	35	166	0.62	77	555	529	7.18	6.28	09/23	07/25	08/25
2002	40	334	304	8.36	14	3	26	0.18	27	337	330	12.28	8.64	08/06	06/26	06/26
2003	69	514	385	7.44	67	46	152	0.69	68	560	537	8.23	6.45	10/02	08/27	09/06
2004	20	257	240	12.79	27	18	64	0.69	23	276	304	11.92	7.45	08/23	06/28	07/13
Mean	55	431	340	8.68	39	28	110	0.69	47	459	450	10.19	7.61	09/15	07/30	08/12
CV	55.6	40.5	37.5	26.9	49.4	54.8	62.3	31.7	47.6	40.6	40.6	20.0	14.9			

production during low DO years that is related to high plankton productivity, i.e., low mean DO is associated with high plankton production (anchovy prey) (Jung and Houde 2004b).

Collaborative research with the NOAA Chesapeake Bay Office (collaborator Robert Wood) demonstrated significant effects of climatologies on adult anchovy distributions (Figure 19) in which distributions were demonstrated to differ significantly in wet and dry years (Wood et al. 2004). These differences help to explain why the modified Ricker stock-recruitment model that includes adult distribution parameters (Figure 17) accounts for a large fraction of the variance in observed anchovy recruitment levels (Jung and Houde 2004a).

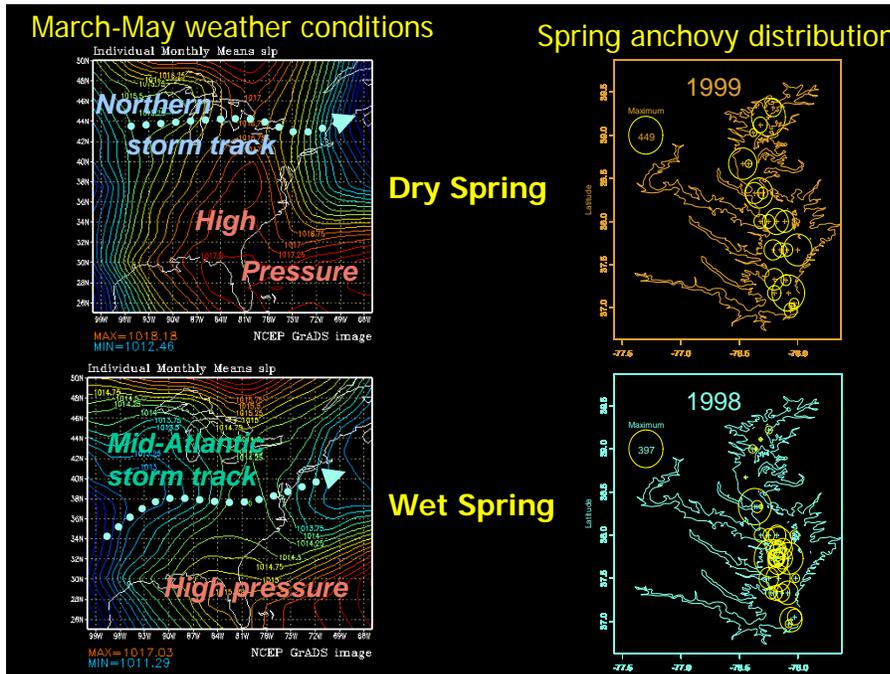


Figure 19. Examples of wet (1998) and dry (1999) spring conditions and observed distribution of adult bay anchovy in April-May trawl surveys (TIES Program). Dry years are characterized by atmospheric high pressure over the Chesapeake Bay, while wet years are characterized by atmospheric low pressure in the Mid-Atlantic region.

In analysis of larval bay anchovy data from a five-year series (1995-1999) (Auth 2003; TIES data), larval abundances and mean growth rate were found to be positively, although not significantly, correlated with recruitments in the limited (5-year) time series. Larval growth rates and feeding incidences varied annually and both were strongly correlated with zooplankton abundance. Feeding incidence of anchovy larvae (July) was strongly and significantly correlated with anchovy recruitment (October). It is difficult to evaluate significance in a 5-year time series, but all measures of larval anchovy feeding, growth, and prey (zooplankton) abundance in July were positively correlated with recruitment of YOY anchovy in October (Auth 2003), suggesting strong affinities between high plankton productivity and anchovy recruitment success.

In addition to bay anchovy and striped bass, we made progress in analysis and modeling of recruitment and production of other fish species by evaluating a suite of environmental variables that includes freshwater flow, dissolved oxygen, temperature, and prey levels. Our exploratory modeling and correlation analyses suggest that recruitment levels of some species are related to environmental variables or to a strong predator-prey linkage, e.g., the correlation between predatory young-of-the-year weakfish (*Cynoscion regalis*) abundance and bay anchovy biomass (prey) for years 1995-2003 (Figure 20).

In collaborative research (NOAA Chesapeake Bay Office, with Robert Wood), we began to explore causes of variability in Atlantic menhaden (*Brevoortia tyrannus*) recruitments in response to variable climatology (Wood et al. 2004). A modified Ricker stock-recruitment model with March temperature as an added variable accounted for only 22% of the observed coastwide recruitment variability, but inclusion of a climatology variable representing frequency of ‘Bermuda High’ atmospheric pressure conditions in March accounted for 44% of the recruitment variability. Addition of climatology information in forecasting (or hindcasting) recruitment variability is a promising approach that integrates environmental variability and adds forecasting power.

Our research conducted in this COP Program confirmed that recruitment of striped bass is correlated with the magnitude of spring freshwater flow into upper Chesapeake Bay (Figure 21). Other environmental factors also are important in controlling recruitment levels. Stock-

Striped Bass
YOY Recruitment Index: Upper Chesapeake Bay, 1989-2003

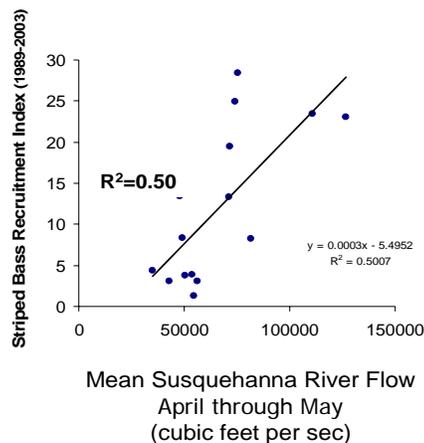


Figure 21. Striped bass. Young-of-the-year recruitment levels (1989-2003) indexed in September (Maryland DNR seine-survey data in relation to river flow in April-May Data available at.: <http://www.dnr.state.md.us/fisheries/juvindex/amweb.xls>)

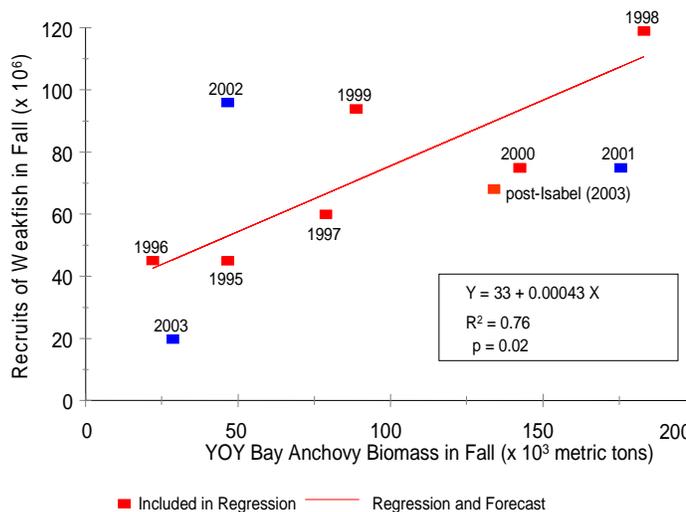


Figure 20. Young-of-the-year recruitment levels of weakfish and bay anchovy in Chesapeake Bay from TIES and CHESFIMS midwater trawl surveys, 1995-2003. Surveys from 1995-2000 were conducted in October. Surveys in 2001-2003 were conducted in September, before age-0 anchovy are fully recruited to the gear, and are not included in the regression. The ‘post-hurricane Isabel survey (Oct-Nov 2003) data are included in the regression.

recruitment modeling indicated that spring water temperatures in weeks preceding the spawning season, combined with adult stock biomass, play a role in controlling recruitment levels (Figure 22).

Three additional approaches were taken to identify and explain processes that control or regulate recruitment of striped bass: 1) an analysis of larval-stage ecology and bio-physical interactions in the upper Chesapeake Bay; 2) analysis of juvenile-stage growth and survival; and 3) evaluation of maternal influences on recruitment potential. Analysis and modeling employing these approaches are continuing.

Striped Bass (1995-2003)

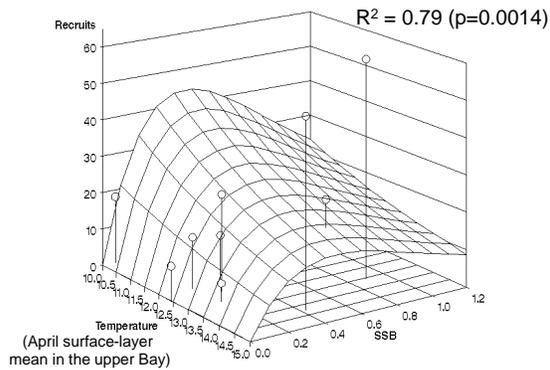


Figure 22. Modified Ricker stock-recruitment model for upper Chesapeake Bay, 1995-2003, with spawning stock biomass (SSB) and April water temperature as independent variables. Adult stock biomass as catch-per-unit effort from Maryland DNR gillnet surveys. Recruits are age-0 juveniles in the Maryland DNR summer seine survey (<http://www.dnr.state.md.us/fisheries/juvinde/amweb.xls>)

In years 2001-2003, feeding-stage larval densities differed among years: larval concentrations were lowest in 2002, 10X higher in 2001, and 1000X higher in 2003, and indicated higher egg and larval-stage survival in 2001 and 2003, the stronger recruitment years. Highest larval survival and young-of-the-year (YOY) recruitment were associated with the highest freshwater flow, observed in 2003. Larval growth rates were highest in 2003, the year of highest recruitment success (Martino and Houde 2004). YOY recruitment (in September) can be described by a simple multiple regression of freshwater flow and water temperature in spring months preceding the spawning season (Figure 17). This relationship may have potential for forecasting YOY striped bass abundances; the YOY abundances in 2004 and 2005 were forecast successfully from flow and temperature variables in 2004 and 2005 (Figure 23).

Striped Bass Predicted and Observed Age-0 Recruitment Strength, Upper Chesapeake Bay

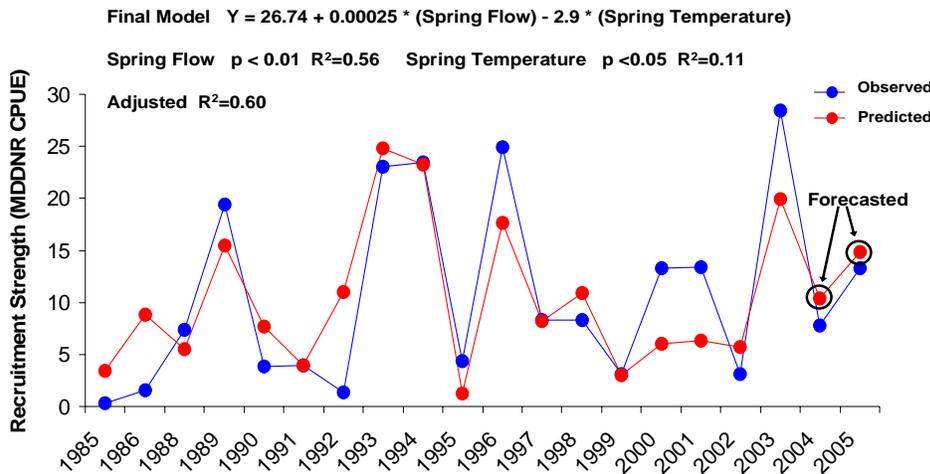


Figure 23. Observed and modeled--hindcast (1985-2003), forecast (2004 and 2005) recruitments of age-0 striped bass based on a multiple regression model for upper Chesapeake Bay. Independent variables are spring freshwater flow, and spring water temperature in the upper Chesapeake Bay.

Although larval survival and production are strongly correlated with subsequent YOY abundances 100-150 days post hatch, fishery-independent survey data of age-0 juvenile striped bass (Maryland DNR seine-survey data) and VPA-derived estimates of

Young-of-the Year Striped Bass Growth and Mortality

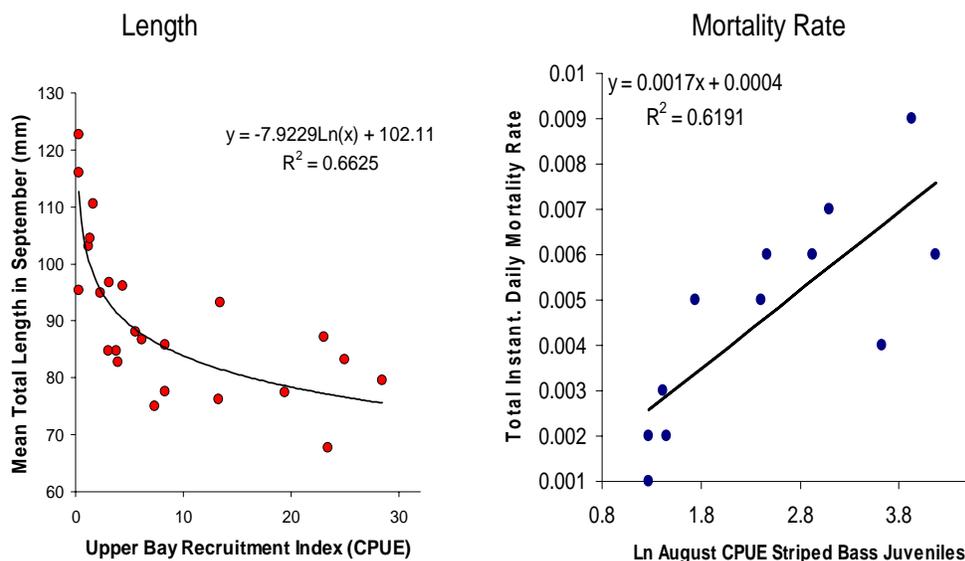


Figure 24. Left panel: relationship between length of age-0 striped bass in September and the Maryland DNR upper Bay recruitment index. Right panel: instantaneous daily mortality rates of age-0 to age-1 striped bass from September to the following August in relation to \log_e catch-per-unit-effort (CPUE) of YOY striped bass in September.

age-1 abundances (Atlantic States Marine Fisheries Commission) indicated that juvenile-stage lengths and survival were lowest in the high-flow years (Figure 24), a strong density-dependent response (Martino and Houde 2004).

Age-0 juvenile length at the end of the growing season in upper Chesapeake Bay was inversely related to striped bass age-0 abundance, indicating density-dependent growth of post-larval-stage striped bass (Figure 24). Age-1 abundances, based on VPA estimates, indicate that overwinter compensatory mortality has a strong effect on ultimate recruitment to the fishery (Figure 11). In years when striped bass age-0 juveniles are abundant, they grow slowly. It is probable that density-dependent growth is attributable to competition for limited prey by juveniles in years of high larval survival. Resulting smaller sizes of late-summer age-0 juveniles then lead to size-selective, compensatory overwinter mortality. Although the compensatory response appears to be strong and stabilizing, it does not overwhelm the advantage that year classes receive from high larval-stage survival, which is the predominant factor controlling recruitment levels.

In stock-recruitment modeling, spawning stock biomass alone accounts for only a small portion of the inter-annual variability in recruitments of striped bass in Chesapeake Bay. Although spawning stock biomass may account for <15% of the variability in recruitment, it still contributes substantively. Not only spawning stock biomass, but the age structure and diversity of the spawning population contribute to the success of recruitments. Including age-structure diversity of adult females (a maternal effect) in a modified Ricker spawner-recruit model, along with a measure of salinity (proxy for freshwater flow), accounted for 84% of the variability in the Chesapeake Bay YOY recruitment time series (Figure 25).

Modified Ricker-type S-R Model for Striped Bass in Chesapeake Bay

$$R = 0.2626 S \exp(-0.0818 S + 2.24 H_n - 0.35 \text{ Sal})$$

R: Recruitment = MDNR juvenile index

S: Spawning stock biomass of the upper Bay in the spring

H_n : Age diversity of females ≥ 5 yr in the upper Bay

Sal: Mean surface salinity in the middle Bay for April, July and October (CBP)

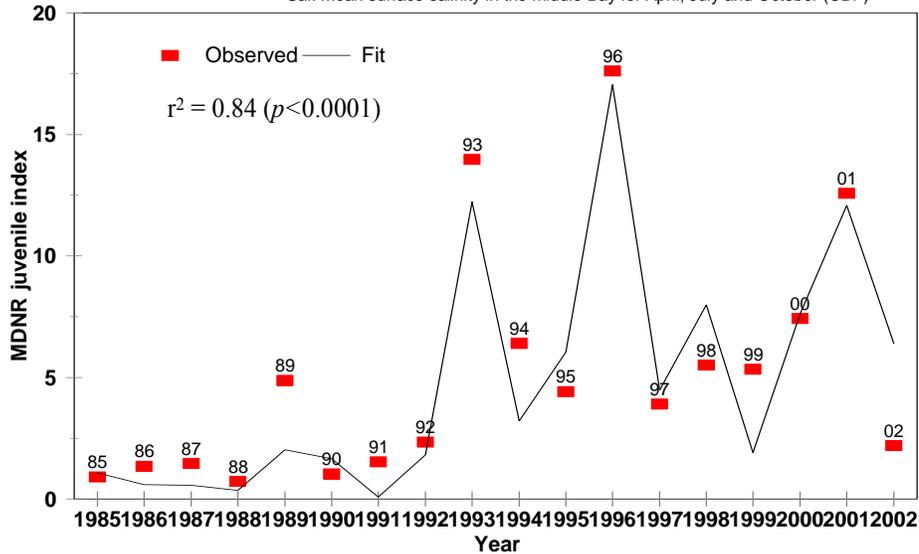


Figure 25. Striped bass, upper Chesapeake Bay. Observed and modeled young-of-the-year recruitments from 1985-2002. Observed values from Maryland DNR seine survey data. Modeled values from a fitted, modified Ricker stock-recruitment model. H_n is age diversity of adult females, expressed as the Shannon-Wiener diversity index.

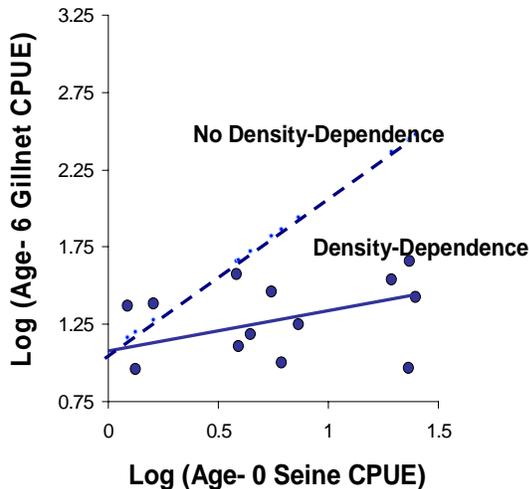


Figure 26. Relationship between age-6 abundance at recruitment to the fishery and age-0 abundance (fitted data, solid line; slope coefficient < 1.0). The dashed line is the predicted relationship if there were no density dependence (slope coefficient = 1.0). The observed data falls below the dashed line indicating density-dependent survival.

The evidence for compensatory growth (or size-selective predation) and survival in the early juvenile stage of striped bass suggests that the current age-0 recruitment index based on Maryland DNR seine surveys in Chesapeake Bay may overestimate recruitment potential of striped bass in high recruitment years. For example, the MD-DNR age-0 recruitment index varied >30 -fold between 1991 and 2002, but abundances of age classes that are recruited to the fishery varied substantially less, indicating that compensation occurred (Figure 26). Density-dependent growth in summer and size-selective over-winter mortality of small age-0 striped bass apparently occur in Chesapeake Bay as a compensatory response that is especially prominent in years of high age-0 striped bass production.

Task 5: Development of multispecies surplus production

We were able to analyze CPE and catch data from 1982 – 2001. Benthivore (aggregate of Atlantic croaker, spot, summer flounder, channel catfish, white catfish) and pelagic piscivore (aggregate of striped bass, white perch, bluefish, weakfish) CPE were larger similar with both guilds rising to a peak from 1981 – to the early 1990s and then stabilizing. Conversely, trends in catch diverged between the two guilds in the early 1990s, as benthivore yield nearly tripled between 1991 and 2001 whereas pelagic piscivore yield increased by only 70%. The dramatic increase in benthivore yield can be largely attributed to Atlantic croaker, whose catch increased from less than 1000 tonnes in 1991 to more than 10,000 tonnes in 2001. Production results from the aggregate benthivore guild suggested that benthivore biomass was more than twice B_{msy} (Figure 27a). Correspondingly, recent rates of fishing mortality are only a fraction of the F_{msy} (Figure 27b). These results are a consequence of the dramatic increase in benthivore yield in the 1990s, without having a negative impact on benthivore CPE. Production results from the aggregate pelagic piscivore guild revealed the guild to have been near MSY in the late 1980s (Figure 28a), and then fishing mortality subsequently decreased (Figure 28b) until piscivore biomass was 50% larger than B_{msy} in the early 1990s. Relative to the benthivore guild, however, the pelagic piscivore guild is currently much closer to its B_{msy} . Finally, when we aggregated the benthivore and pelagic piscivore guilds to represent the Chesapeake Bay community, the results were loosely similar to those of the pelagic piscivore guild. In the first model, the catch data included only those species for which we had CPE data (Figure 29, closed circles). As in the pelagic piscivore guild, the B/B_{msy} ratio increased until it reaches an asymptote at around 1.5, and the F/F_{msy} ratio was relatively bowl-shaped. In a second model, we included the catch data from all of the other important species except menhaden, which would have caused undue influence on the results because menhaden are annually at least 75% of the commercial catch (by weight). Hence, this model included blue crab, Eastern oyster, American eel, the Alosids (alewife, Buck shad, Hickory shad, American

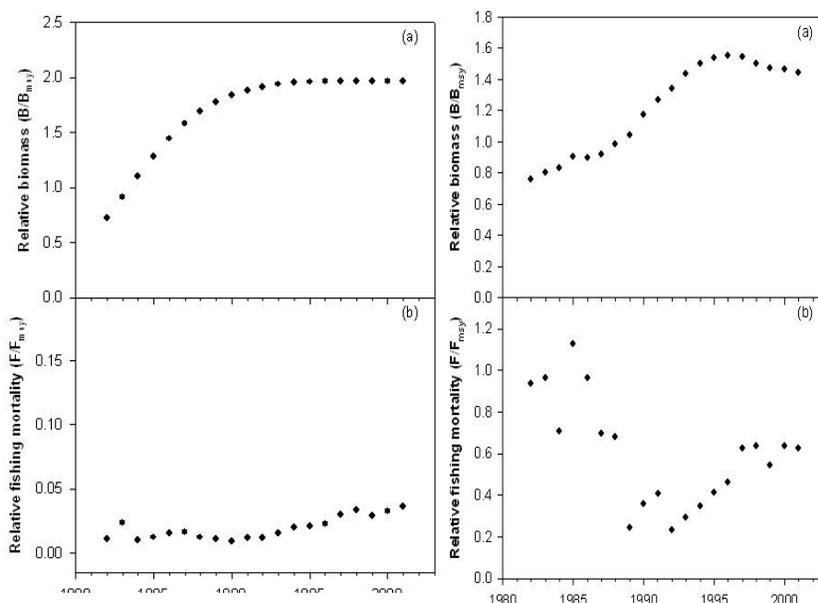


Figure 27. Time series of (a) relative biomass and (b) fishing mortality from the single guild benthivore surplus production model

Figure 28. Time series of (a) relative biomass and (b) fishing mortality from the single guild piscivore surplus production model

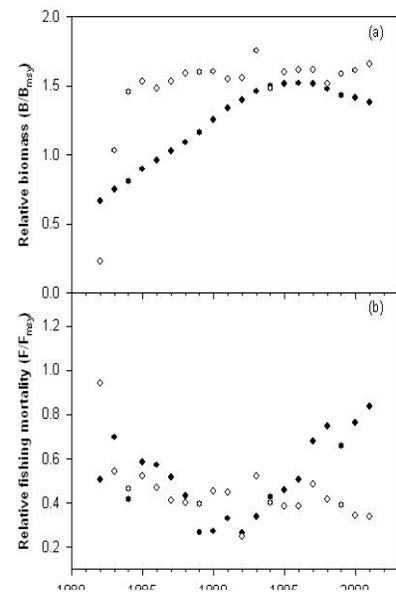


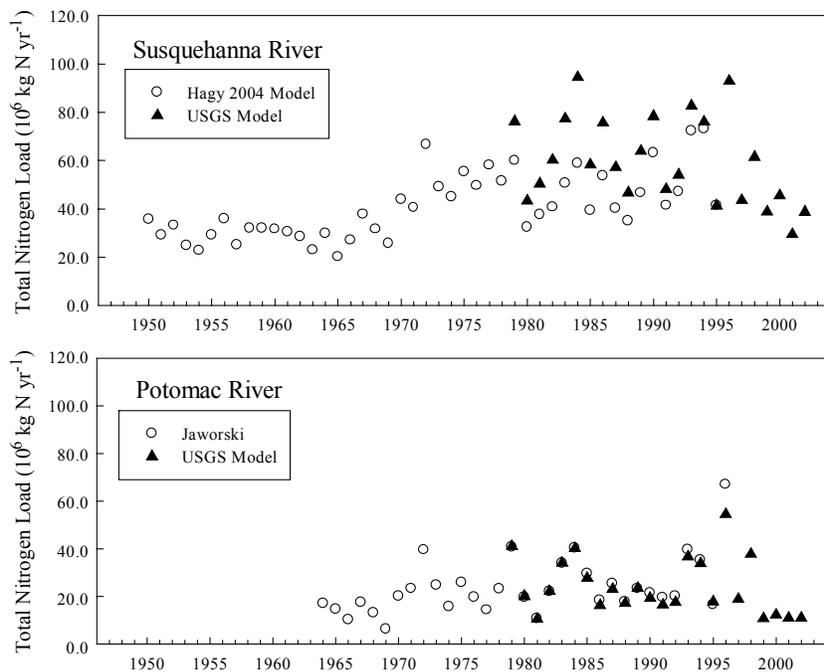
Figure 29. Time series of (a) relative biomass and (b) fishing mortality from the aggregate surplus production model. Solid circles refer to models in which only catch for species for which CPE data were available were entered in the model. Open circles we used catch data for the entire Chesapeake Bay.

Shad), gizzard shad, yellow perch, and clams, and we assumed that the CPE of the species that we had was representative of the CPE of the entire Chesapeake Bay fishery community. These results differed only slightly from the model that included fewer species in the commercial catch (Figure 29). In the second model (open circles), the B/B_{msy} ratio was largely similar to the first, with recent biomass estimates being at least 50% higher than the biomass at MSY. The ratio of F/F_{msy} was similar between the two models until 1996, when the model that included all species demonstrated an increasing ratio that neared 1.0 by 2001.

Task 6: Changes in fish community structure:

Nutrient loads (as 10^6 kg N/yr) have been calculated for the Susquehanna and Potomac Rivers from river discharge and total nitrogen concentrations at or near the fall line of each system (Figure 24). Susquehanna loads were determined from a model by Hagy et al (2004) for the time period 1950-1994. We combined this data with recent loads calculated by the USGS model for the period 1979-2002. A similar analysis was assembled for the Potomac River (from 1965-2002) from total nitrogen concentrations and discharge at Great Falls provided by Jaworski (pers comm.; 1964-1996), and supplemented with the USGS model for the time period of 1979-2002.

For the Susquehanna River, total nitrogen loads appear to be relatively constant throughout the 1950s (mean = 3.0×10^7 kg N yr⁻¹). After 1965, loads increased to a mean of 5.0×10^7 kg N yr⁻¹ based on Hagy et al. (2004), and 6.3×10^7 kg N yr⁻¹ based on USGS estimates before declining slightly. Where the two data sources overlap (1979-1996), the USGS estimates for the Susquehanna River are 22% above estimates by Hagy et al. (2004; Figure 30a). This discrepancy appears to be caused by the difference in locations where nutrient concentrations



and discharge rates were used: Hagy et al.(2004) estimated nutrient loads at Harrisburg, Pennsylvania, while the USGS model estimated loads from station 01578310 at Conowingo, Maryland. Nitrogen loads to the Potomac River appear to be consistent throughout the time period collected (Figure 24b). Furthermore, estimates by Jaworski (calculated at Great Falls), and the USGS (calculated at station 01646570 at Chain Bridge), were more similar due to the proximity of the locations.

In addition to assembling nutrient loads, we created a historical record for changes in water clarity (K_d or Secchi Depth), chlorophyll, nutrient concentrations (nitrogen and phosphorus),

Figure 30. Fall line nitrogen loading (10^6 kg N yr⁻¹) for the Susquehanna (a) and Potomac (b) Rivers. Data for the Susquehanna River were derived from Hagy et al. (2004) and the USGS model. Potomac loads were provided by Norb Jaworski (pers comm.) and the USGS

temperature and dissolved oxygen during the 1945 – 2003 time period. Most water quality variables were measured on a monthly frequency from about 1940-2003; however, large gaps exist for the 1950s and a few other earlier time periods. An example of the data coverage for chlorophyll is provided in Table 3. The majority of recent data came from the Chesapeake Bay Program. Earlier data (pre-1985) for the Potomac, and Chesapeake Bay needed to be assembled from multiple sources, including some published works (Harding Jr. and Perry 1997), unpublished data sets (e.g., Jaworski, pers comm.), published data reports (e.g., Chesapeake Bay Institute Data Reports) and many other sources. In most cases, these data were manually entered from sources to a data management system. Due to the time needed to accomplish this task, we hired temporary help to compile and enter this data.

Active chlorophyll concentrations at the surface for different salinity regimes of the Chesapeake Bay and Potomac River are presented in Figure 31. Data displayed large inter-annual variability, with the majority of variability and largest concentrations observed during the period of 1960s-

1980s. Though the largest chlorophyll concentrations observed were in the tidal fresh regions of both water bodies, there does not appear to be a significant difference among salinity regimes. Therefore, subsequent chlorophyll data for the analyses with fisheries landings were averaged across all regions within each water body (see the following section).

Commercial fisheries harvest by species was compiled from NOAA, Maryland Department of Natural Resources, and the Potomac River Fisheries Commission. It was necessary to distinguish the reported landings

Table 3. The historical coverage for chlorophyll spanning 1950-2003. Data is separated by Chesapeake Bay Program segments (listed in columns). Colors and labels for each year represent the data source: "H1" represents data from Harding and Perry (1997), "CBI" represents the Chesapeake Bay Institute data reports, "JAW" represents unpublished data collected from Norb Jaworski, and "CBP" represents the Chesapeake Bay Program.

Year	CBP 1998 Segments											POTMH	POTNT	POTOH	POTTF	
	CB1TF	CB2OH	CB3MH	CB4MH	CB5MH	CB6PH	CB7PH	CB8PH	POTMH	POTNT	POTOH					POTTF
Pre 1950																
1950	H1/CBI	H1/CBI	H1/CBI	H1/CBI	H1/CBI	H1/CBI	H1/CBI	H1	H1/CBI							
1951	CBI	H1/CBI	H1	H1/CBI	H1/CBI	H1	H1/CBI	H1	H1/CBI							
1952			H1	H1												
1953																
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1963																
1964	H1	H1	H1	H1												
1965	H1	H1	H1	H1	H1					JAW			JAW	JAW		
1966	H1	H1	H1	H1	H1					JAW			JAW	JAW		
1967	H1	H1	H1										JAW	JAW	JAW	
1968	H1	H1	H1							JAW			JAW	JAW	JAW	
1969		H1	H1		H1			H1		JAW			JAW	JAW	JAW	
1970		H1	H1	H1	H1			H1		JAW			JAW	JAW	JAW	
1971	H1	H1	H1	H1				H1								
1972		H1	H1													
1973		H1	H1	H1												
1974	H1	H1	H1	H1	H1											
1975	H1	H1	H1	H1	H1			H1								
1976	H1	H1	H1	H1	H1			H1	H1				JAW	JAW		
1977	H1	H1	H1	H1	H1								JAW	JAW	JAW	
1978	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1	H1/CBP	H1/CBP								
1979	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP		H1/CBP	H1/CBP	JAW				JAW	JAW	JAW	
1980	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1	H1/CBP	H1/CBP	JAW				JAW	JAW	JAW	
1981	H1		H1		H1								JAW	JAW	JAW	
1982										JAW			JAW	JAW	JAW	
1983			H1	H1	H1		H1	H1	JAW				JAW	JAW	JAW	
1984	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1985	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1986	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1987	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1988	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1989	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1990	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1991	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1992	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1993	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1994	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	H1/CBP	1/CBP/JA	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1995	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1996	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP/JAW	CBP	CBP	CBP
1997	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
1998	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
1999	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
2000	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
2001	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
2002	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP	CBP
2003					CBP	CBP	CBP	CBP	CBP							

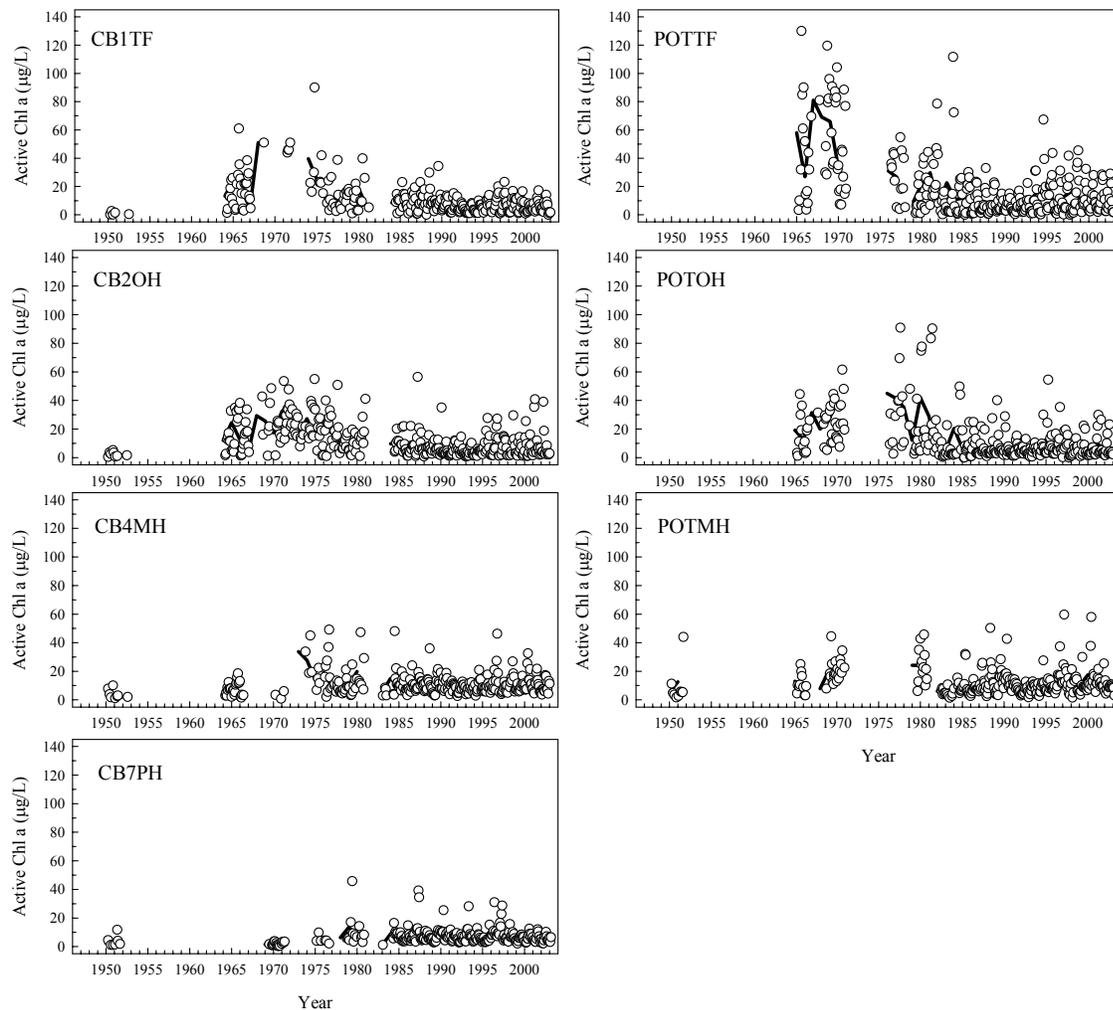


Figure 31. Average surface active chlorophyll a concentrations at various salinity regimes of the main stem Chesapeake Bay (left column), and the Potomac River (right column). Legends are as follows: CB1TF and POTTF are tidal fresh segments of the main stem Chesapeake Bay (left column), and the Potomac River (right column). Legends are as follows: CB1TF and POTTF are tidal fresh segments of the main stem Chesapeake Bay and Potomac River, respectively. CB2OH and POTOH are the oligohaline segments, CB4MH and POTMH are the mesohaline segments, and CB7PH is the polyhaline segment of the Chesapeake Bay. Note there is no polyhaline segment in the Potomac River.

based on particular water bodies since many fishing regulations differ along the tributary boundaries and because we were interested in establishing relationships between specific water bodies and fishery yields from specific estuaries. We assembled complete fisheries landings data by species and specific water body for the Potomac River (Maryland and Virginia landings; from 1965-2002), and data for the mainstem Bay (excluding tributaries; from 1981-2002). A considerable amount of interannual variability exists in total landings for both water bodies. For the mainstem Chesapeake Bay, 89% of these landings were menhaden. The second and third ranked dominant species caught in the mainstem were blue crabs and Atlantic croaker, though both landings together were ~10% of the total landings. In recent years (1995-2001), total landings declined significantly for the mainstem Chesapeake Bay, while Potomac landings appeared to decline in the 1960s, and again after the mid 1980s. Dominant species caught in the Potomac River are striped bass, oysters and blue crabs. Though the dominance of each species

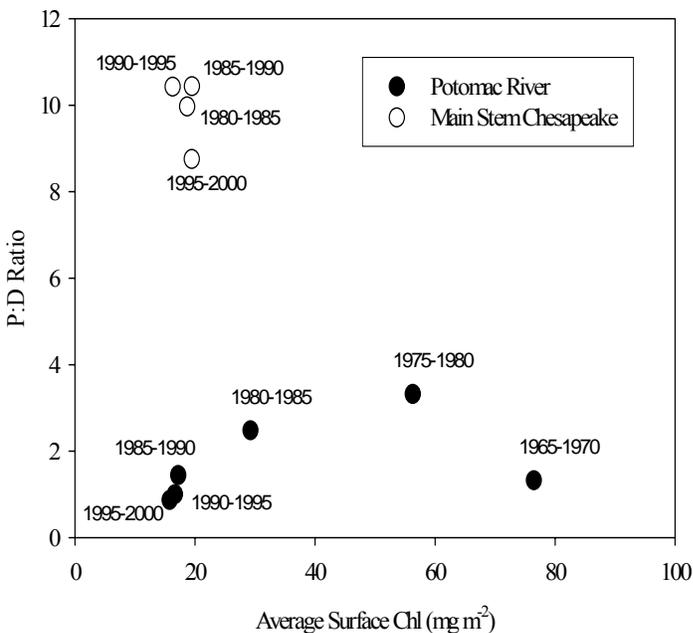
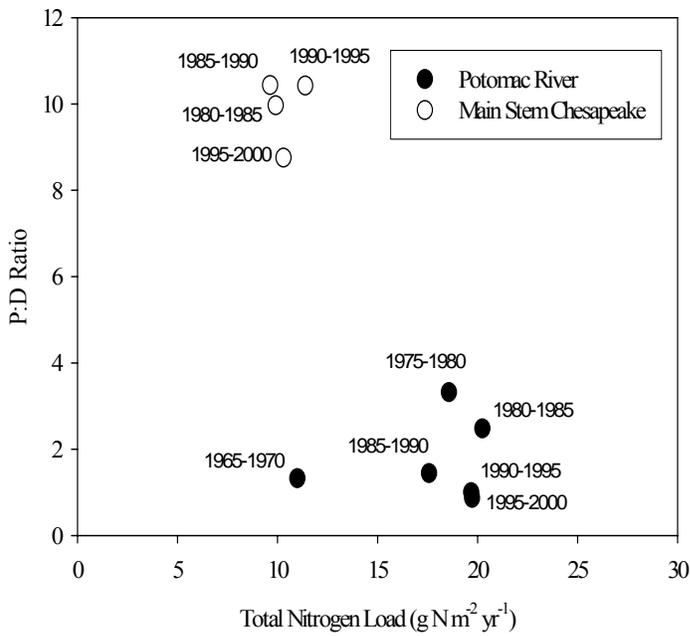


Figure 32. The relationship between pelagic:demersal ratio of commercially harvested fish and the total nitrogen load into the estuary (a), and the average surface chlorophyll concentration (b). Data are normalized to aerial area, and averaged over half-decade time series for the entire Potomac River and the main stem of the Chesapeake Bay (without tributaries).

Chesapeake Bay when compared to P:D ratios of the Potomac River appear to reflect the dominance of purse-seine landings of menhaden in the mainstem, which is prohibited in the Potomac River. Recent declines in the P:D ratio in the mainstem (1995-2000) don't appear to be explained by nutrient loading or surface chlorophyll concentration.

The patterns of P:D ratios we observed in these two systems are the results of many factors as well and some unevaluated errors. In the case of Chesapeake Bay there was a modest

has changed throughout the time period, blue crabs comprise the largest landings of any harvested species in the Potomac. Oysters and striped bass are also dominant species, though appear to be declining steadily throughout the landings record. The reduction in striped bass landings during the late 1980s was caused by a fishing moratorium on this species because of very depressed stocks.

We also assigned pelagic and demersal designations for all species landed in these regions based on habitat use and traditional natural history of the species involved. The relationship between pelagic:demersal ratios (P:D) from commercial landings and selected aspects of water quality data are presented in Figure 32. Data were combined into half-decade averages for the time periods available for reasons mentioned earlier. To allow for comparisons between the Potomac and mainstem Chesapeake, aerial surface areas were calculated for those regions, and used to determine area normalized nutrient loading and surface chlorophyll concentrations.

Inter-decade variability in chlorophyll concentration is most obvious in the Potomac River (Figure 32 b), with the highest values occurring from 1965-1970, and lowest values in the 1990's. In part these chlorophyll patterns result from high loading rates of both nitrogen and phosphorus during the early period followed by sharp reductions in phosphorus loads during later years. The higher P:D ratios of the

inter-decadal amount of variation in the P:D ratio as a function of nutrient loading rate. This is consistent with current patterns of water quality in the mainstem Bay. Since the mid-1980's deep water dissolved oxygen levels have been depressed during warm months of all years and benthic habitat conditions have also been poor, both of which would promote conditions suggesting an elevated P:D ratio. These observations are consistent with detailed studies indicating degraded benthic habitat under hypoxic conditions in this and other estuaries (Baden et al. 1990, Howell and Simpson 1994, Diaz and Rosenberg 2001, Breitburg 2002). However, the declining P:D ratio (1995-2000) in the mainstem Bay is mainly the result of declining menhaden landings rather than further declines in demersal species. If fishery landings for just the mainstem Bay had been more readily available for the several decades prior to 1980, there may well have been a broader distribution of P:D ratio. Using nutrient loading and fisheries landing data for the full Chesapeake Bay system Kemp et al (2005) reported a distinct increase in the P:D ratio that was caused by both increases in pelagic catch and decreases in demersal catch. This pattern was accompanied by increasing nutrient loads, declining SAV communities, increasing algal stocks, intensification of hypoxic duration and extent and declines in the efficiency in the transfer of primary production to higher trophic levels. The mainstem Bay P:D ratio as a function of algal biomass is quite similar to that observed as a function of nitrogen loading rate and probably results from the fact that nitrogen loading rate and chlorophyll are reasonably well correlated in the Bay (Boynton and Kemp 2000). However, there was a relatively large range in both chlorophyll concentrations and P:D ratio in the Potomac River estuary, in part because this data set spans a longer period of time during which several management actions took place. In this case, the P:D ratio was quite low (~1.8) during the earliest period of the record when chlorophyll concentrations were highest, increased as chlorophyll levels declined (2.3 – 3.3) and declined further when chlorophyll levels fell below 20 mg/l (1985 – 2000). It is clear that both algal biomass and fisheries composition changed substantially during this 30 year period. Kemp et al (2005) observed that changes in fishery stocks and rates of harvest are tied to fishing preferences, fishing effort, market demands, fishing techniques and regulations as well as habitat, water quality and climate variability. Despite these many factors, a clear pattern, on half-decade time scales, emerged from the Potomac River data set.

Task 7. Forecasts of ecosystem-level changes

Although total fisheries harvest in the Bay has generally increased during the last fifty years, the mean trophic level of this harvest has declined steadily, from approximately 2.6 in the early 1950s to about 2.3 in the late 1990s (Fig. 33, upper panel). Most of this change occurred between 1950 and 1975. The computed time-series for the pelagic fraction of fisheries production exhibited modest year-to-year variations, but a significant increase from <0.6 in the early 1950s to >0.8 in the mid 1990s (Fig. 33, middle panel). There was a radical shift in the 1950 to 1960 decade followed by a more gradual increase thereafter. Changes in menhaden harvest rates during this period have contributed substantially to these trends.

During this same half century time-period, human populations and agricultural activities in the estuary's watershed have increased, resulting in generally increasing nutrient inputs to Chesapeake Bay. We have used recently published estimates of nitrate loading to the estuary for this time (Hagy et al. 2004) and relationships between inputs of nitrate and total nitrogen (Hagy et al. 2004) and between total nitrogen and phytoplankton production (Boynton et al. 1982) to estimate primary productivity trends during the last five decades. It appears that primary

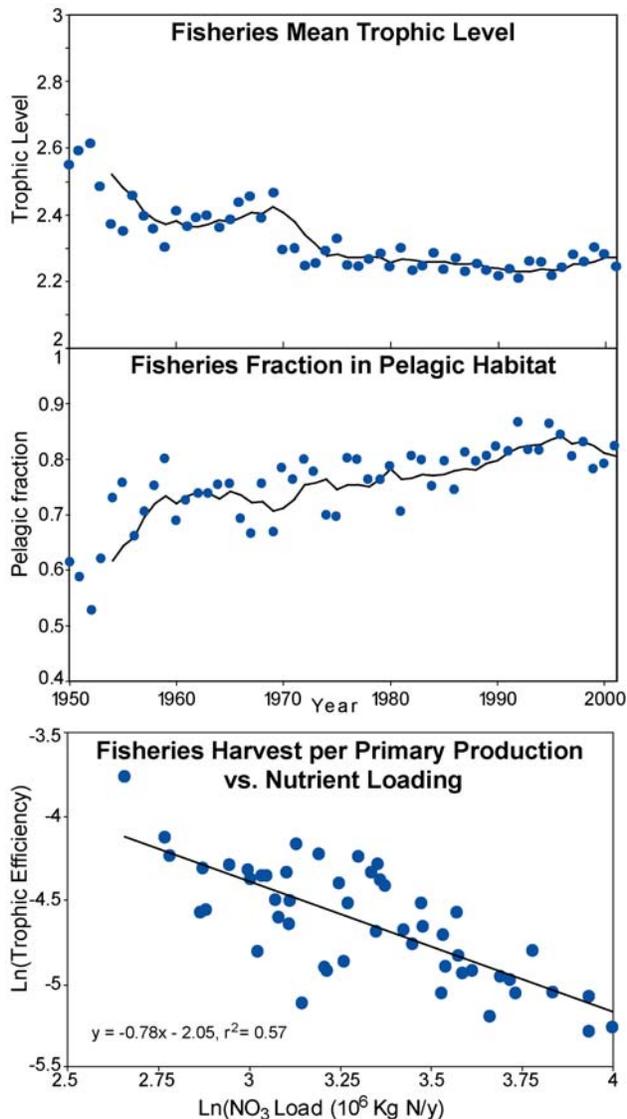


Figure 33. Trends in ecological properties (see Fig. 1) of Chesapeake Bay fisheries harvest including temporal changes from 1950 to 2000 in weighted mean trophic level of harvested animals calculated from trophic network model (upper panel), temporal changes in the fraction of the harvest supported by pelagic food webs (middle panel), and the relationship between trophic efficiency (fisheries harvest per primary production) and nitrate loading rate to the Bay (bottom panel).

production has increased more rapidly than has fisheries harvest over this time period, such that the ratio of the fisheries to productivity has actually declined as nutrient enrichment increased in the estuary (Fig. 27, bottom panel). This relationship does not necessarily imply a causal relationship, but it suggests the possibility that trophic efficiency has declined with increased nutrient loading. To the extent that this is the case, we speculate that an increasing fraction of primary production is going to support heterotrophic activity of lower-trophic-level organisms, probably dominated by microbial decomposer communities (Kemp et al. 2001).

Model experiments revealed generally consistent patterns of responses to increased nutrient loading, where total phytoplankton and the ratio of large (diatoms) to small (flagellates) algal cells tended to increase with nutrients, while consumer organism groups follow a hyperbolic response in which biomass increases with initial increases in nutrients but saturates at modest nutrient loading rates (Fig. 34, upper and middle panels). As a consequence, the trophic efficiency (defined as the ratio of consumer production to phytoplankton primary production) tends to exhibit an initial increase at lower nutrient loading rates followed by a marked decline, because consumer biomass does not respond to further nutrient-stimulated increases in phytoplankton (Fig. 34). Model food webs were also modified by replacing fish consumers at the upper two trophic levels with carnivorous plankton but otherwise retaining the same structure. These model food webs with fast-growing (rapid-turnover) top carnivores exhibited increased sensitivity

to nutrient additions and changes in predation pressure. For these planktonic food-webs, changes in trophic structure associated with allowing organisms to feed at multiple trophic levels resulted in radical changes in consumer abundance (Fig. 34e).

This general pattern, whereby consumer organism responses to nutrients saturates at intermediate loading rates, however, depends on the intensity of predation pressure. At low predation pressure, consumer biomass continues to increase with nutrients and there is little evidence of saturation, whereas saturation always occurs when predation pressure is high. In fact, nutrient loading and predation pressure on piscivores (i.e., fishing mortality) produce strong interacting effects on biomass of both planktivorous and piscivorous fish (Fig. 35, left panels). It

is apparent that responses of piscivore biomass to nutrient loading (beyond $1 \mu\text{mol N m}^{-3} \text{d}^{-1}$) are muted at high rates of fishing mortality rates, whereas responses to nutrients are more pronounced at moderate to low mortality rates. The inverse is true for planktivore biomass, which respond more strongly to nutrients when in contrast, at high rates of piscivore mortality, planktivores are released from high predation by piscivores, such that planktivore biomass is more responsive to nutrient increases. At intermediate fishing rates, biomass values for both fish groups exhibit similar hyperbolic saturation functions.

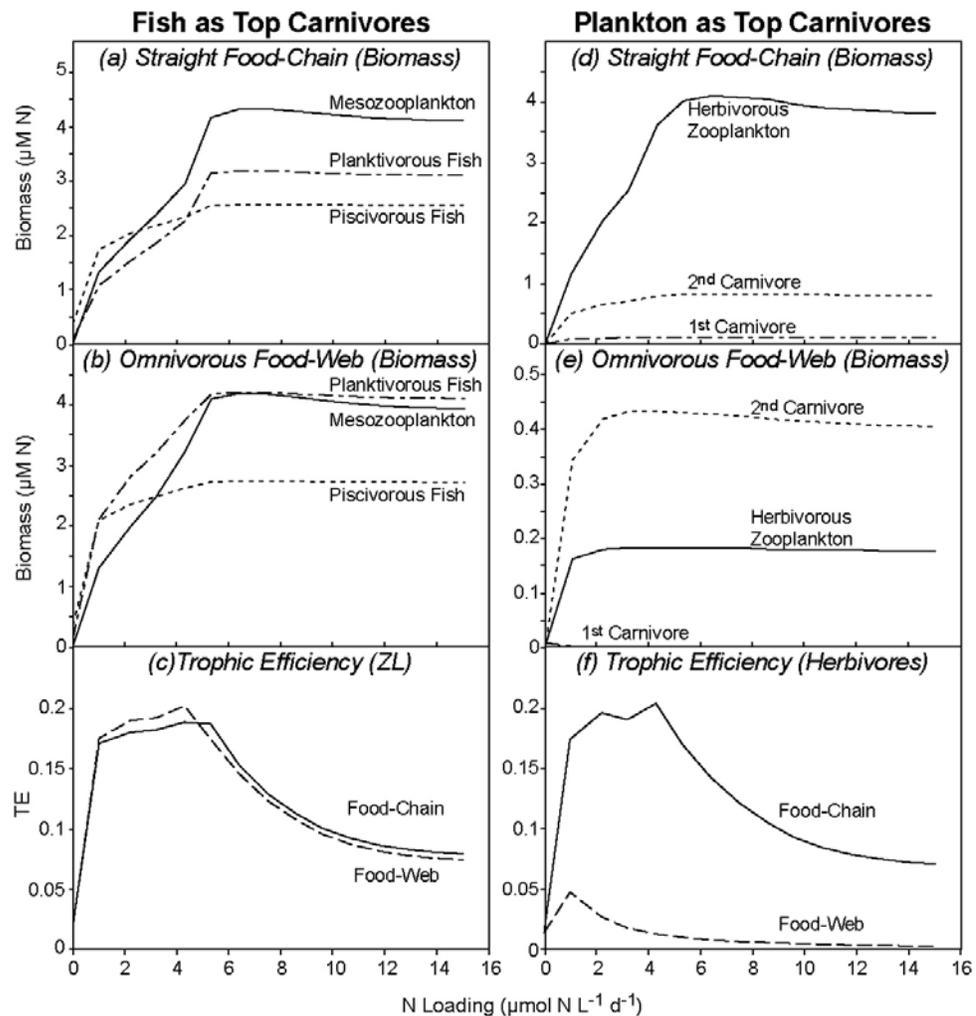


Figure 34. Results of numerical model simulation experiments examining responses of simple pelagic food-webs to nutrient loading in terms of organism biomass (upper and middle panels) and trophic efficiency as zooplankton production per unit phytoplankton (lower panels). The series of panels represent output from models calibrated such that intermediate and top predators are either gelatinous plankton (left side) or fish (right side). Food webs are configured as straight food-chains where predators feed on only one prey type (upper panels) or more complex food-webs where omnivorous predators feed at more than one trophic level (middle panels).

Despite the occurrence of trophic cascades, however, these dynamics always produce consistent parabolic responses of trophic efficiency—first increasing, then peaking, then decreasing—along a gradient of nutrient enrichment (e.g., Fig. 34, bottom panels). Thus, whether the dominant food-chain has three or four links, with strong predation at the top level, nutrient enrichment will elicit this characteristic trophic efficiency response (e.g., Fig. 35, compare left and right panels).

The relevance of these model results for coastal systems such as Chesapeake Bay will depend on where these ecosystems are in their particular nutrient-fishing mortality response surfaces. Although this model is generally calibrated to a observations in a specific system, its lack of spatial and seasonal articulation makes it difficult to discern whether it is to the left or right of the fish saturation point, and how this saturation function moves with fishing pressure. This is very important consideration, for eutrophic coastal systems where nutrient input

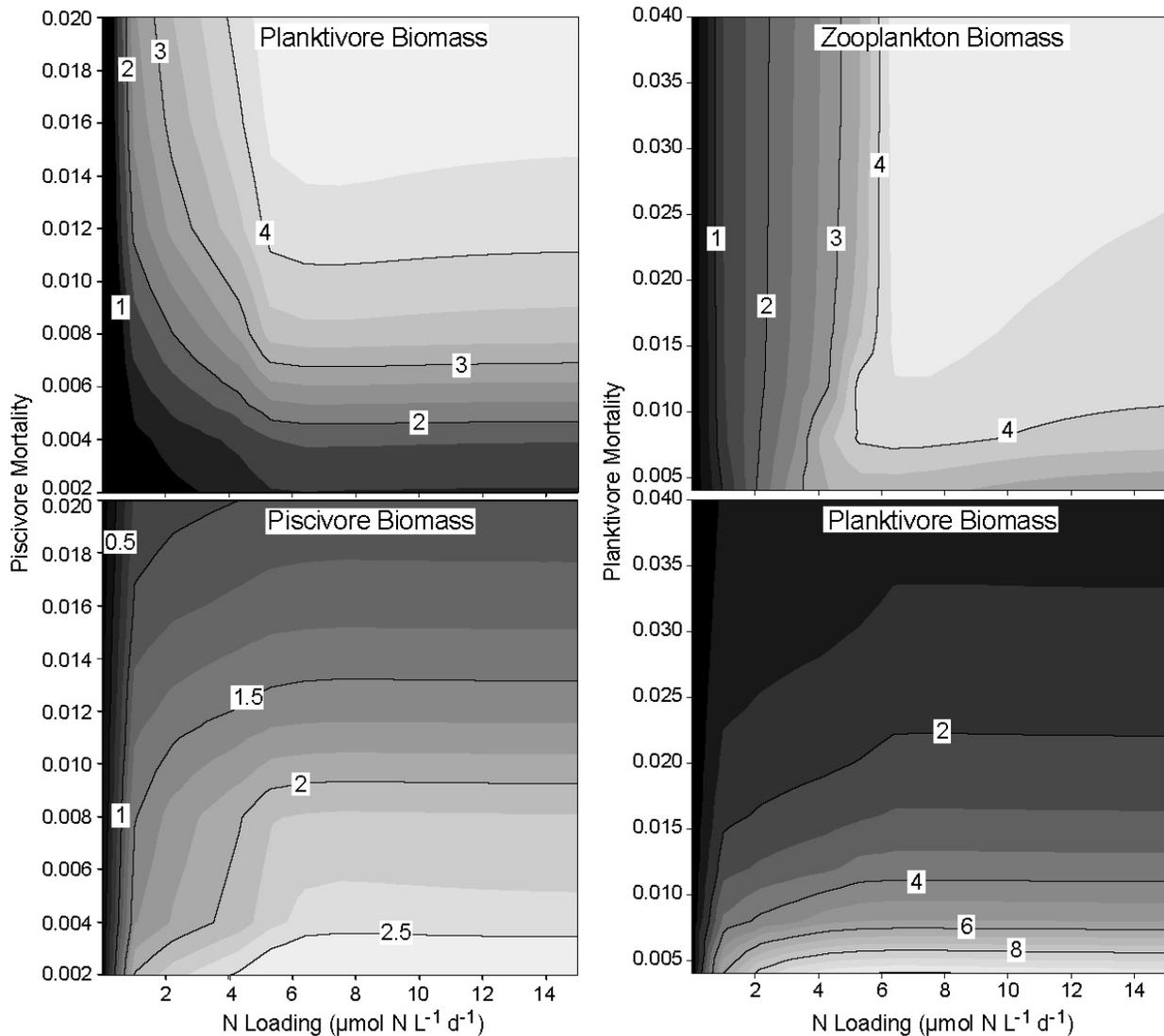


Fig. 35. Summary of numerical model simulation experiments examining responses of consumer biomass to interacting variations in nutrient loading and fishing mortality at the highest trophic level in simple pelagic food-webs. The two left panels represent a model with four nominal trophic levels (phytoplankton, herbivorous zooplankton, planktivorous fish, carnivorous fish); the right two panels represent a 3-trophic-level model).

reduction strategies are being developed. If the system is well to the right of the saturation point, then modest reductions in nutrient input will not affect potential fisheries stocks and production; if the system is near or to the left of the saturation point, the nutrient reduction could contribute to reduced fish production. We have been examining potential for using biomass ratios (for example, large to small algal cells, or phytoplankton to bacteria biomass) as indices of proximity to saturation points. It is anticipated that further analysis will yield deeper understanding of these relationships.

B. If significant problems developed which resulted in less than satisfactory or negative results, they should be discussed.

The most significant challenge we faced was in developing improved forecasts of the distribution of oxygen in the Chesapeake Bay. At the time of writing the proposal we had anticipated that we would have access to both our historical database of observations on the distribution of oxygen from the TIES program, the historical data from the Chesapeake Bay monitoring program and a new continuous stream of oxygen data from monitoring arrays associated with the Chesapeake Bay Observing System. These data streams would have provided sufficient resolution to develop new models of oxygen dynamics that would have sufficient spatial and temporal resolution to develop accurate mixing models. However, this proved not to be the case as the oxygen measures from the observing system did not prove reliable.

The lack of dynamic forecasts of oxygen distributions caused us to change the framework for making forecasts of fish distributions from a bioenergetics-based approach outlined in the proposal to a statistical approach employing general additive models (GAM). While this approach differed from that proposed, it was however extremely successful. The richness of the forecasting platform available to us allowed us to examine the utility of GAMs more critically than other researchers who typically developed a single aggregate model. We were able to use cross-validation approaches to examine the generality of GAMs developed in one year for predicting distributions in other years.

We did not encounter any significant problems with the remaining intra-annual and inter-annual forecasts identified in the original proposal because we knew we had access to the data necessary to develop the models. Of course, that is not to say our findings had a uniformly high forecasting ability. However, data availability was not a limiting factor.

This was not the always the case for the decadal-scale forecasts. At the outset of this project we anticipated we would encounter some difficult issues related both to the conceptual underpinning of the proposed work (e.g., separating effects of fishing pressure versus changes in water quality and habitat conditions on fishery yields) and with the availability and appropriateness of data sets needed for this work. These concerns turned out to be accurate and it is worth indicating areas where substantial problems arose.

We were able to compile useful time-series of a selection of nutrient input and water quality conditions for the two main study sites (mainstem Chesapeake Bay and Potomac River estuary). Data collected after 1984 (in some cases after 1978) was reasonably available from the Chesapeake Bay Program and a variety of other sources. There were few serious issues regarding the quality of these data sets. Thus, there was a record of these variables of about two decade's length and, in many ways, this is an impressive record. However, it is also true that habitat (e.g., bottom water dissolved oxygen, SAV coverage) and water quality conditions (e.g., turbidity, algal blooms) in many portions of Chesapeake Bay and some tributary rivers had deteriorated sharply before the reliable time-series record began. Thus, there was an absolute requirement to attempt a re-construction of such things as nutrient loading rates and a variety of water quality and habitat conditions farther back in time to a period when severe degradation was not as well developed (circa 1950; Kemp et al. 2005) and during which we could examine relationships to pre-eutrophication fisheries yields. We were partially successful in this effort. For example, nutrient loads to the mainstem Bay have been reconstructed back to 1945, turbidity patterns back to the early 1960's and some chlorophyll-a data to the 1950's. A few of these early

records were summarized in Hagy et al (2004) and Kemp et al (2005). Other early records may still be available but we have not yet located and examined these, if they do exist. The point here is that the effort needed to find, review and enter these bits of information into our data set was very substantial, well beyond our estimates of the time required. Data issues, such as those presented here, provided important motivation for the creation of the current Chesapeake Bay monitoring program.

Similar, and in some instances even more formidable, issues arose relative to fisheries data. In a more perfect world estimates of stock size would have been available for all the major stocks. At the outset we knew this not to be the case and planned to use catch per unit effort data to relate fishery yields to stocks. Immediate problems arose in that different type of gear was used for major fisheries in the Bay. For example, purse seining is the major gear used for menhaden in the Virginia portion of Chesapeake Bay but use of this gear is not allowed in the Maryland portion of the Bay or in the Potomac River estuary. Other examples exist for other species. In addition, some effort data were in the form of licenses for a particular fishery. It became clear that some of these licenses were not being used and were thus not an accurate measure of fishing effort. Considerable effort was also required to be assured that fisheries landings for the mainstem Bay and Potomac River estuary did not include landings data from other areas of the Bay system (i.e., tributaries of the mainstem). Finally, the most abundant fish in the Bay system (bay anchovy) is not the focus of either a commercial or recreational fishery. In recent years considerable work has been completed which has really improved understanding of this species regarding recruitment patterns, stock size and environmental conditions regulating abundance (e.g., Jung and Houde 2000; Jung and Houde 2003). However, characteristics of this species during periods prior to severe eutrophication of the Bay and Potomac River estuary were not available. Possible indirect assessments included examination of the long-term shoreline monitoring data sets and review of entrainment studies conducted at power plants located in estuarine waters but both possibilities were judged to be beyond the scope of this project. Ultimately, we used fisheries yield and fisheries yield scaled to estuarine area with neither adjusted for fishing effort. In general, we averaged data for multi-year periods to average out severe effects of effort or gear changes following the reasoning of Caddy (1993) and Moreno et al (2000).

C. Description of need, if any, for additional work.

There are numerous areas that would benefit from additional research effort. We identify these areas in two phases: those that would assist meeting unmet goals in individual research tasks, and then those that would assist in the integration of research tasks across temporal scales.

Clearly, additional work to improve our ability to forecast oxygen distributions within the Chesapeake Bay would be highly desirable. This was a significant impediment to our ability to employ the approaches to understand the distribution of fish and their prey identified in the proposal. We remain convinced that the coupled bioenergetic model based approach that we proposed is still relevant, and worth pursuing. However, we note that we made substantial progress in developing predictive models of fish distributions. We have validated the forecasting ability of these models using testing and training datasets. However, we have yet to test their forecasting ability against wholly independent datasets. We have also yet to examine the scale-dependence of our forecasting models.

The synoptic climatological approach that we developed and employed within this project has substantial potential for understanding physical controls on production, and forecasting how climate change and other low frequency climatic variation may impact future levels of production in the nation's estuaries. We are actively pursuing this approach to understanding the dynamics of a range of taxa. We anticipate important insights will develop from this work, similar to those we have uncovered for zooplankton and fish recruitment. Such work is worthy of increased attention.

Work to understand and predict the distribution of fish would benefit greatly from additional attention. This work is increasingly important as the region moves toward ecosystem-based approaches to fisheries management. The work would help to define essential fish habitat, overlap between predators and prey, and exchanges between bay-specific and coastal components of the population. This work could include additional statistical analysis, deployment of passive acoustics and increased monitoring.

We made substantial progress in developing analytical and modeling approaches to describe and forecast recruitment variability of fishes in Chesapeake Bay, especially for YOY production and abundances of bay anchovy and striped bass. We made some, but less, progress in developing methods to predict inter-annual recruitment variability or to forecast recruitments more than several months into the future. Tools and data sets to move forward were developed in this COP project. We are now continuing with research on bay anchovy, Atlantic menhaden, and striped bass, funded through other sources, to determine how environmental factors, including plankton dynamics operating across many temporal and spatial scales, affect long-term recruitment and production variability of these fishes. In the case of striped bass, there is strong potential to build on the statistical models derived in the COP project to develop a forecasting capability for striped bass at age-3 when they recruit to the fishery.

In the future it would be useful to continue expanding the historical (pre-1985) nutrient loading, habitat and water quality time series for selected areas of the Bay to compliment existing data sets and to place more recent ecological conditions in a pre-eutrophication perspective. To address data gaps in the historical data, it would also be useful to develop a back-propagation neural network to interpolate missing data. Missing phytoplankton primary production rates could be estimated in multiple ways, including regressions with nutrient loading (e.g., Boynton et al. 1982, Boynton and Kemp 2000), using chlorophyll-a data combined with assimilation ratios (PP/Chla) for phytoplankton, neural networks, and vertically integrated empirical models. Furthermore, recent evaluations of in-situ primary production in the Bay have suggested the importance of micro-benthic primary production in environments with water transparency greater than what is now the case; attempts could be made to compute benthic primary production based on water clarity data and P versus I relationships for benthic microalgal communities (e.g., Kemp et al 2005). Food web analyses, based on pre-eutrophication conditions in the Bay, would also provide information useful in furthering understanding of changes in food web structure and performance (Baird et al. 1995) compared to current, more eutrophic conditions.

VII. Evaluation

A. Describe the extent to which the project goals and objectives were attained. This description should address the following:

1. *Were the goals and objectives attained? How? If not, why?*
2. *Were modifications made to the goals and objectives? If so, explain.*

We attained the majority of the goals outlined in the proposal. We have described above in Section VI B those areas in which we did not meet project goals and how we overcame these challenges. The combined body of work that has resulted from the project represents a substantial increase in our understanding of climatic controls and anthropogenic nutrient additions on estuarine production and dynamics. The work has led to insights into the influence of both factors on the distribution, structure and dynamics of both phytoplankton and zooplankton communities. We have developed tools that can be used to forecast fish recruitments and predict the distribution of fish within seasons. At the longest time scales we have sought to quantify how estuarine systems changed in response to increases in nutrient run-off and how they might change in the future as attempts are made to reverse these anthropogenic changes.

B. Dissemination of Project results:

We have assembled a large collection of water quality, nutrient loading, and fisheries data gathered from various university, state and federal sources for the mainstem Chesapeake Bay and for the Potomac River estuary, a major tributary of Chesapeake Bay. We are working toward making these databases freely available to other potential user groups. We have already made much of the fish survey results available (see hjord.cbl.umces.edu/CHESFIMS), and will continue to expand these efforts to other summaries of raw data. For example, we expect a user-queriable database housing the historical water quality observations to be available soon on a designated section of W. R. Boynton's research website on the CBL web page (www.cbl.umces.edu).

We have already used various aspects of this research in developing professional presentations and publications. We expect, as is usually the case, that additional presentations and publications will be developed as these data sets are further examined after the formal termination of this project.

1. Completed student theses relying on COP support

- Auth, T. D. 2003. Interannual and regional patterns of abundance, growth, and feeding ecology of larval bay anchovy (*Anchoa mitchilli*) in Chesapeake Bay. Master of Science Thesis, University of Maryland, College Park, MD.
- Brooks, M.T. 2003. Trophic complexity, transfer efficiency and microbial interactions in pelagic ecosystems: A modeling study. . Master of Science Thesis, University of Maryland, College Park, MD.

- Coakley, J. M. 2004 Growth of Eastern oyster, *Crassostrea virginica* in Chesapeake Bay. Master of Science Thesis, University of Maryland, College Park, MD.
- Curti, K. L. 2005. Biology of hogchoker in Chesapeake Bay. . Master of Science Thesis, University of Maryland, College Park, MD.
- Olaf P. Jensen, O. P. 2004 Spatial ecology of blue crab (*Callinectes sapidus*) in Chesapeake Bay. . Master of Science Thesis, University of Maryland, College Park, MD.

2. Scientific Publications

- Acker, J.G., L.W. Harding, G. Leptoukh, T. Zhu, and S. Shen. 2005. Remotely-sensed chl a at the Chesapeake Bay mouth is correlated with annual freshwater flow to Chesapeake Bay. *Geophys. Res. Lett.* 32, L05601, doi:10.1029/2004GL021852, 2005.
- Adolf, J.E., C.L. Jordan, W.D. Miller, M.E. Mallonee, and L.W. Harding, Jr. 2006. Phytoplankton floral composition, biomass, and primary productivity in Chesapeake Bay. *Estuar. Coast. Shelf Sci.* 67(1-2): 108-122.
- Adolf, J.E., D.K. Stoecker, and L.W. Harding, Jr. 2006. The balance of autotrophy and heterotrophy during mixotrophic growth of *Karlodinium micrum* (Dinophyceae). *J. Plankton Res.* (revised, in review)
- Brooks, M. T., R. R. Hood, and W. M. Kemp. 2006. Non-linear response of simulated estuarine food-webs to variations in nutrient input and predation pressure. *Mar Ecol Prog Ser (in preparation)*.
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- Harding, L. W. 2005 Review, Biological Oceanography by Charles B. Miller, Oxford and Malden (Massachusetts). Blackwell Science. Quaterly Review of Biology 80:494.
- Harding, L.W., Jr., Mallonee, M.E., and Perry, E.S. 2002. Toward a predictive understanding of primary productivity in a temperate, partially stratified estuary. *Estuar. Coast. Shelf Sci.* 55: 47-46.
- Harding, L.W., Jr., Magnuson, A., and Mallonee, M.E. 2005. Bio-optical and remote sensing observations in Chesapeake Bay. *Estuar. Coast. Shelf Sci.* 62: 75-94.
- Houde, E. D., J. Bichy and S. Jung. 2005. Effects of Hurricane Isabel on fish populations and communities in Chesapeake Bay. pp. 193-199. In: Sellner, K. G. (ed.). Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.
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3. Scientific Presentations

- Adolf, J.E. 2003. Ecological consequences of the phylogenetic diversity of phytoplankton. Maryland Sea Grant Research Fellow Summer Symposium 2003. Chesapeake Biological Lab, Solomons, Maryland, June 2003.
- Adolf, J.E., and L.W. Harding, Jr. Interpreting phytoplankton indicators against a backdrop of high spatial and temporal variability in Chesapeake Bay. EPA STAR EaGLEs meeting, Duluth, MN, Sept., 2004
- Adolf, J.E., and L.W. Harding, Jr. Variability of phytoplankton floral composition and size structure in Chesapeake Bay. Estuarine Research Federation Biennial Meeting, Norfolk, VA, Oct., 2005.
- Adolf, J.E., Jordan, C.J., Mallonee, M.E., Miller, W.D., and Harding, L.W., Jr. 2004. Phytoplankton floral composition and primary productivity in Chesapeake Bay. Poster, ASLO/TOS, Honolulu, Hawaii, Feb. 2004.
- Adolf, J.E., Mallonee, M.E., Miller, W.D., Hoover, M., and Harding, L.W. Jr. 2004. Integrating phytoplankton indicators: relationships between phytoplankton floral composition and size structure in Chesapeake Bay. All EaGLEs meeting, Duluth, Minnesota, Sept. 2004.
- Adolf, J.E., Mallonee, M.E., Miller, W.D., Hoover, M., Benjamin, J., and Harding, L.W. Jr. 2003. Phytoplankton indicators in two differentially impacted sub-estuaries of Chesapeake Bay. Poster, U.S. EPA STAR, EaGLEs Meeting, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.
- Adolf, J.E., Miller, W.D., Mallonee, M.E., Harding, L.W. Jr. 2004. Interpreting phytoplankton indicators against a backdrop of high spatial and temporal variability in Chesapeake Bay. All EaGLEs meeting, Duluth, Minnesota, Sept. 2004.
- Curti, K. L., T. J. Miller and E. D. Houde. Patterns in the abundance, size structure and distribution of the hogchoker, *Trinectes maculatus*, in the Chesapeake Bay, USA. American Fisheries Society Meeting, Quebec Cité, Quebec, Canada. August 2003
- Curti, K. L., and T. J. Miller. Patterns in the abundance, size structure and distribution of the hogchoker, *Trinectes maculatus*, in the Chesapeake Bay, USA. Annual Meeting of the Tidewater Section of the American Fisheries Society Meeting. Salisbury, MD. Jan. 2004.
- Curti, K. L. and T. J. Miller. Patterns in the distribution, size and age structure of the hogchoker, *Trinectes maculatus*, in the Chesapeake Bay. American Fisheries Society Meeting. Madison, WI. August 2004.
- Harding, L.W., Jr. 2003. Aircraft remote sensing in Chesapeake Bay. NOAA Coastal Services Center, Charleston, South Carolina, Oct. 2003.
- Harding, L.W., Jr. 2003. Aircraft remote sensing in Chesapeake Bay in support of chlorophyll criteria attainment. Tidal Monitoring Work Group, Chesapeake Bay Program, Laurel, Maryland, Oct. 2003.

- Harding, L.W., Jr. Supporting leading-edge science to advance our understanding of estuarine and coastal processes. Session chair, Maryland Sea Grant Performance Appraisal Team, Annapolis, MD, Sept., 2005.
- Harding, L.W., Jr. Chesapeake Bay Remote Sensing Program. Chesapeake Bay Remote Sensing Symposium, Smithsonian Environmental Research Center, Edgewater, Maryland. Jan., 2006.
- Harding, L.W., Jr., J.E. Adolf, and W.D. Miller. Variability and trends of chl-a in Chesapeake Bay. Estuarine Research Federation Biennial Meeting, Norfolk, VA, Oct., 2005.
- Harding, L.W., Jr., Adolf, J.E., Miller, W.D., and Mallonee, M.E. 2003. Aircraft remote sensing in Chesapeake Bay. NASA/EPA meeting ALL EaGLes meeting, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.
- Harding, L.W., Adolf, J.E., Miller, W.D., and Mallonee, M.E. 2003. Spatial and temporal scales of variability of phytoplankton indicator in Chesapeake Bay. ALL EaGLes meeting, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.
- Harding, L.W., Jr., J.E. Adolf, W.D. Miller, and M.E. Mallonee. Predictions of phytoplankton biomass and primary productivity using data from *in-situ* and remote sensing observations in Chesapeake Bay, USA. ASLO/TOS, Honolulu, HI, Feb., 2004
- Harding, L.W., Jr., and Scardi, M. 2002. Phytoplankton primary production in Chesapeake Bay: a comparison between neural networks and other models. 3rd Conf. International Society for Ecological Informatics, Rome, Italy, Aug. 2002.
- Houde, E. D. August 2003. Invited Keynote Presentation. “Dancing in Hjort’s shadow.” American Fisheries Society, Larval Fish Conference, Santa Cruz, CA.
- Houde, E. D. September 2003. Invited presentation. “Fish recruitments: biology, physics and features in estuarine ecosystems.” Estuarine Research Federation, Biennial Meeting, Seattle, WA.
- Houde, E.D., W.C. Boicourt, L.W. Harding, and M.R. Roman. 2004. Trophic Indicators of Ecosystem Health, ACE INC, Chesapeake Bay. ACE INC All Hands Meeting, Morehead City, NC, Apr., 2004.
- Houde, E.D., Harding, L.W., Jr., Roman, M.R., Adolf, J.E., Jung, S., Kimmel, D., and Miller, D. 2003. Evaluating trophic relationships and environmental variability to develop integrated indicators of estuarine state. U.S. EPA STAR, EaGLes Meeting, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.
- Houde, E. D., S. Jung, R. J. Wood, T. D. Auth, G. C. Rilling and J. B. Bichy. February 2004. Hindcasting and predicting bay anchovy recruitments in Chesapeake Bay. American Society of Limnology and Oceanography, Annual Meeting, Honolulu, HI.
- Houde, E. D., J. Bichy and S. Jung. November 2004. Effects of Hurricane Isabel on fish populations and communities in Chesapeake Bay. Hurricane Isabel in Perspectives Conference, Linthicum Heights, Maryland.
- Jung, S. and E. D. Houde. March 2005. Estimating production and recruitment variability of bay anchovy *Anchoa mitchilli* in Chesapeake Bay: application of size-based theory. Atlantic Estuarine Research Society Annual Meeting, Solomons, Maryland.
- Jung, S. and E. D. Houde. October 2005. Variability in recruitment and productivity of bay anchovy in Chesapeake Bay. Estuarine Research Federation Biennial Meeting, Norfolk, Virginia.
- Jung, S., Kimmel, D.G., Adolf, J.E., Houde, E.D., Roman, M.R., and Harding, L.W., Jr. 2003. Biomass size spectra: linking spectra across trophic levels as indicators of estuarine state. Poster presentation. U.S. EPA STAR, EaGLes, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.

- Jung, S., D.G. Kimmel, J. Adolf, E.D. Houde, M.R. Roman, and L.W. Harding, Jr. 2004. Biomass size spectra: linking spectra across trophic levels as indicators of estuarine state. EPA STAR, EaGLEs, University of California, Bodega Marine Laboratory, Bodega Bay, CA. Poster presentation, Apr., 2004.
- Jung, S, D.G. Kimmel, J. Adolf, E.D. Houde, M.R. Roman, and L.W. Harding, Jr. 2004. Biomass size spectra as integrative trophic indicators in Chesapeake Bay. EPA STAR EaGLEs 2004 Annual Meeting. Duluth, MN. Poster presentation, Sept., 2004
- Kemp, W.M., M. Brooks, W.R. Boynton. 2003. "Trophic yield, nutrient enrichment and environmental variation in Chesapeake Bay." Estuarine Research Federation Meeting. Seattle (September).
- Kemp, W.M. 2004. "Linking nutrient enrichment and fisheries harvest in coastal ecosystems: implications for integrated estuarine ecosystem management." Plenary Speaker. Joint Meeting of the Estuarine, Coastal Science Association and Estuarine Research Federation. Balina, NSW, Australia (June).
- Kimmel, D. G. and Roman, M. R. Weather patterns as indicators of mesozooplankton dynamics in the Chesapeake Bay. *The Earth's Eyes: Aquatic Sciences Through Space and Time*: American Society of Limnology and Oceanography. Salt Lake City, UT, USA. February 2003.
- Kimmel, D. G. and Roman, M. R. Influence of water quality parameters on zooplankton abundance and community composition in the northern Chesapeake Bay: implications for climate change. *Interdisciplinary Linkages in Aquatic Sciences and Beyond*. American Society of Limnology and Oceanography. Victoria, British Columbia, Canada. June, 2002.
- Kimmel, D.G., Miller, W.D., Roman, M.R., and Harding, L.W., Jr. 2003. Synoptic scale climatic forcing of plankton dynamics in Chesapeake Bay. Poster, U.S. EPA STAR, EaGLEs, University of California, Bodega Marine Laboratory, Bodega Bay, California, Dec. 2003.
- Kimmel, D.G., Zhang, X., Roman, M.R., Boicourt, W.C. and others. 2004. Spatial and temporal variability of mesozooplankton biomass size spectra in Chesapeake Bay as measured by an optical plankton counter. ASLO/TOS. Honolulu, Hawaii, Feb. 2004.
- Kimmel, D. G. and Roman, M. R. Weather patterns influence mesozooplankton dynamics in the Chesapeake Bay: implications for climate change. *Estuaries on the Edge*: Estuarine Research Federation. Seattle, WA, USA. September 2003.
- Kimmel, D. G. and Roman, M. R. Long-term changes in zooplankton abundance in the upper Chesapeake Bay. Chesapeake Bay Colloquium. Chesapeake Research Consortium/Estuarine Research Federation. Norfolk, VA, USA. October 2005
- Kimmel, D. G., Miller, W. D., Wood, R. J., Harding Jr, L. W. and Roman, M. R. Regional scale climate forcing of Chesapeake Bay trophic dynamics. *Estuarine Interactions: Biological-Physical Feedbacks and Adaptations*. Estuarine Research Federation. Norfolk, VA, USA. October 2005
- Martino, E. J. and E. D. Houde. March 2005. Role of environmental and density-dependent factors in control and regulation of recruitment in Chesapeake Bay striped baas. Atlantic Estuarine Research Society Annual Meeting, Solomons, Maryland.
- Martino, E. J. and E. D. Houde. October 2005. Sources of variability and stability in recruitment of Chesapeake Bay striped bass. Estuarine Research Federation Biennial Meeting, Norfolk, Virginia.
- Miller, W. D., Harding, L. W. and Kimmel, D. G. Predicting the spring discharge of the Susquehanna River from a synoptic climatology for the eastern United States. *Estuarine Interactions: Biological-Physical Feedbacks and Adaptations*. Estuarine Research Federation. Norfolk, VA, USA. October 2005.

- Miller, W.D., and Harding, L.W., Jr. 2003. Climate and phytoplankton dynamics. Atlantic Coast Environmental Indicators Consortium (ACE INC) Annual Meeting. Charleston, South Carolina, May 2003.
- Miller, W.D., and Harding, L.W., Jr. 2003. Influence of synoptic-scale climate variability on Chesapeake Bay phytoplankton biomass. Poster, Estuarine Research Federation, Seattle, Washington, Sept. 2003.
- Miller, W.D., L.W. Harding, Jr., and J.E. Adolf. The influence of Hurricane Isabel on Chesapeake Bay phytoplankton dynamics. Hurricane Isabel in Perspective Conference, Linthicum Heights, MD. Nov., 2004.
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- Nye, J. A. and T. J. Miller. Evaluation and application of a bioenergetic model of Atlantic croaker, *Micropogonias undulatus*, in Chesapeake Bay. American Fisheries Society Meeting. Anchorage, AK, Sept. 2005.
- Nye, J. A., D. L. Loewensteiner and T. J. Miller. Biotic and abiotic factors influencing the distribution and diet of Atlantic croaker in Chesapeake Bay. American Fisheries Society Meeting. Anchorage, AK, Sept. 2005.
- Nye, J. A. and T. J. Miller. Interspecific interactions between Atlantic croaker (*Micropogonias undulatus*) and weakfish (*Cynoscion regalis*) in Chesapeake Bay. American Fisheries Society Meeting. Madison, WI. August 2004.
- Nye, J. A, T. J. Miller and D. D. Davis. Maternal effects in *Fundulus heteroclitus* larvae exposed to contaminated sediment. Larval Fish Conference, Santa Cruz, CA. August 2003.

4. Seminars

- Adolf, J.E. 2004. Physical forcing of phytoplankton community structure, function, and fate in Chesapeake Bay. Horn Point Laboratory, Cambridge, Maryland, 20 October 2004.
- Boynton, W. R. Nutrient History of Chesapeake Bay. Distinguished Scientist Seminar. Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA October 2004
- Boynton, W. R. Dissolved Oxygen Effects in Chesapeake Bay. Md Sea Grant Symposia on Dissolved Oxygen in Chesapeake Bay. August, 2004
- Boynton, W. R. A Nutrient History of the Patuxent River Estuary. Univ MD IVN Seminar Series. Annapolis, MD May 2004
- Houde, E. D. March 2003. Invited Seminar. "What controls and regulates recruitments in estuarine-dependent fishes?" Louisiana State University, Baton Rouge, LA.
- Harding, L.W., Jr. 2004. Recent progress in aircraft and satellite remote sensing of Chesapeake Bay Integration and Application Network (IAN), University of Maryland Center for Environmental Science, 7 October 2004, Annapolis, Maryland.
- Harding, L.W., Jr. Recent progress in using aircraft and satellite remote sensing to study phytoplankton dynamics in Chesapeake Bay and the mid-Atlantic bight. Horn Point Laboratory, Cambridge, MD. Apr., 2005
- Kemp, W.M. 2002. Eutrophication and trophic transfer efficiency in aquatic ecosystems. Invited seminar speaker, Institute of Ecosystem Studies, Millbrook, NY. (March).
- Kemp, W.M. 2004. Eutrophication and fisheries harvest in coastal ecosystems. Invited seminar. UMCES, Chesapeake Biological Laboratory (December).
- Kemp, W.M. 2005. Linking nutrient enrichment and fisheries production in coastal marine ecosystems. UMCES, Horn Point Laboratory (February).

- Kemp, W. M. 2005. Nutrient Enrichment and Fisheries: Thoughts for Food Webs, Invited Workshop, *Response of Aquatic Food Webs to Nutrient Enrichment: Assessing the State of the Science*, US EPA, Gulf Ecology Research Lab, Gulf Breeze, FL (March)
- Kimmel, D. G. Jan 2003. Weather patterns as indicators of mesozooplankton dynamics in the Chesapeake Bay. Invited Seminar: Maryland Dept. Nat. Resources. Oxford, Maryland.
- Kimmel, D. G. Feb 2003. Weather patterns as indicators of mesozooplankton dynamics in the Chesapeake Bay. Invited Seminar: Chesapeake Biological Laboratory. Solomons, Maryland.
- Kimmel, D. G. Mar 2003. Weather patterns as indicators of mesozooplankton dynamics in the Chesapeake Bay. Invited Seminar: Horn Point Laboratory. Cambridge, Maryland.

VII. Literature Cited

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- Harding Jr., L. W., M. E. Mallonee, and E. S. Perry. 2002. Toward a predictive understanding of primary productivity in a temperate, partially stratified estuary. *Estuarine, Coastal and Shelf Science* **55**:46-47.
- Harding Jr., L. W., and E. S. Perry. 1997. Long-term increase of phytoplankton biomass in Chesapeake Bay, 1950-1994. *Marine Ecology Progress Series* **157**:39-52.
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- Kemp, W. M., M. T. Brooks, and R. R. Hood. 2001. Nutrient enrichment, habitat variability and trophic transfer efficiency in simple models of pelagic ecosystems. *Marine Ecology Progress Series* **223**:73-87.
- Kimmel, D. G., W. D. Miller, and M. R. Roman. 2006. Regional scale climatic forcing of Chesapeake Bay zooplankton dynamics. *Estuaries* **In Press**.
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