Forage Status and Trends Report for the Chesapeake Bay

Forage Action Team

November 2023

Chesapeake Bay Program
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Forage Action Team

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Acknowledgements

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Executive Summary

The 2014 Chesapeake Bay Watershed Agreement aimed to improve effectiveness of restoration and management in the Bay by explicitly listing outcomes that would be carried out by designated Goal Implementation Teams. The Forage Outcome was developed with a goal of better understanding the role of forage in the Chesapeake Bay ecosystem and to determine if there is sufficient prey available to sustain key predator populations such as striped bass and summer flounder. The Forage Action Team (FAT), through various funding opportunities, has worked to address this outcome by identifying important forage taxa in the Bay, assessing their status and trends in abundance over time, and developing a suite of indicators. The purpose of this report is to summarize these forage-focused projects to answer the overarching questions: How is the Chesapeake Bay forage base changing over time, and is there enough food available for key predators?

Overall, forage abundance in the Chesapeake Bay exhibits high interannual variability, although some long-term trends were identified in the time series. Abundances of young-of-the-year forage fishes have been relatively low since the 2000s compared to historic estimates. Total benthic invertebrate biomass throughout the Chesapeake Bay appears to be relatively stable, fluctuating around an average, and perhaps exhibiting a slight increase over time. This slight increase is likely driven primarily by polychaetes, whereas mysid biomass appears to have declined over time. Diet analyses determined that polychaetes were the most important prey taxa for a suite of Chesapeake Bay fish predators, but relative contributions of Atlantic menhaden and bay anchovy to diets have increased over time. Insects also play a large role in the diet of resident striped bass in the shallow waters of the Bay tributaries. Total annual consumption by all Chesapeake Bay predators examined (striped bass, summer flounder, Atlantic croaker, white perch, weakfish, spot) decreased substantially since 2004, leveling out around 2011.

Forage abundance is influenced by habitat and environmental conditions (e.g., water quality, climate, structured habitat) in the Chesapeake Bay, and these relationships are often species-dependent. Shoreline hardening alters nearshore habitat, which has negative effects on forage species' growth and abundance, particularly above thresholds of 10-30% hardened shoreline in the watershed. Abundance of the most important benthic (polychaetes) and finfish (bay anchovy) forage taxa increases when Bay water temperatures warm quickly in late winter-early spring and precipitation levels are high. The extent of suitable habitat is significantly, positively correlated with the abundance of juvenile spot in summer and bay anchovy in winter, suggesting that environmental conditions affect the carrying capacity of the Chesapeake Bay for these two key forage species during a portion of the year. Additional studies focused on the effects of environmental conditions and habitat could be expanded to include other key forage species (e.g., Atlantic menhaden, mysids) to better capture potential future impacts on the forage base as a whole.

Although much has been learned through this body of work, some key data gaps remain. For example, there is a need to better understand predator nutritional requirements, prey nutritional

value, and the implications of prey switching. Zooplankton monitoring and assessment would also improve our ability to track and assess the forage base because zooplankton is a key energy source in the food web, particularly for planktivorous forage fishes such as Atlantic menhaden and bay anchovy. The decline in fish predator consumption raises questions about mechanisms driving predator and prey populations (i.e., bottom-up vs. top-down processes) and changes in predator body condition over time. To directly address the question of whether sufficient prey are available for Chesapeake Bay predators, absolute abundance estimates of both forage and predators are also needed, but this is beyond the purview of the FAT as it requires additional, high-resolution data.

While this report is a culmination of research completed to achieve the Forage Outcome since 2014, the FAT will continue to track the status and trends of the forage base in Chesapeake Bay by selecting several indicators to update on a regular basis (e.g., benthic invertebrate biomass, hardened shorelines). The National Oceanic and Atmospheric Administration's Chesapeake Bay Office (NCBO) will also continue to build on the consumption profile for striped bass using new Bay-specific abundance estimates and additional diet data from recent years. Results of the indicator updates and additional research will be shared with interested stakeholders through Sustainable Fisheries Goal Implementation Team meetings, NCBO seasonal summaries, and possibly a Chesapeake Bay state of the ecosystem report (e.g., Bay Barometer).

Introduction

Background

The Chesapeake Bay is the largest estuary in the United States, providing critical forage, nursery, and spawning habitat for many ecologically and economically important species along the East Coast such as striped bass (*Morone saxatilis*) and summer flounder (*Paralichthys dentatus*). Commercial and recreational fishing in the Bay support the economy, with more than 500 million pounds of seafood harvested each year. To preserve this valuable ecosystem, resource managers use best management practices to ensure healthy habitat conditions and sustainable fisheries.

In 2014, partners in the Chesapeake Bay Program (CBP) signed the Chesapeake Bay Watershed Agreement. The Agreement aimed to improve the effectiveness of restoration and management in the Bay by explicitly listing outcomes that would be carried out by designated Goal Implementation Teams (GITs). The Sustainable Fisheries GIT (SFGIT) applies an ecosystem-based approach to “protect, restore, and enhance finfish, shellfish, and other living resources, their habitats, and ecological relationships to sustain all fisheries and provide for a balanced ecosystem in the watershed and Bay” (Chesapeake Bay Program 2014). The Forage Outcome in particular was developed with ecological relationships and ecosystem-based fisheries management (EBFM) in mind, striving to “continually improve the partnership’s capacity to understand the role of forage fish populations in the Chesapeake Bay…and to develop a strategy for assessing the forage fish base available as food for predatory species.”

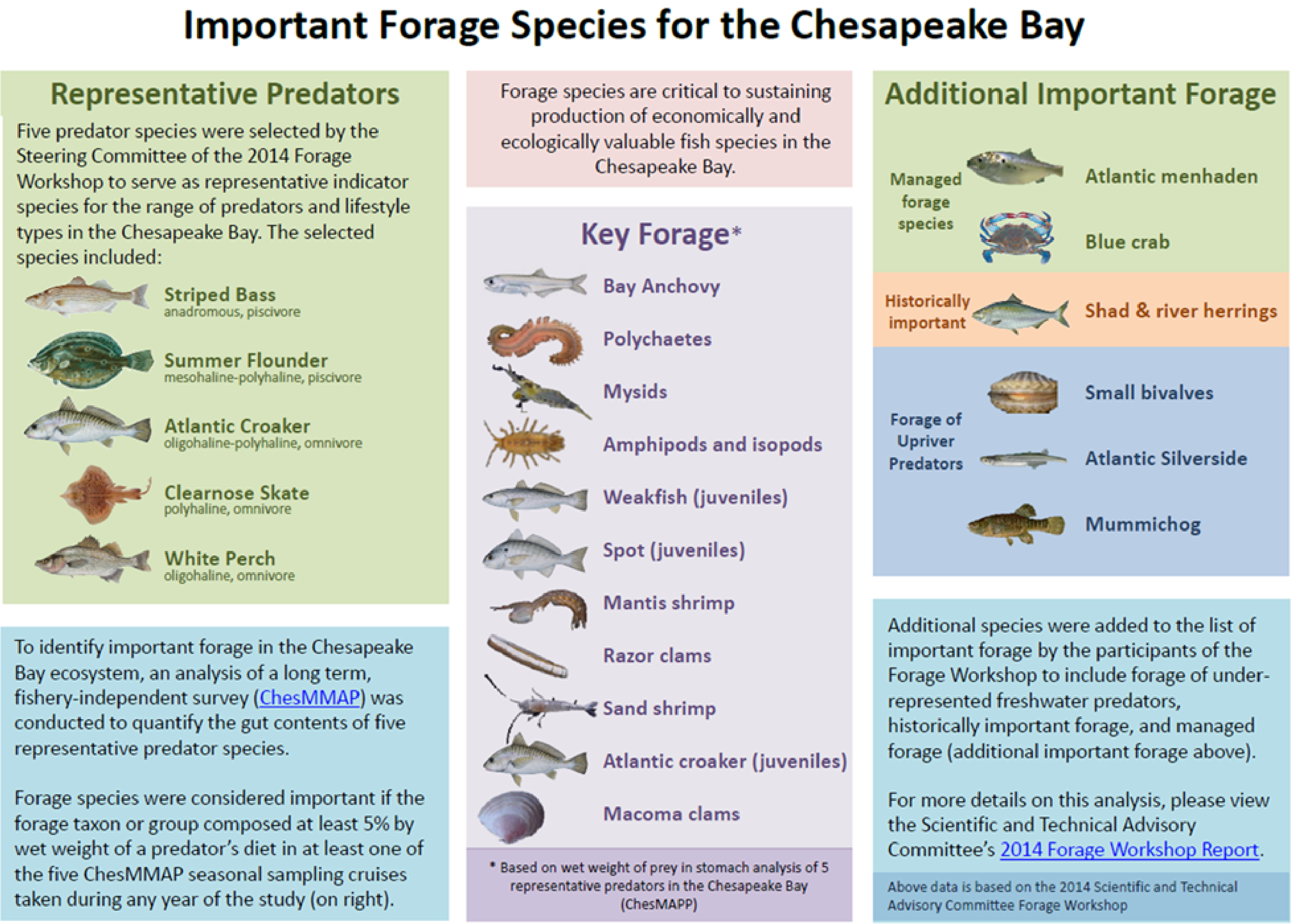
With the signing of the Agreement, the Forage Action Team (FAT) was established within the CBP structure to address the Forage Outcome. One of the first tasks of the FAT was conducting a forage workshop in partnership with CBP’s Scientific and Technical Advisory Committee (STAC). The STAC forage workshop determined the need for forage indicator development and identified key forage species in the Chesapeake Bay (Figure 1; Ihde et al. 2015). The FAT has continued to build off of the recommendations in the STAC workshop report to develop a suite of indicators that can be used to assess the status of the forage base in the Bay, and published the Forage Indicator Development Plan in 2020.

Indicator Framework

The Forage Indicator Development Plan laid out a framework for creating a suite of indicators that could be used to assess and track the health of forage in the Chesapeake Bay, with the goal of informing CBP and management priorities previously identified by the FAT (e.g., water quality, habitat conservation/restoration, forage abundance, predator-prey relationships). The framework for indicator development is based on a tiered approach with increasing complexity. Tier 1 is a time series of abundance (or biomass) for a given forage species (or taxa), including benthic invertebrates and finfishes, to determine the status and trends of forage availability in the Chesapeake Bay. Tier 2 indicators quantify relationships between environmental and/or habitat factors and forage abundance to improve our understanding of ecological relationships and to use those relationships to track and predict forage availability over time. Tier 3 tracks changes in predator consumption of forage to better understand how prey consumption changes over time and the relationship between prey preference and availability.

Purpose

Since the 2014 STAC workshop, several projects focused on forage have been completed that lend support to the development of indicators. This report summarizes those projects and their results in the context of assessing the forage base to draw conclusions about the status and trends of forage availability in the Chesapeake Bay. Remaining knowledge gaps and a path forward for forage indicators are also identified.



Important Forage Species for the Chesapeake Bay

Representative Predators

Five predator species were selected by the Steering Committee of the 2014 Forage Workshop to serve as representative indicator species for the range of predators and lifestyle types in the Chesapeake Bay. The selected species included:

- **Striped Bass** anadromous, piscivore
- **Summer Flounder** mesohaline-polyhaline, piscivore
- **Atlantic Croaker** oligohaline-polyhaline, omnivore
- **Clearnose Skate** polyhaline, omnivore
- **White Perch** oligohaline, omnivore

To identify important forage in the Chesapeake Bay ecosystem, an analysis of a long term, fishery-independent survey (ChesMMAP) was conducted to quantify the gut contents of five representative predator species.

Forage species were considered important if the forage taxon or group composed at least 5% by wet weight of a predator's diet in at least one of the five ChesMMAP seasonal sampling cruises taken during any year of the study (on right).

Forage species are critical to sustaining production of economically and ecologically valuable fish species in the Chesapeake Bay.

Key Forage*

- Bay Anchovy
- Polychaetes
- Mysids
- Amphipods and isopods
- Weakfish (juveniles)
- Spot (juveniles)
- Mantis shrimp
- Razor clams
- Sand shrimp
- Atlantic croaker (juveniles)
- Macoma clams

* Based on wet weight of prey in stomach analysis of 5 representative predators in the Chesapeake Bay (ChesMAPP)

Additional Important Forage

Managed forage species	Atlantic menhaden Blue crab
Historically important	Shad & river herrings
Forage of Upriver Predators	Small bivalves Atlantic Silverside Mummichog

Additional species were added to the list of important forage by the participants of the Forage Workshop to include forage of under-represented freshwater predators, historically important forage, and managed forage (additional important forage above).

For more details on this analysis, please view the Scientific and Technical Advisory Committee's 2014 Forage Workshop Report.

Above data is based on the 2014 Scientific and Technical Advisory Committee Forage Workshop

Figure 1. Graphic from the 2014 STAC workshop report identifying the most important forage species in the Chesapeake Bay based on the diets of five representative predators from different trophic guilds (Ihde et al. 2015).

Tier 1 Indicators: Forage Abundance

Finfishes

Overview

One of the primary objectives of the Forage Outcome is to track and assess the status of forage populations in the Chesapeake Bay to determine the amount of food available for commercially and recreationally important fish predators. A study supported by the Chesapeake Bay Trust's GIT Funding Program took the first step in developing forage indicators, creating indices of relative abundance of forage fish species to monitor their status over time (Buchheister & Houde 2016). The forage species examined in this study were identified as important in the 2014 STAC workshop report (Figure 1; Ihde et al. 2015), and included Atlantic menhaden (*Brevoortia tyrannus*), bay anchovy (*Anchoa mitchilli*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestilvalis*), Atlantic silverside (*Menidia menidia*), Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), and weakfish (*Cynoscion regalis*).

Methods

Relative annual abundance of young-of-the-year (YOY) forage fishes was calculated using catch data from existing fisheries-independent surveys throughout the Chesapeake Bay including the Virginia Institute of Marine Science (VIMS) Juvenile Striped Bass Seine Survey and the Juvenile Finfish Trawl Survey, the Maryland Department of Natural Resources (MDNR) Juvenile Striped Bass Survey and the Blue Crab Summer Trawl Survey, and the University of Maryland Center for Environmental Science (UMCES) Chesapeake Bay Fishery-Independent Multispecies Survey (ChesFIMS). Delta-lognormal generalized linear models (delta-GLMs) were used to develop abundance indices for each species from each survey, and then a single index of abundance was calculated for each species using a Bayesian hierarchical model (Conn 2010). Time series of relative abundance were developed for each of the six predators from 1959 to 2014, although this report primarily focuses on trends since 2000.

Results and Discussion

All forage fish species examined exhibited considerable interannual variability in abundance, although a few patterns were detected (Figure 2). Abundances of Atlantic croaker and weakfish, members of the Sciaenidae family, were positively correlated over the time series, and both species were relatively abundant from 2005 to 2012. Relative abundances of YOY Atlantic menhaden and spot were also positively correlated, and each experienced a peak around 2005-2006. Bay anchovy abundance was relatively low and stable after experiencing a decline in the mid-1990s. While specific mechanisms driving large-scale patterns in abundance (as seen in this study) are unclear, research suggests potential links to climate and other environmental factors (Wingate & Secor 2008, Wood & Austin 2009, Buchheister et al. 2016).

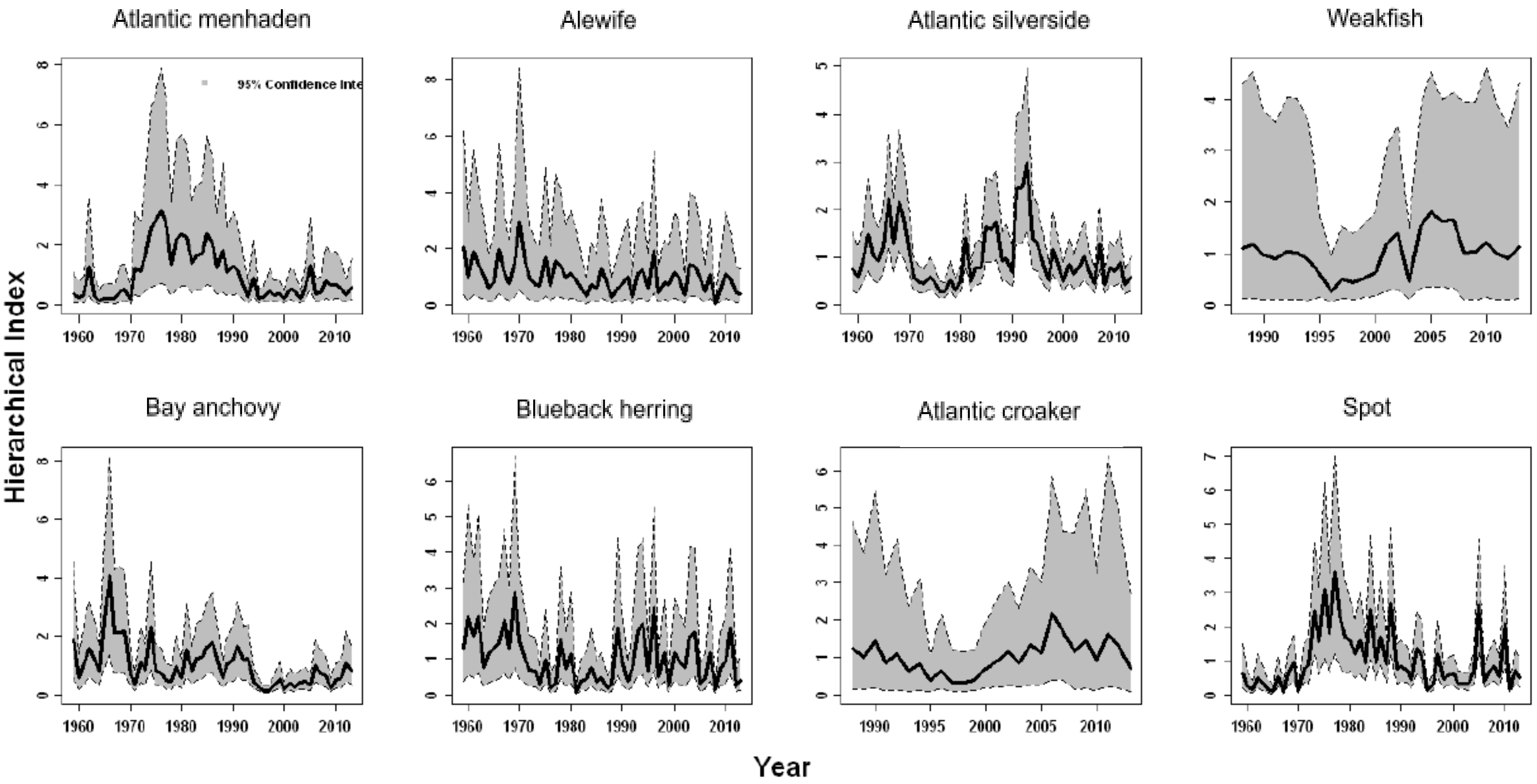


Figure 2. Relative YOY abundance indices for eight forage fish species. The indices were derived using data from multiple surveys and a hierarchical Bayesian analysis, which standardized the indices to a mean of 1 (Buchheister & Houde 2016).

Benthic Invertebrates

Overview

In addition to finfishes, the 2014 STAC workshop determined that benthic invertebrates are an important component of the forage base (Figure 1; Ihde et al. 2015). NCBO developed a time series of biomass estimates for key benthic taxa to track changes in prey availability in the Chesapeake Bay over time. These analyses focused on the following benthic taxa that were identified as critical for sustaining valuable fish species in the 2014 STAC workshop report: polychaetes, mysids, amphipods, isopods, razor clams, and macoma clams.

Methods

Biomass data from the Chesapeake Bay Benthic Monitoring Program were grouped by taxa of interest to develop time series of relative biomass throughout the Bay from 1995 to 2019. The total relative biomass of all the benthic taxa examined was also estimated over time. To model relative invertebrate biomass over time, a delta-generalized linear model (delta-GLM) approach was implemented in R (version 1.7.2). Year, depth, and stratum were included in the models as explanatory variables, and a gamma distribution was assumed for the positive observations. A jackknife routine was used to estimate coefficients of variation (CVs), which were then used to calculate confidence intervals for the time series. Linear regression models were run to examine long-term trends in the biomass indices over time.

Results and Discussion

Polychaete biomass indices in the Chesapeake Bay were highly variable, with a slight increase over the time series (Figure 3). Biomass indices were particularly high in 1995 and 2011, but there was an extended period of lower biomass from 2004 to 2008. Amphipod biomass indices primarily fluctuated around the average, with only a negligible positive trend over time (Figure 4). Notable years of relatively high biomass include 2003, 2004, and 2011, while 1995, 2005, 2012, and 2019 had some of the lowest biomass estimates of the time series. Biomass indices of isopods also fluctuated around an average, with higher estimates at the beginning (1995-1996) and end (2015-2019) of the time series (Figure 5). Mysid indices exhibited the most notable long-term trend, with relative biomass decreasing over time (Figure 6). Biomass fluctuated somewhat regularly from year to year until about 2013, at which point biomass leveled off except for the substantially high estimate in 2016. Razor and macoma clam biomass indices showed regular annual variability and no long-term trends over the time series (Figures 7,8). In general, indices of total biomass of key benthic invertebrates throughout the Bay varied annually, fluctuating around some average that appears to increase marginally over time (Figure 9). The slight increase in total forage biomass was likely driven by polychaetes.

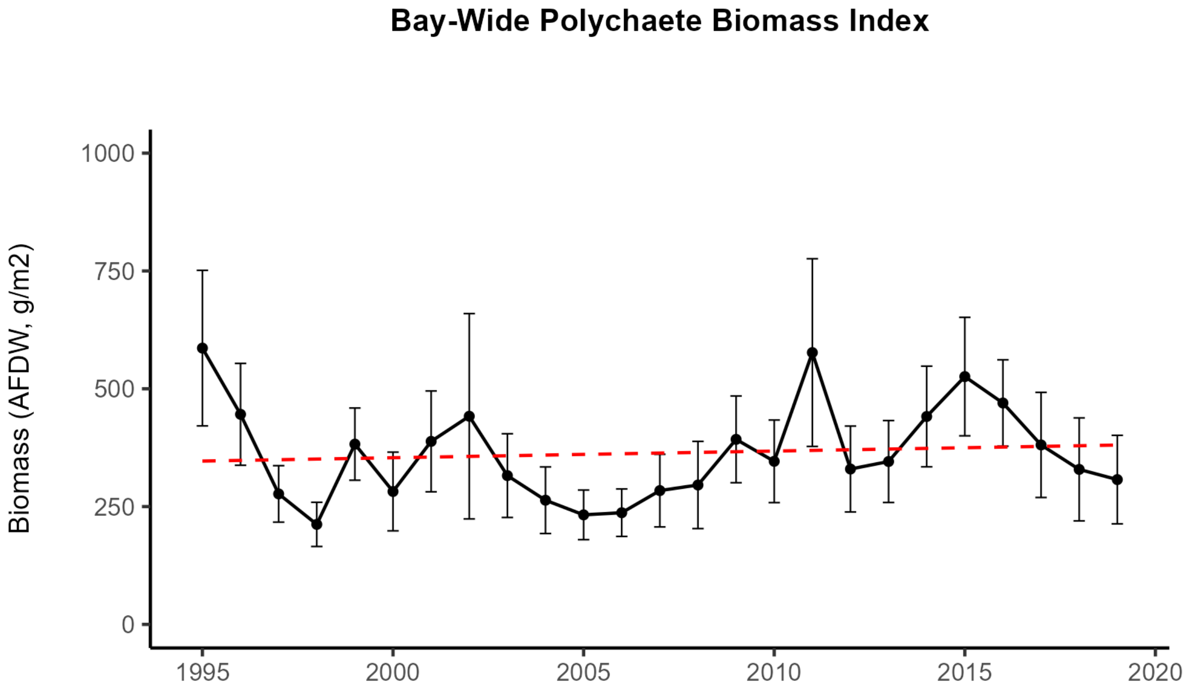


Figure 3. Relative polychaete biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction.

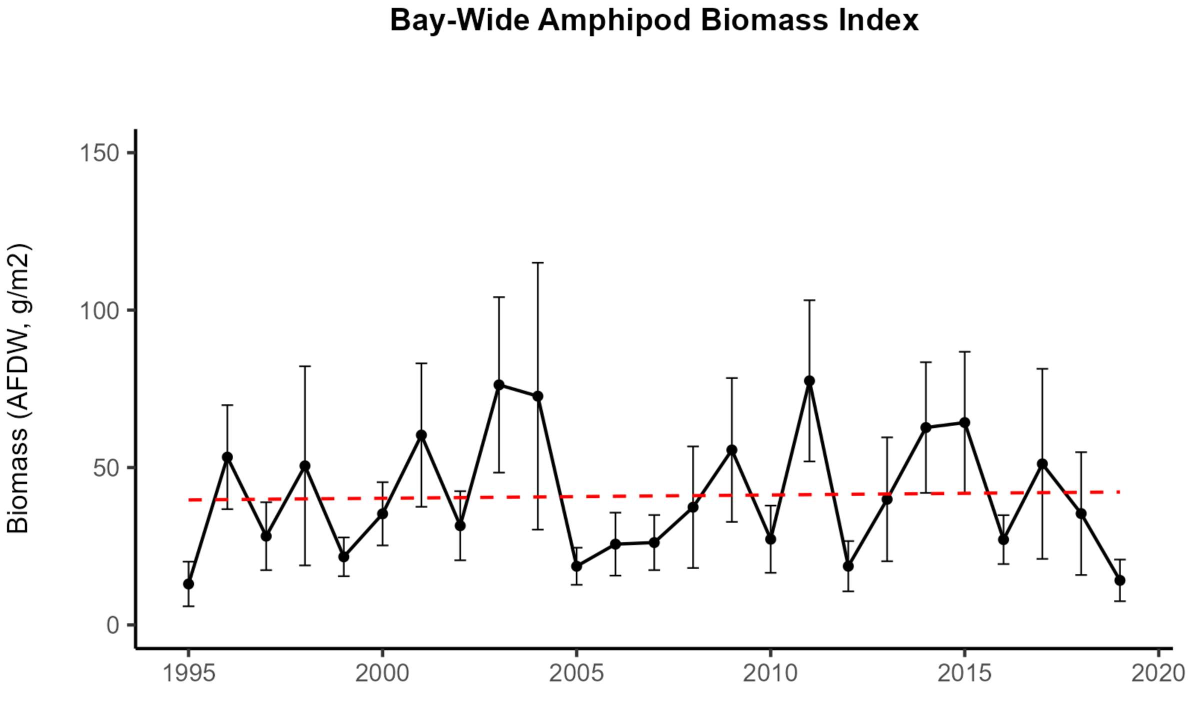


Figure 4. Relative amphipod biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction.

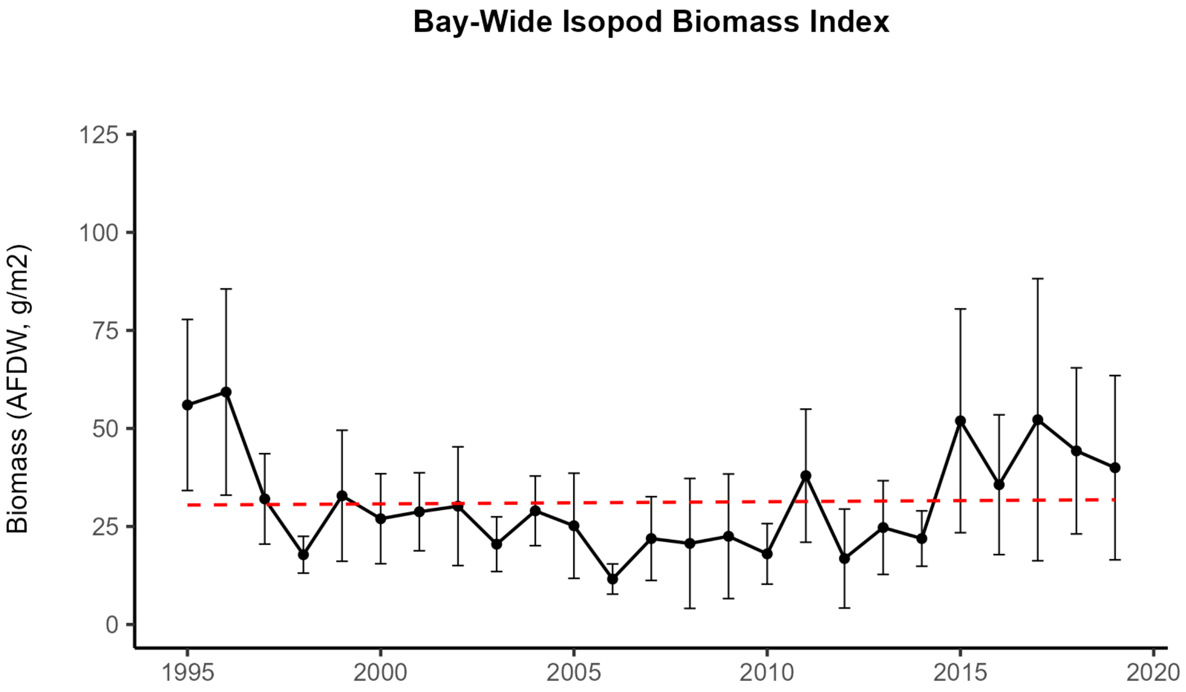


Figure 5. Relative isopod biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction.

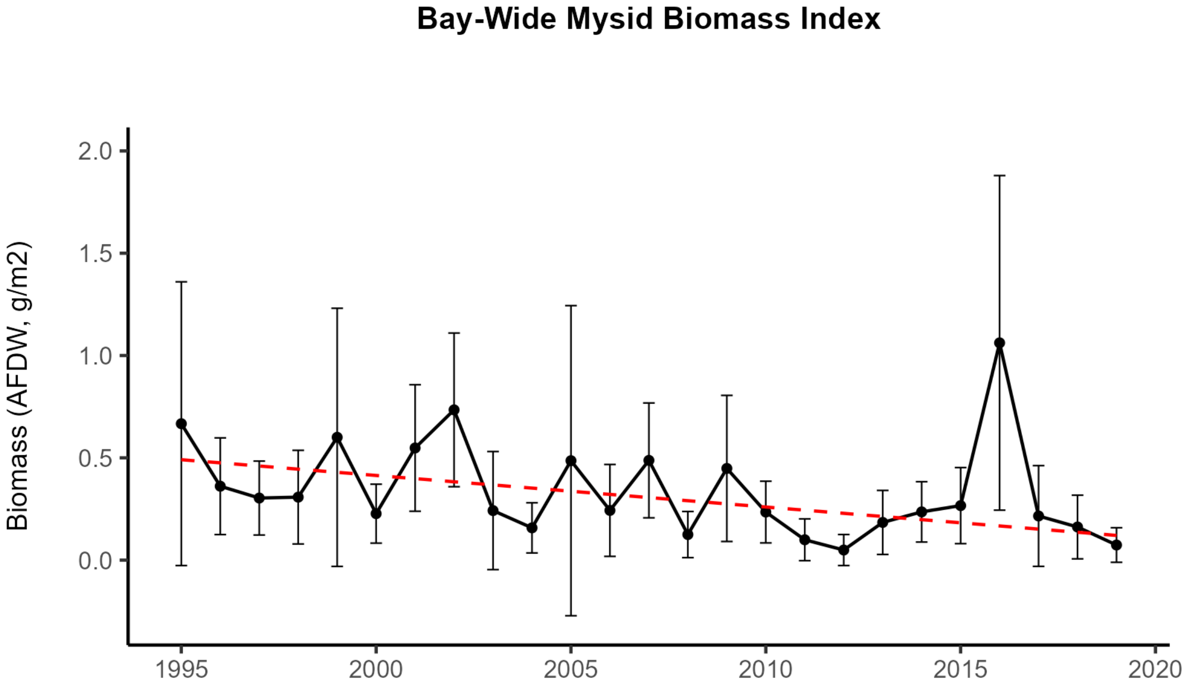


Figure 6. Relative mysid biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual and the dashed red line represents the linear regression model prediction.

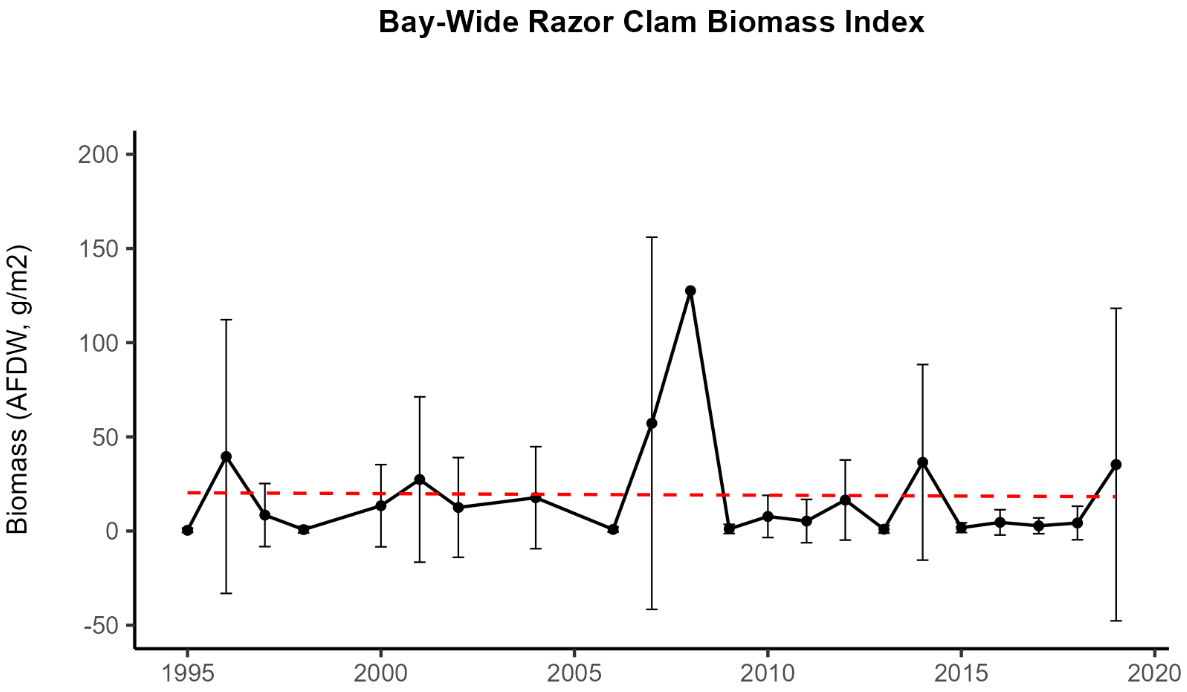


Figure 7. Relative razor clam biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction.

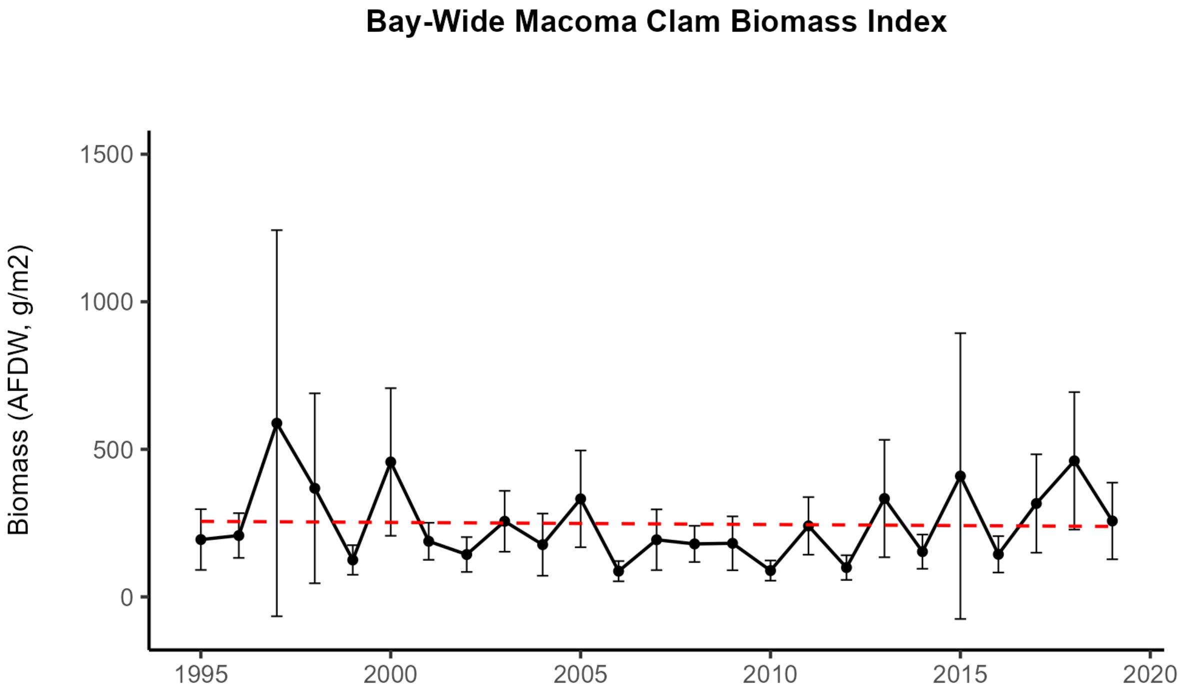


Figure 8. Relative macoma clam biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction.

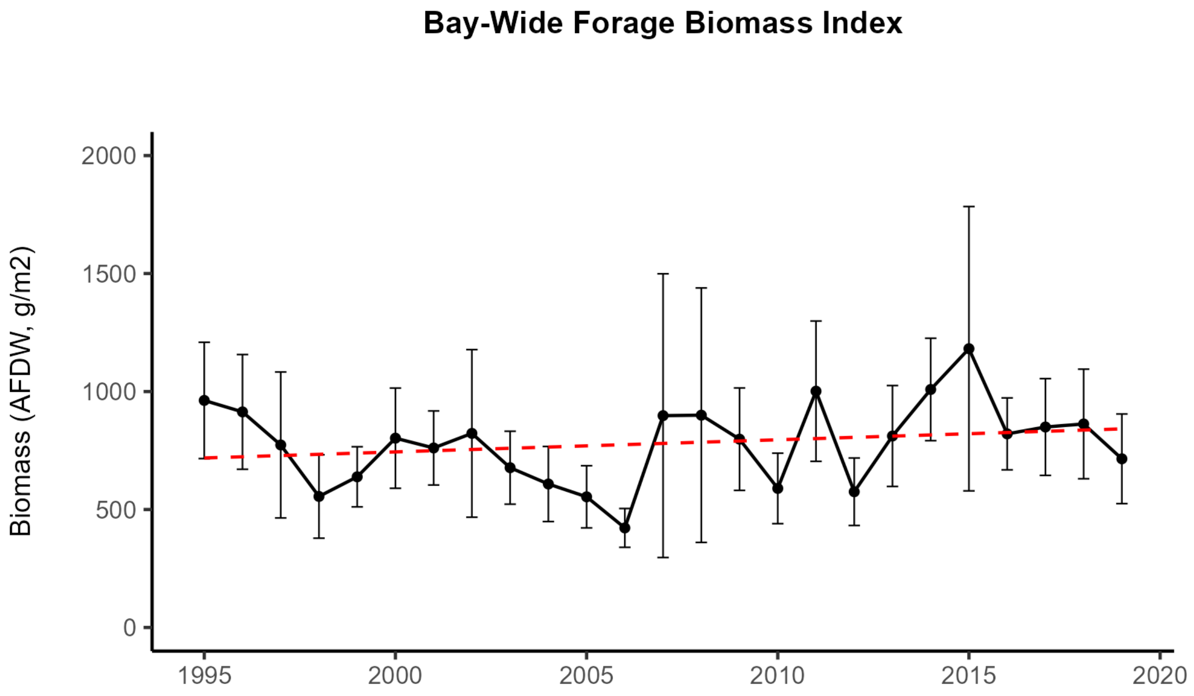


Figure 9. Relative benthic forage biomass in the Chesapeake Bay from 1995 to 2019. Error bars represent the 95% confidence intervals of the annual estimates and the dashed red line represents the linear regression model prediction. Taxa analyzed include polychaetes, amphipods, isopods, mysids, razor clams, and macoma clams.

Tier 2 Indicators: Habitat and Environmental Factors

Shoreline Hardening

Overview

Shoreline hardening has been linked to lower abundances of benthic invertebrates (i.e., bivalves, crabs) and small, shallow-water forage fish species (i.e., mummichog [*Fundulus heteroclitus*], striped killifish [*Fundulus majalis*], naked goby [*Gobiosoma bosc*]) throughout the tributaries of the Chesapeake Bay (Seitz et al. 2006, Kornis et al. 2017). Two GIT-funded studies were conducted to quantify the effects of shoreline hardening on key forage species at the Bay-wide (Seitz et al. 2019) and tributary (York River; Tuckey et al. 2019) scales. The primary goal of these projects was to develop metrics of shoreline hardening and identify thresholds above which forage species are negatively affected.

Methods

Bay-wide study:

Existing shoreline condition and nekton abundance data spanning 39 tributaries and 587 sample sites (Kornis et al. 2017) were used to evaluate relationships between percent hardened shoreline within a given tributary and the mean abundance of various forage species including Atlantic menhaden, bay anchovy, hogchoker (*Trinectes maculatus*), silversides (*Menidia* spp.), Atlantic croaker, spot, and blue crab (*Callinectes sapidus*). A graphical approach was implemented to fit non-linear curves (i.e., piecewise regression, sigmoid function) to the data to identify thresholds. Data from the VIMS Juvenile Blue Crab Survey were also used to evaluate the relationship between juvenile blue crab density and percent hardened shoreline within 250 m of crab sampling locations. Locally estimated scatterplot smoothing (LOESS) was used to fit a smooth curve through the juvenile blue crab data to assess the relationship.

York River study:

Land use and shoreline data and fishery-independent survey data from the VIMS Juvenile Finfish Trawl Survey and Juvenile Striped Bass Seine Survey were used to run generalized additive models (GAMs) to assess the quality (i.e., abundance, biomass, size) of 15 forage species relative to the fraction of shoreline that is hardened in the York River. Other covariates incorporated into the GAMs included water temperature, salinity, submerged aquatic vegetation coverage, land use, and flow.

Results and Discussion

The effect of hardened shorelines on forage abundance and quality varied by species. The Bay-wide analysis identified a range of threshold values from 10 to 30% hardened shoreline, suggesting that the abundance of key forage species decreases when 10 to 30% of the shoreline is hardened (Figures 10-16). Atlantic croaker, bay anchovy, blue crab, and spot were most vulnerable to shoreline hardening with a threshold of 10%, whereas Atlantic menhaden and hogchoker were more tolerant with a threshold of 30% (Table 1). Silverside abundance reached a threshold at 20% hardened shoreline. Although a threshold was not identified for juvenile blue crabs, juvenile density generally declined with increasing shoreline development, such that for every 1% increase in hardened shoreline, there is a 0.4% decrease in juvenile blue crab density (Figure 17).

In the York River, shoreline hardening had mixed effects depending on species and data source (i.e., trawl vs. seine survey; Table 2). Shoreline hardening had a significant negative effect on weakfish biomass in the York River based on trawl survey catch data (Figure 18). There was also a negative effect of hardening on white perch mean length and biomass as observed in both the trawl and seine survey catches (Figure 19).

Overall, hardened shorelines negatively affect key forage species at both Bay-wide and tributary scales. At the Bay-wide scale, thresholds of 10 to 30% hardening can be used to inform land use management decisions related to shoreline development and targeted conservation and restoration efforts to protect important forage species within the Chesapeake Bay ecosystem. For example, based on the results of this work, the lower James River, the Potomac River, the lower Patuxent River, and most of the upper Bay from the Choptank River to the Gunpowder River were identified as areas of high potential risk for forage due to the high percentage of shorelines that have been hardened in these regions (Figure 20). Prioritizing the restoration and conservation of natural shorelines in these areas would improve habitat availability for key forage species.

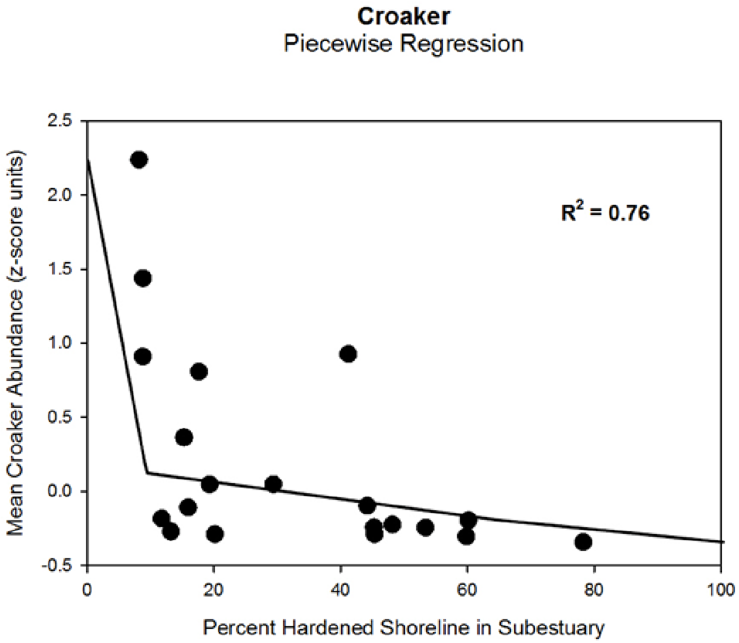


Figure 10. Mean relative abundance of Atlantic croaker in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a piecewise regression (Seitz et al. 2019).

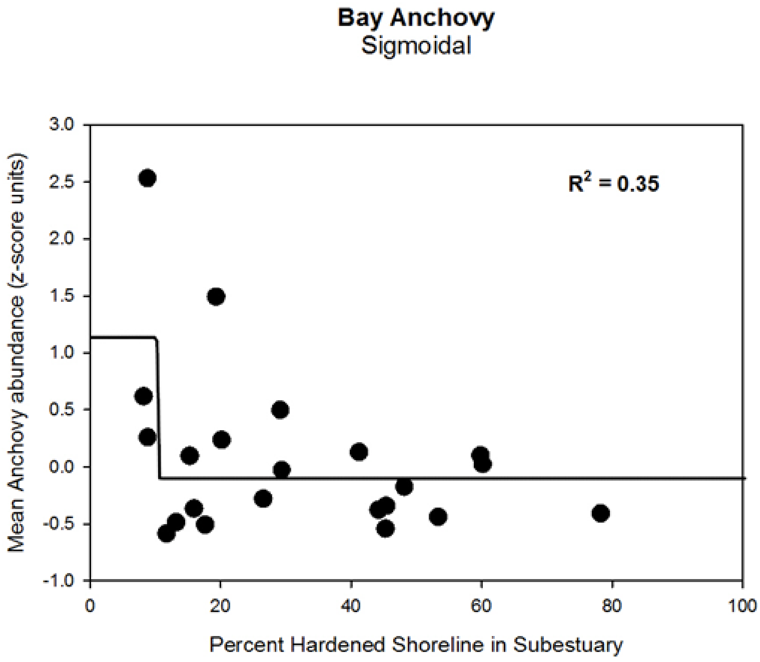


Figure 11. Mean relative abundance of bay anchovy in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a sigmoid function (Seitz et al. 2019).

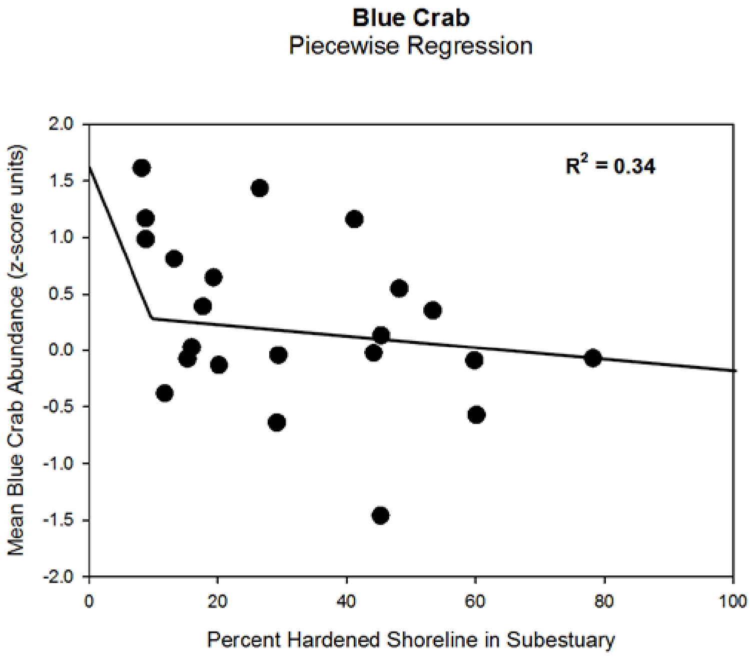


Figure 12. Mean relative abundance of blue crab in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a piecewise regression (Seitz et al. 2019).

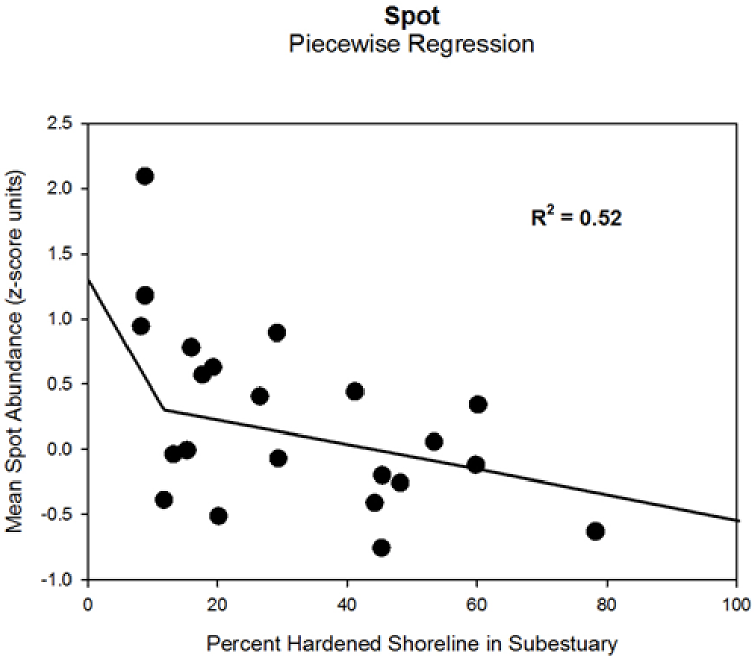


Figure 13. Mean relative abundance of spot in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a piecewise regression (Seitz et al. 2019).

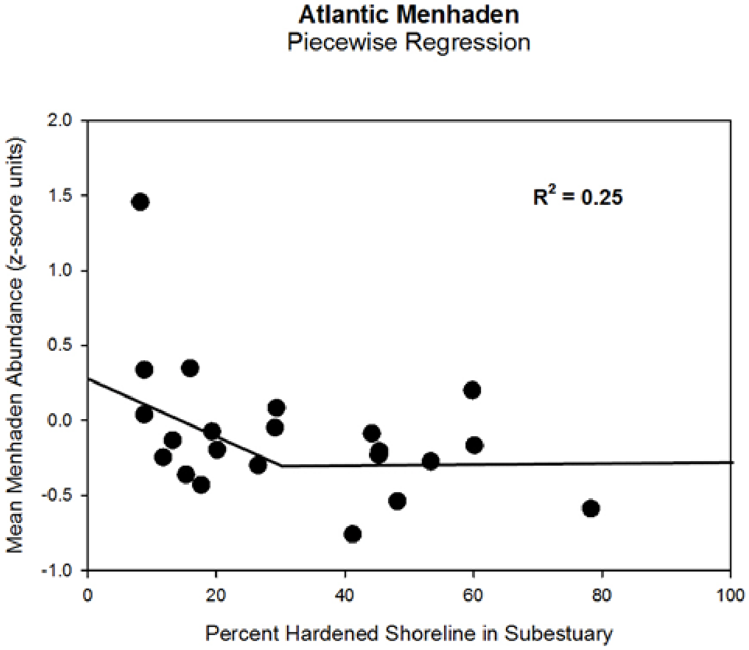


Figure 14. Mean relative abundance of Atlantic menhaden in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a piecewise regression (Seitz et al. 2019).

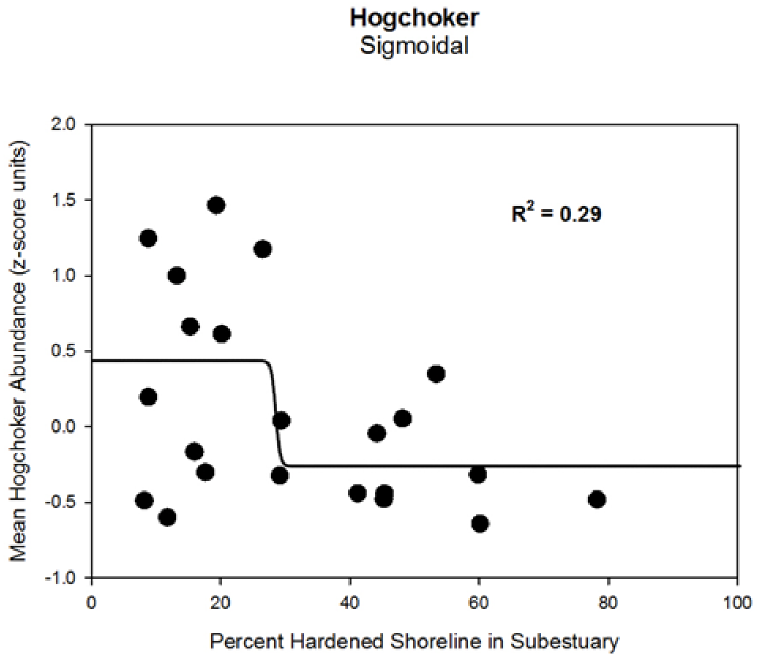


Figure 15. Mean relative abundance of hogchoker in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a sigmoid function (Seitz et al. 2019).

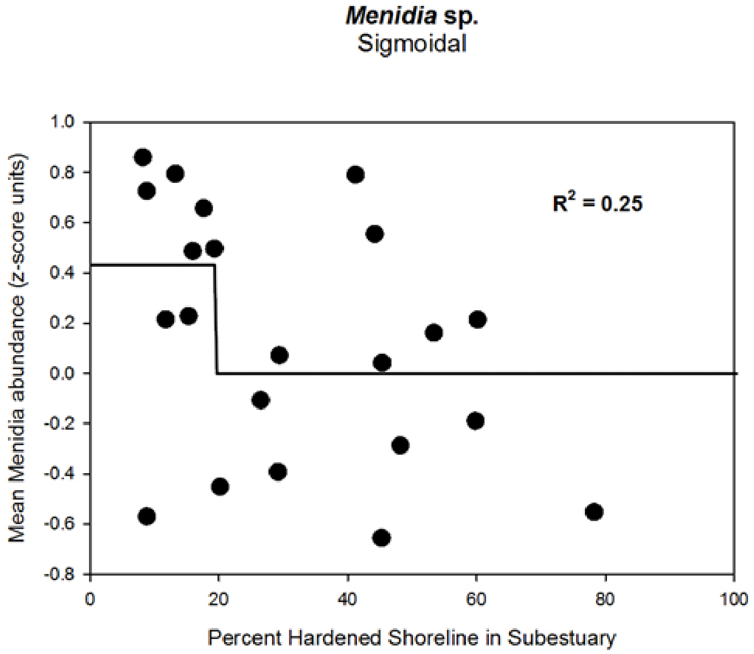


Figure 16. Mean relative abundance of silversides in Chesapeake Bay tributaries of varying degrees of shoreline hardening, fit with a sigmoid function (Seitz et al. 2019).

Table 1. Thresholds of percent hardened shoreline for several key forage species in the Chesapeake Bay (Seitz et al. 2019). When these values are exceeded in a given tributary, species abundance is likely to decrease.

Species	**Threshold Value (% Hardened Shoreline)**
Atlantic croaker (*Micropogonias undulatus*)	10%
Bay anchovy (*Anchoa mitchilli*)	10%
Blue crab (*Callinectes sapidus*)	10%
Spot (*Leiostomus xanthurus*)	10%
Silversides (*Menidia* spp.)	20%
Atlantic menhaden (*Brevoortia tyrannus*)	30%
Hogchoker (*Trinectes maculatus*)	30%

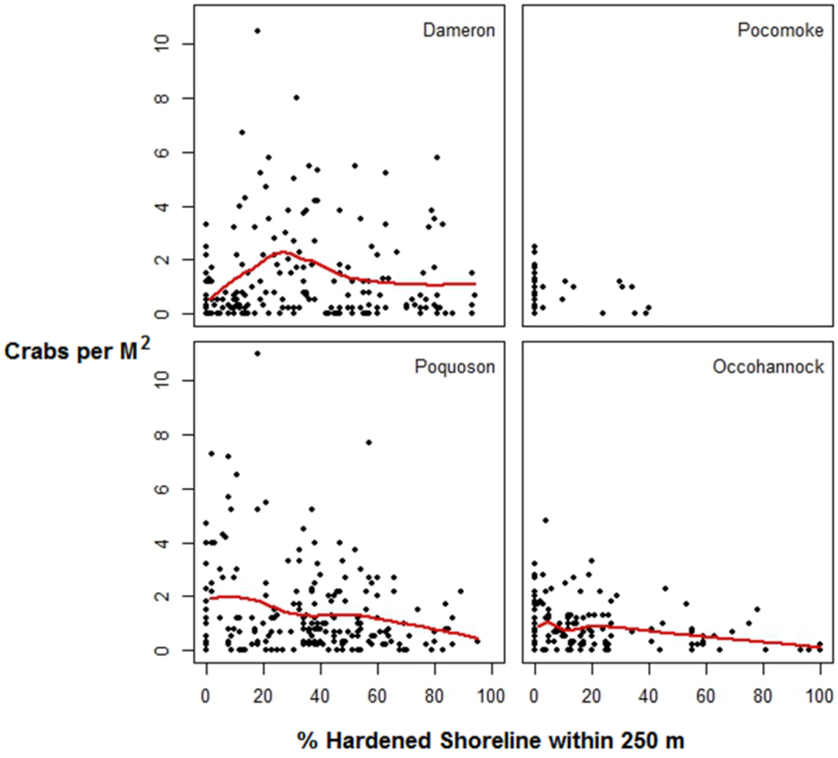
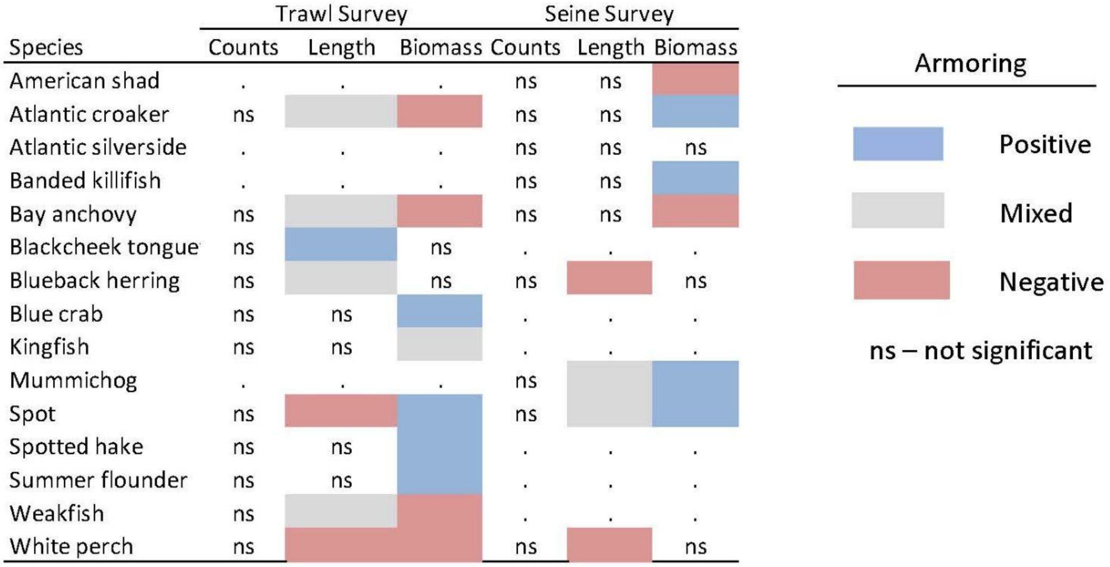


Figure 17. Juvenile blue crab density at varying levels of shoreline hardening within four shallow-water sampling regions in the lower Chesapeake Bay, fit with LOESS curves (red; Seitz et al. 2019). Only crab samples within 250 m of shoreline were used in the analysis.

Table 2. The effects of shoreline armoring (hardening) on various forage species in the York River, Virginia, based on data from the VIMS Juvenile Finfish Trawl Survey and the Juvenile Striped Bass Seine Survey (Tuckey et al. 2019).



	Trawl Survey			Seine Survey		
Species	Counts	Length	Biomass	Counts	Length	Biomass
American shad	.	.	.	ns	ns	🟥
Atlantic croaker	ns	⬜	🟥	ns	ns	🟦
Atlantic silverside	.	.	.	ns	ns	ns
Banded killifish	.	.	.	ns	ns	🟦
Bay anchovy	ns	⬜	🟥	ns	ns	🟥
Blackcheek tongue	ns	🟦	ns	.	.	.
Blueback herring	ns	⬜	ns	ns	🟥	ns
Blue crab	ns	ns	🟦	.	.	.
Kingfish	ns	ns	⬜	.	.	.
Mummichog	.	.	.	ns	⬜	🟦
Spot	ns	🟥	🟦	ns	⬜	🟦
Spotted hake	ns	ns	🟦	.	.	.
Summer flounder	ns	ns	🟦	.	.	.
Weakfish	ns	⬜	🟥	.	.	.
White perch	ns	🟥	🟥	ns	🟥	ns

Armoring	
🟦	Positive
⬜	Mixed
🟥	Negative

ns – not significant

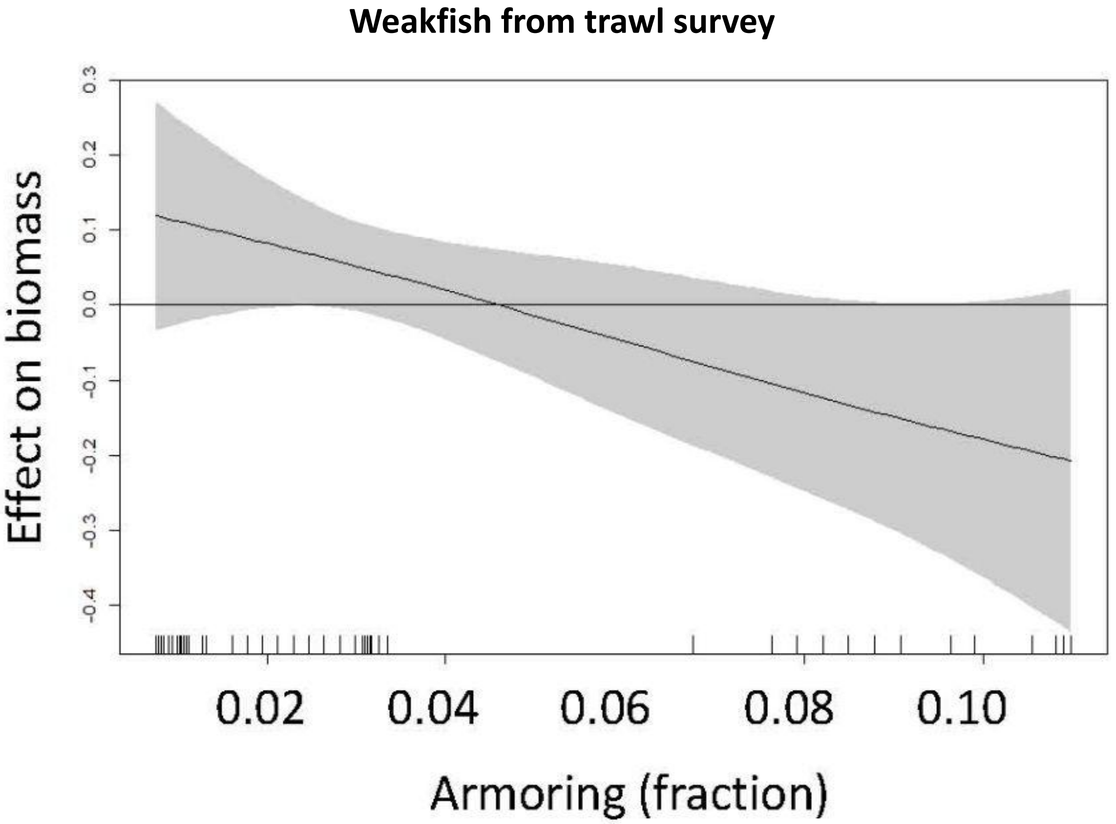
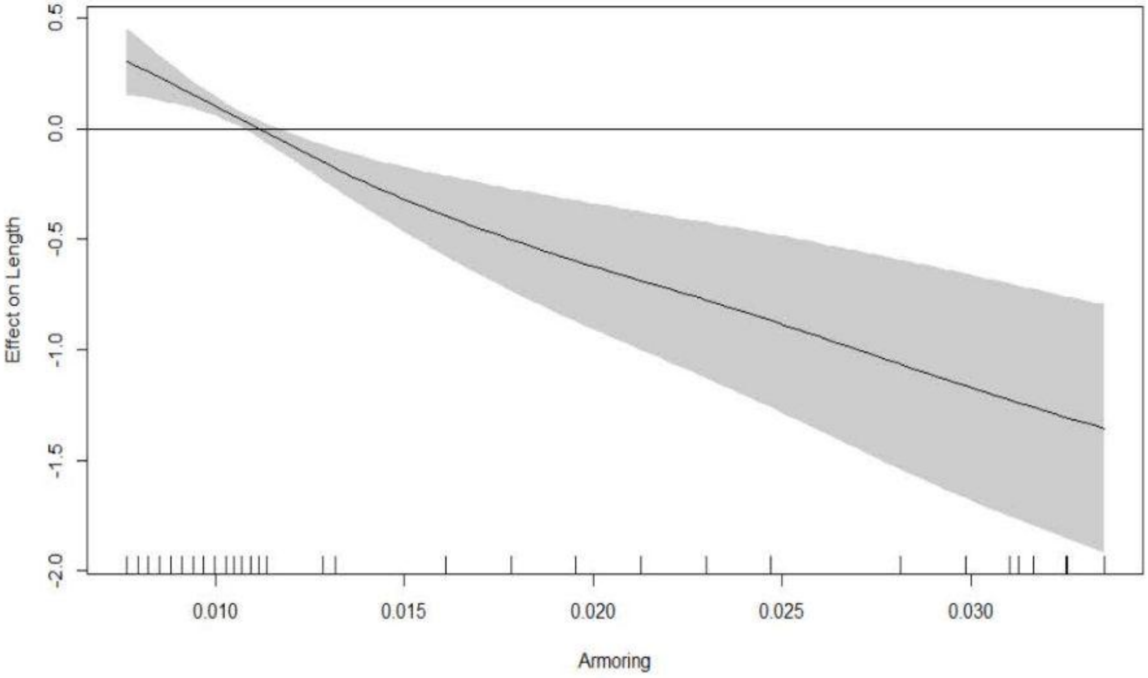


Figure 18. The effect of shoreline armoring (hardening) on weakfish biomass based on data from the VIMS Juvenile Finfish Trawl Survey (Tuckey et al. 2019).

A) White perch from seine survey



B) White perch from trawl survey

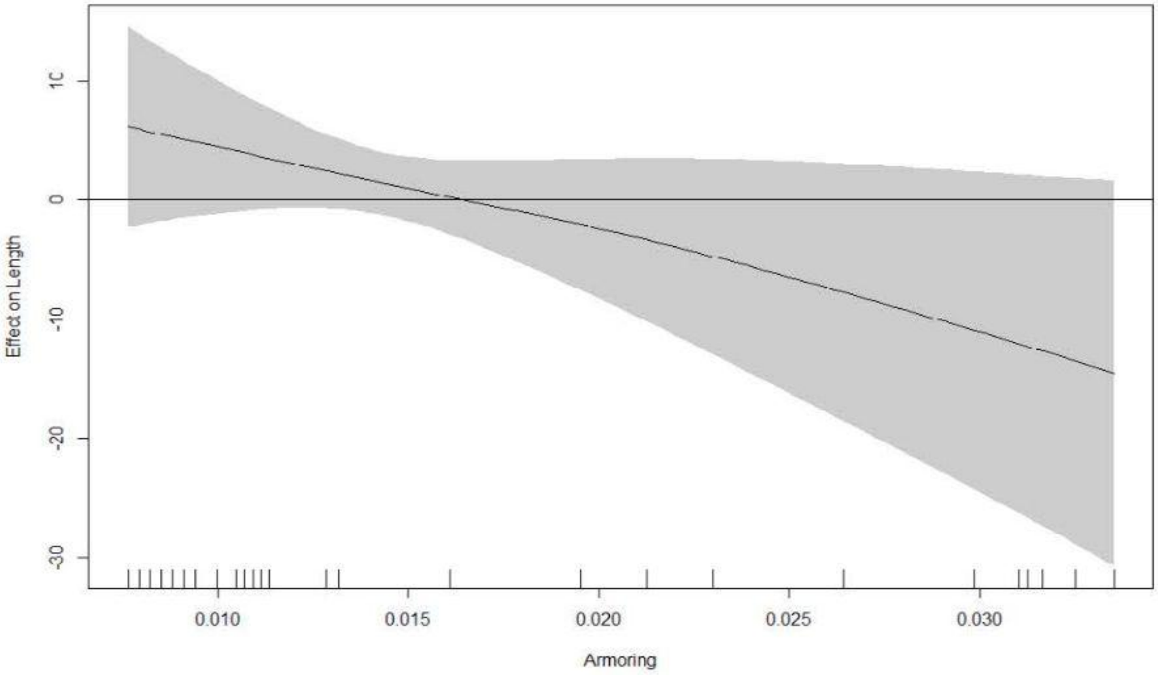


Figure 19. The effect of shoreline armoring (hardening) on white perch length based on catch data from the VIMS (A) Juvenile Striped Bass Seine Survey and (B) Juvenile Finfish Trawl Survey.

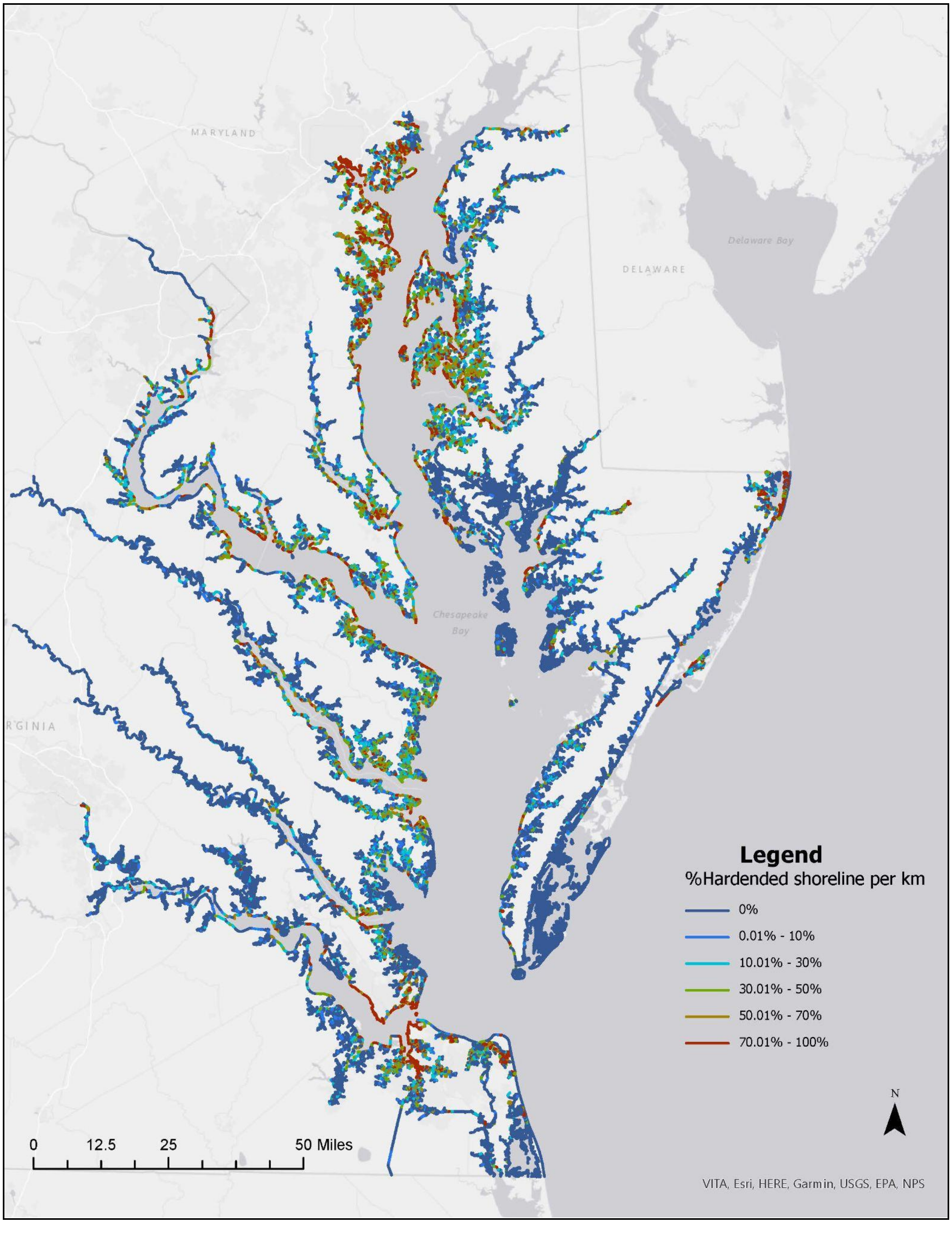


Figure 20. The extent of hardened shorelines throughout the Chesapeake Bay as of 2022. Note that the mapping of shoreline status is not yet complete for four Maryland counties (Caroline, Cecil, Harford, Prince George's).

Water Quality and Climate Indices

Overview

Impacts of environmental conditions, particularly those related to water quality and climate change, on forage availability have been a critical knowledge gap in climate-ready EBFM. A GIT-funded study conducted by Woodland et al. (2017) examined environmental gradients associated with spatial and temporal patterns in relative abundance of forage taxa in the Chesapeake Bay, focusing specifically on the important forage taxa identified by Ihde et al. (2015; Figure 1). A follow-up GIT-funded study was conducted to further evaluate the relationship between two notable climate indices (10°C degree-day [DD] index, Atlantic Multidecadal Oscillation [AMO]) and two key forage taxa (polychaetes, bay anchovy) to develop environmental indicators for the Chesapeake Bay forage base (Woodland et al. 2022).

Methods

Time series of relative forage abundance were developed for each majority tributary and salinity regime within the Chesapeake Bay using delta-GLMs, delta-GAMs, and random forest (RF) models. Invertebrate biomass data were obtained from the Chesapeake Bay Benthic Monitoring Program. Forage fish abundance data were obtained from various fishery-independent surveys, including the VIMS Juvenile Striped Bass Seine Survey and the Juvenile Finfish Trawl Survey, the MDNR Juvenile Striped Bass Survey, and the UMCES CHESFIMS Survey. Environmental variables examined in the 2017 study included salinity, temperature, dissolved oxygen concentration (DO), springtime chlorophyll-a, DD indices (indicating the timing of warming water temperatures [phenological index] and the total daily temperature anomalies), freshwater flow, hypoxic volume, AMO, and the North Atlantic Oscillation (NAO). The 2022 study focused solely on the phenological DD index (timing of warming) and AMO. Tercile-based classifications were used to define and visualize the status of the DD indicator over time.

Results and Discussion

The 2017 study results showed that relative interannual abundance of many forage taxa covaried with the timing of springtime warming (DD), winter-spring flow volume, and AMO (Table 3). A positive relationship between the DD index and forage abundance suggested that years in which water temperatures warm slowly from winter to spring are conducive to higher summertime forage abundance. In the Chesapeake Bay mainstem, there was a positive relationship between AMO and forage fish abundance, but a negative relationship between AMO and invertebrate biomass. Positive phases of the AMO are typically associated with warmer sea surface temperatures, positive northwesterly wind anomalies along the Mid-Atlantic Bight, and increased precipitation over the mid-Atlantic states (Nye et al. 2014). These conditions are typically associated with higher year-class strength of anadromous species in estuaries along the East Coast (Wood & Austin 2009), but could enhance stratification and subsequent hypoxia of estuarine waters, decoupling productive pelagic areas from benthic food webs and negatively influencing the growth, productivity, or survival of benthic invertebrates (Nixon et al. 2009). In the tributaries, flow was positively associated with YOY Atlantic menhaden, amphipods and isopods, and macoma clams, but negatively associated with bay anchovy. Winter-spring flows are predicted to increase in the Chesapeake Bay with climate change (Najjar et al. 2010), and how these freshet conditions covary with water temperature is likely to have consequences for the composition and productivity of forage communities.

In contrast to the 2017 study results, model results from the 2022 study indicated a negative relationship between polychaete biomass and both DD and AMO (Table 4, Figure 21). This suggests that a “good” year for polychaetes would be preceded by a relatively warm and dry autumn, and a late winter-early spring in which Chesapeake Bay waters warm relatively rapidly despite experiencing relatively cool air temperatures and high precipitation. This interaction suggests a nuanced relationship between polychaete biomass and climate conditions that depends on the timing of particular climate conditions, including water temperature and, potentially, freshwater inputs and salinity. Additionally, climate conditions favoring reproductive success and juvenile survival (i.e., recruitment) could differ from climate conditions associated with high subadult and adult survival during the spring and early summer.

Similar to polychaetes, bay anchovy recruitment and abundance indices were also negatively associated with AMO values for the current year and DD indicators, i.e. years in which waters warm relatively rapidly in the late winter but are associated with cooler air temperatures and higher precipitation are associated with high bay anchovy recruitment and total abundance later in the summer (Table 4, Figure 22). The contrasting results between the 2017 and 2022 studies are likely driven by differences in how the indices and climate-environmental models were structured and fitted; the 2017 models included covariates that were not included in the 2022 models, and the AMO was treated as a single annual index rather than an integrated, moving monthly aggregate.

The DD indicator suggests that Chesapeake Bay waters have been warming up more quickly in the spring than they did previously (Figure 23). Given the relationship between both polychaetes and bay anchovy and DD found in the 2022 study, these forage taxa could flourish as climate change continues to rapidly warm the waters of the Bay. However, environmental and biological factors other than DD can influence population dynamics and drive interannual variability. Some of these additional factors, such as DO and primary production, are likely to interact in complex, spatially dependent ways.

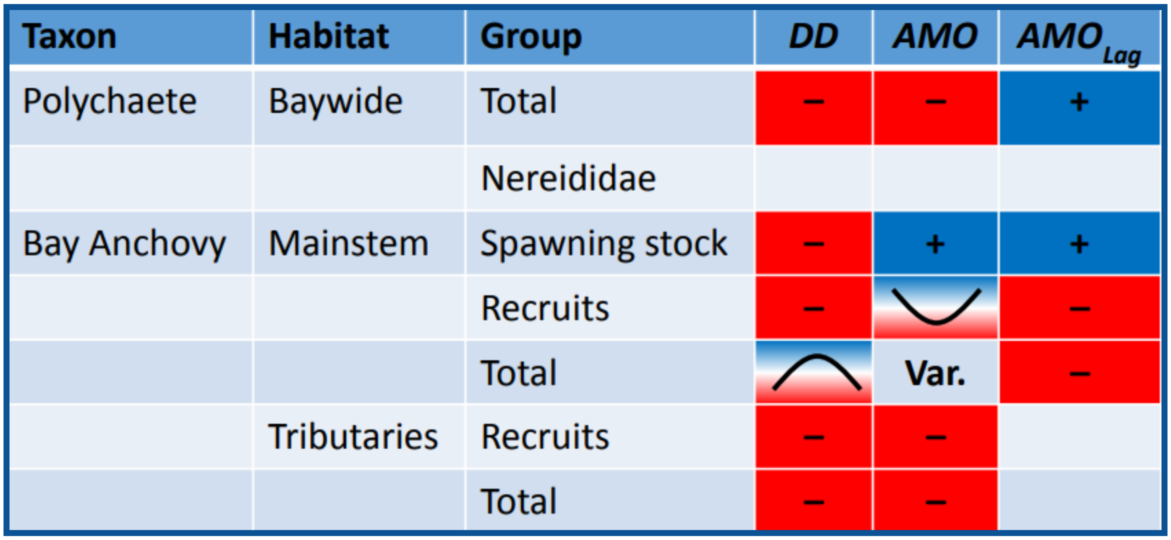
Table 3. Model results from GLMs relating abundance indices of forage taxa to environmental parameters in the mainstem and major tributaries of the Chesapeake Bay (Woodland et al. 2017). Environmental variables include the Atlantic Multidecadal Oscillation (AMO), spring chlorophyll-a intensity (CHL), 5°C degree-day phenology variable (DD), January-June flow intensity (Flow), and hypoxic volume (HYP). Bolded parameter estimates are potentially informative at α ≤ 0.10-0.05; bolded estimates with an asterisk (*) indicates significance at α ≤ 0.05.

Estuary region	Forage type	Taxon	AMO	CHL	DD	Flow	HYP
Mainstem	Fish	Alewife	0.96	-0.08	0.78	0.62	0.09
		Anchovy	**0.94**	-0.30	**0.62***	-0.32	-0.18
		Blueback herring	-0.63	0.90	1.41	**2.18***	-0.71
		Atl. croaker	0.56	-0.20	-0.0003	-0.68	0.37
		Atl. menhaden	1.14	-0.26	0.49	0.09	-0.21
		Silverside	**1.85***	0.90	0.29	0.04	**-1.05***
		Spot	**1.86**	-0.11	0.43	-0.61	-0.27
		Weakfish	**1.12**	-0.41	**0.53**	-0.63	-0.05
	Invertebrate	Amphipods/Isopods	**-0.25***	-0.03	**0.26***	0.05	0.03
		Macoma clams	-0.24	-0.06	0.19	0.15	-0.01
		Other bivalves	-0.12	-0.09	0.13	0.04	-0.08
		Polychaetes	**-0.23***	**-0.13***	**0.11***	-0.03	0.03

Estuary region	Forage type	Taxon	AMO	CHL	DD	Flow	HYP
Tributaries	Fish	Alewife	3.07	0.41	**0.90***	-0.32	0.33
		Anchovy	0.92	-0.12	**0.37***	**-0.33***	0.21
		Blueback herring	-0.31	**0.28**	0.23	0.18	0.15
		Atl. croaker	-2.00	-0.23	-0.09	-0.18	**-0.64**
		Killifish	**3.08***	**0.13**	**0.17***	-0.11	0.05
		Atl. menhaden	**-4.22***	-0.03	0.29	**0.61***	0.22
		Mummichog	**2.35***	0.02	0.04	-0.12	0.21
		White perch	**1.90***	**0.48***	**0.53***	0.07	0.11
		Silverside	-0.43	**0.17***	**0.18***	**-0.35**	-0.07
		Spot	0.77	0.01	**0.35***	-0.14	-0.04
	Invertebrate	Amphipods/Isopods	**-2.73***	0.02	0.10	**0.20***	-0.15
		Macoma clams	**-1.56**	0.06	-0.10	**0.27***	0.08
		Other bivalves	-0.48	**-0.24**	**0.21**	-0.14	0.20
		Polychaetes	**-0.89**	-0.02	**0.10**	-0.04	-0.04

*Forage fish models only include time-series of indices of abundance from the Rappahannock, York and James Rivers. Invertebrate forage models include time-series from all 5 tributaries.

Table 4. Relationships between key forage taxa (polychaetes, bay anchovy) and climate variables (10°C degree-day phenology [DD], Atlantic Multidecadal Oscillation [AMO], AMO lagged one year [$\mathrm{AMO}_{\mathrm{Lag}}$]) based on random forest models (Woodland et al. 2022). Red (-) indicates a negative relationship; blue (+) indicates a positive relationship. Parabolas indicate a nonlinear relationship.



Taxon	**Habitat**	**Group**	***DD***	***AMO***	***$\mathrm{AMO}_{\mathrm{Lag}}$***
Polychaete	Baywide	Total	−	−	+
		Nereididae			
Bay Anchovy	Mainstem	Spawning stock	−	+	+
		Recruits	−	∪	−
		Total	∩	**Var.**	−
	Tributaries	Recruits	−	−	
		Total	−	−	

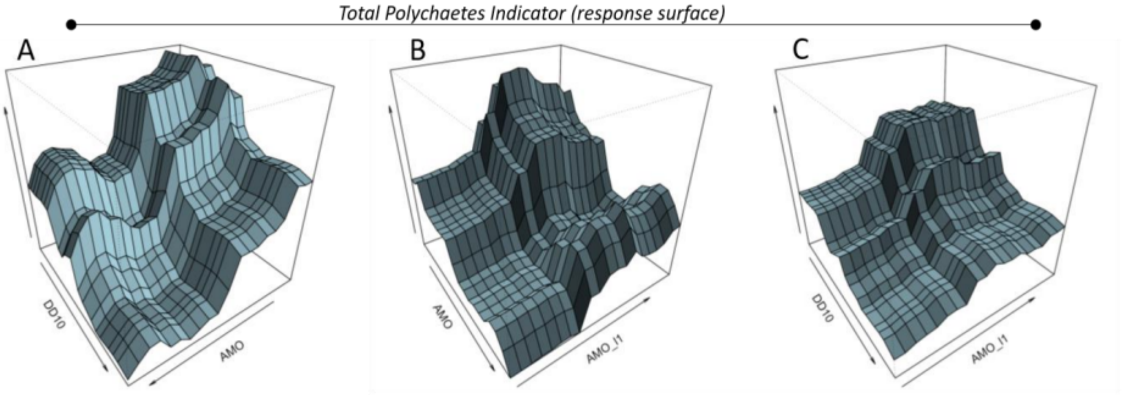


Figure 21. Response surfaces for the total polychaete indicator based on the random forest climate models, showing relationships among total polychaete biomass and: (A) DD & AMO; (B) AMO & AMO_L1 (AMO lagged one year); and (C) DD & AMO_L1 (Woodland et al. 2022).

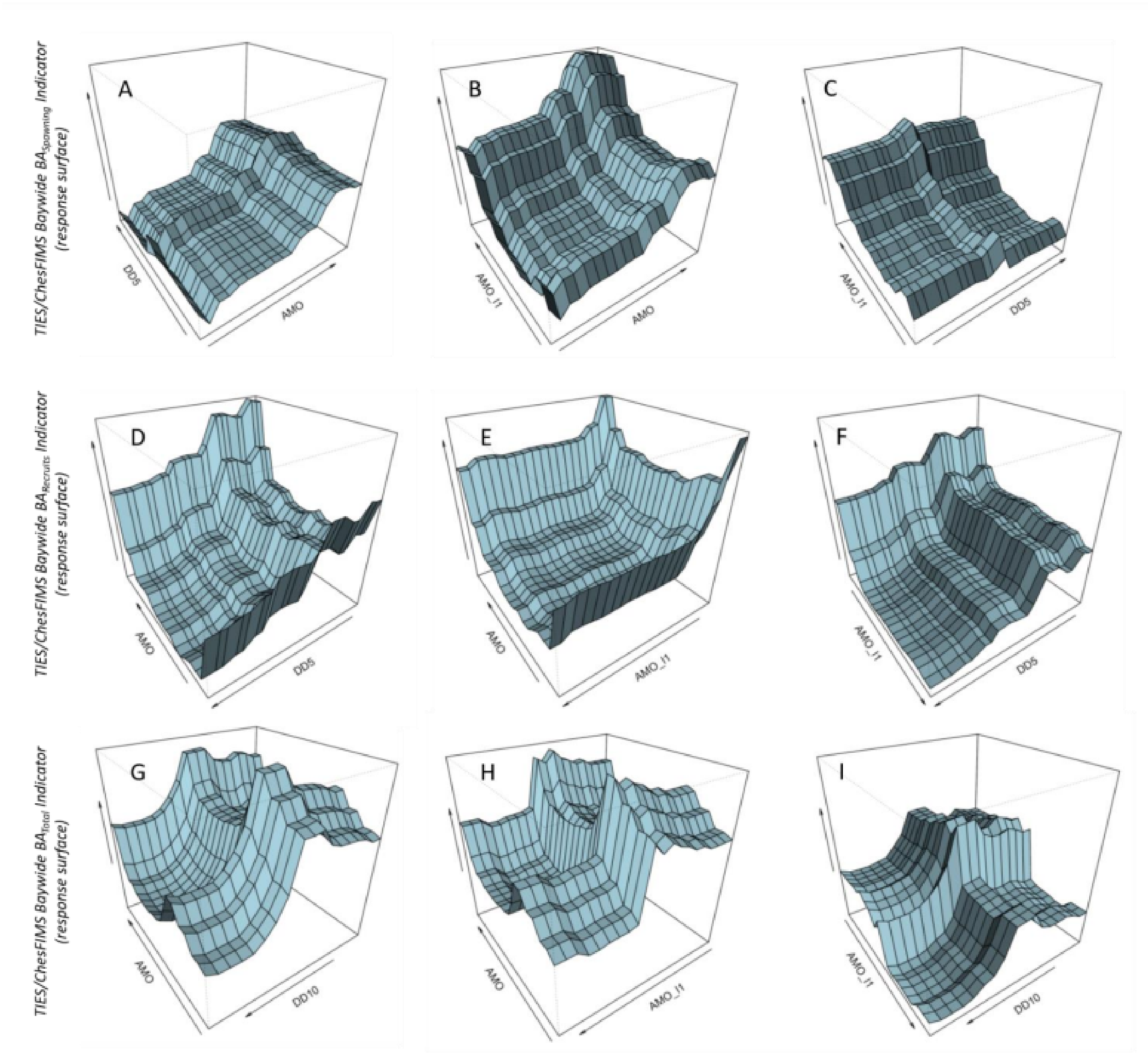


Figure 22. Bay anchovy spawning stock (BA$_{\text{Spawning}}$, A-C), recruits (BA$_{\text{Recruits}}$, D-F), and total population (BA$_{\text{Total}}$, G-I) Bay-wide indicator response surfaces based on random forest (BA$_{\text{Spawning}}$, BA$_{\text{Total}}$) and GLM (BA$_{\text{Recruits}}$) climate models using the TIES/ChesFIMS data (Woodland et al. 2022). Surfaces show relationships among bay anchovy indicators and best-fitting AMO, AMO_L1 (AMO lagged one year), and DD predictors for each model.

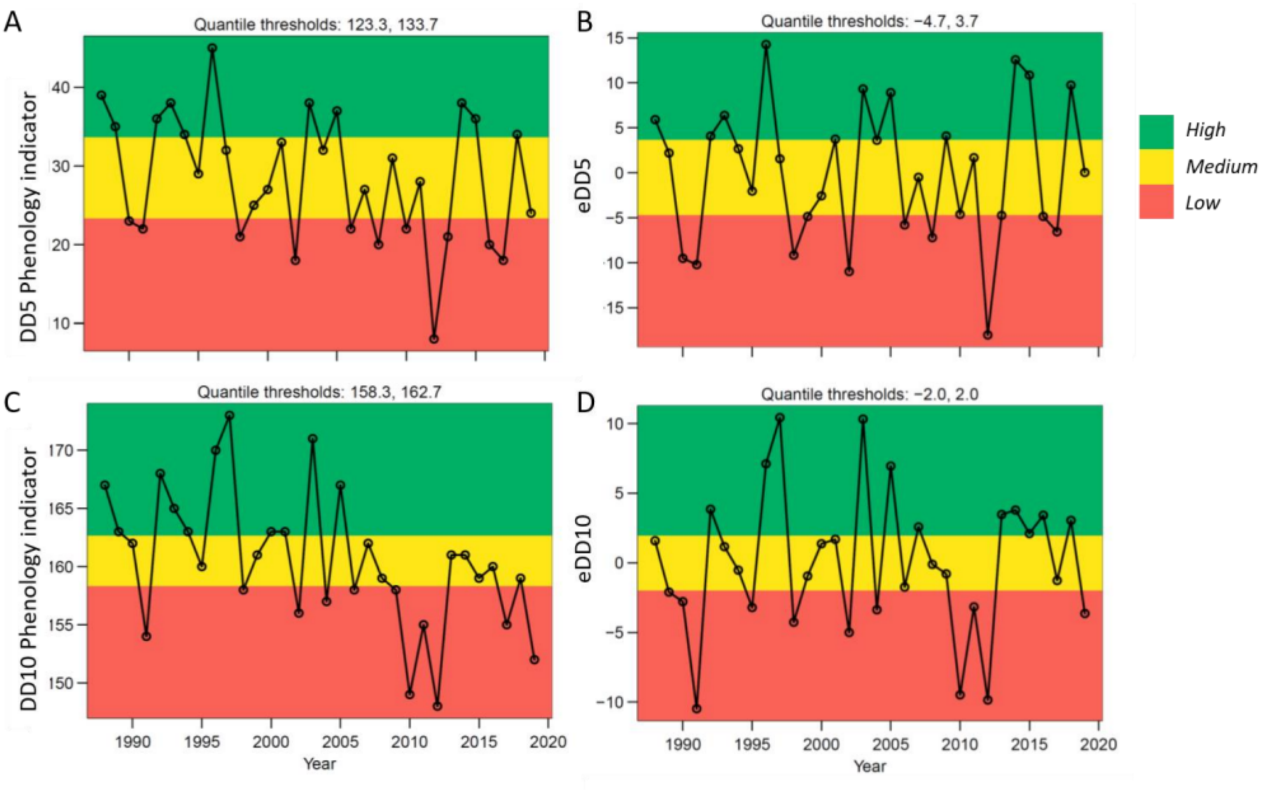


Figure 23. Time series of the (A) 5°C degree-day indicator (DD5), (B) detrended DD5 (eDD5), (C) 10°C degree-day indicator (DD10), and (D) detrended DD10 (eDD10) from 1988 to 2019 in Chesapeake Bay with the associated tercile-based classifications representing High (green), Medium (yellow), and Low (red) values of the indicator distributions (Woodland et al. 2022).

Habitat Suitability Indices

Overview

Defining and identifying suitable habitat are key components of understanding species distribution and abundance. In a dynamic estuarine system like the Chesapeake Bay, suitable habitat includes physical environmental conditions such as salinity, temperature, DO, and depth. These conditions can vary widely across multiple spatial and temporal scales, and often dictate the phenology and distribution of fishes (Buchheister et al. 2013). A study funded by NCBO's Chesapeake Bay Fisheries Research Program (CBFRP) was conducted to quantify seasonal suitable habitats in the Bay for four key forage fishes, and to assess the relationship between suitable habitat extent and annual relative abundance of forage fishes (Fabrizio et al. 2020). The species examined were bay anchovy, juvenile spot, juvenile weakfish, and juvenile spotted hake (*Urophycis regia*).

Methods

Forage abundance data from the VIMS Juvenile Finfish Trawl Survey and the MDNR Blue Crab Summer Trawl Survey were coupled with hindcasts from a numerical DO model and a 3D hydrodynamic model of the Chesapeake Bay that provided dynamic covariates at multiple temporal and spatial scales for salinity, temperature, DO, depth, and current speed. Sediment composition and distance to shore were also included as model covariates. Boosted regression trees were used to identify influential habitat covariates for each species, which were then used to construct habitat suitability models. Habitat suitability indices for each species, ranging between 0 (poor habitat) and 1 (superior habitat), were assigned to each location in the 3D model grid for each season. Based on the estimated habitat suitability index and using GIS, suitable habitat (defined as habitats with an index > 0.5) was quantified throughout the Chesapeake Bay and its tidal tributaries. To assess the role of suitable habitat extent in driving forage fish abundance, nonparametric regressions were used to relate seasonal estimates of suitable habitat extent to seasonal Bay-wide estimates of fish relative abundance.

Results and Discussion

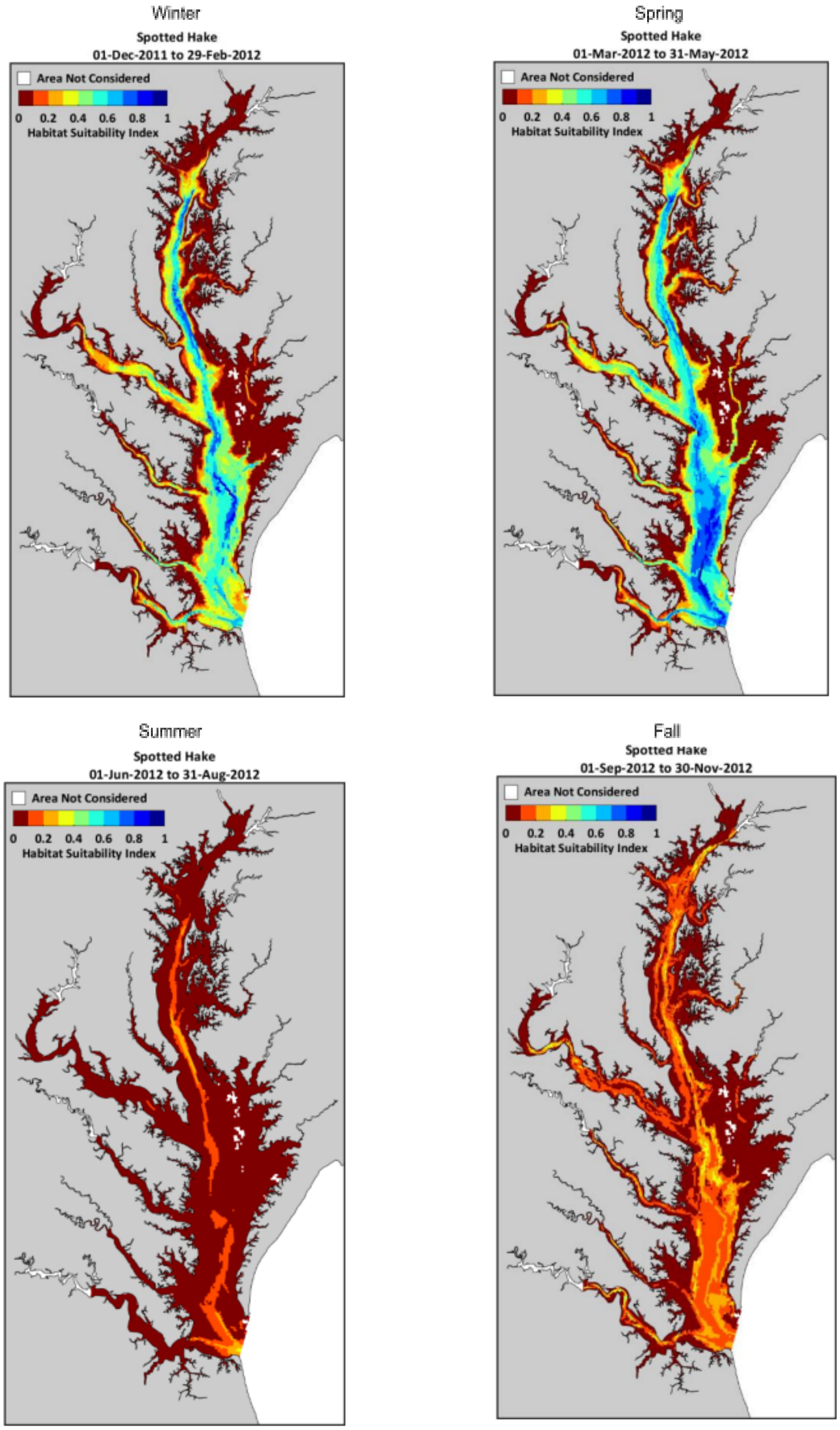
Spring provided the greatest extent of suitable habitat throughout the Chesapeake Bay for juvenile spotted hake, followed closely by winter, primarily in the deeper channels of the mainstem and major tributaries (Figure 24). There was essentially no suitable habitat available in summer and fall for this species. In addition to deeper waters, suitable habitat for juvenile spotted hake was primarily characterized by tidally averaged bottom temperatures between 5.3 and 14.2°C. The seasonal pattern in suitable habitat for spotted hake appears to be driven by seasonal changes in water temperature. Winter habitat extent increased during years when waters began to warm earlier in winter (2012) than when waters warmed later in winter (2011). With changes in the timing and magnitude of warming from winter into spring, winter suitable habitat may expand for juvenile spotted hake in the Bay.

Suitable habitat extent was greatest in summer for juvenile spot, particularly in the deeper portions of the Bay and its tributaries (Figure 25). In spring, however, suitable habitat was restricted to shallow waters near the shoreline. There was relatively little suitable habitat for juvenile spot in the Bay in fall and winter. DO was an important physical attribute that characterized suitable habitat for spot. In summer, spot occupied low-DO habitats (< 4.8 mg/L), with maximum suitability occurring at concentrations between 2.2 and 3.2 mg/L. In fall, maximum suitability occurred in habitats with DO concentrations between 4.0 and 5.3 mg/L.

Suitable habitat extent for juvenile weakfish was greatest in the fall in the deeper channels of the mainstem and the major tributaries, particularly in the lower Bay (Figure 26). Summer suitable habitat was primarily concentrated in the shallower water of the tributaries and nearshore waters of the mainstem. Spring suitable habitat was restricted to a small region near the mouth of the Bay, and there was no suitable winter habitat for juvenile weakfish in the Bay. Suitable habitat was characterized by tidally averaged bottom temperatures greater than 25.9°C in summer, and greater than 24.5°C in fall.

Spring provided the greatest extent of suitable habitat for bay anchovy throughout the Chesapeake Bay (Figure 27). There was also generally more suitable habitat for bay anchovy in summer than in winter. Suitable habitat was primarily found in the deeper channels of the lower Bay in all seasons. In summer, bay anchovy suitable habitat was characterized by tidally averaged bottom temperatures between 23.7 and 27.0°C and tidally averaged surface salinity ranging from 17.1 to 26.0 psu. Winter suitable habitat was different, with tidally averaged salinity greater than 23.7 psu and bottom DO concentrations between 6.6 and 10.4 mg/L.

A significant positive relationship between relative abundance and suitable habitat extent was found for two species: juvenile spot in summer and bay anchovy in winter (Figures 28). This suggests that environmental conditions affect the carrying capacity of the Chesapeake Bay for these two key forage species during a portion of the year. As such, estimates of the minimum habitat area required to produce a desired forage abundance may be used to establish quantitative habitat reference points for management. In an ecosystem-based approach, important habitats may be targeted for protection or other best management practices, thereby ensuring production of sufficient forage for predators.



Winter

Spotted Hake

01-Dec-2011 to 29-Feb-2012

Spring

Spotted Hake

01-Mar-2012 to 31-May-2012

Summer

Spotted Hake

01-Jun-2012 to 31-Aug-2012

Fall

Spotted Hake

01-Sep-2012 to 30-Nov-2012

Figure 24. Seasonal habitat suitability for juvenile spotted hake throughout the Chesapeake Bay in 2012 (Fabrizio et al. 2020). The habitat suitability index ranges from 0 (red), indicating poor habitat, to 1 (dark blue), with any shade of blue indicating suitable habitat.

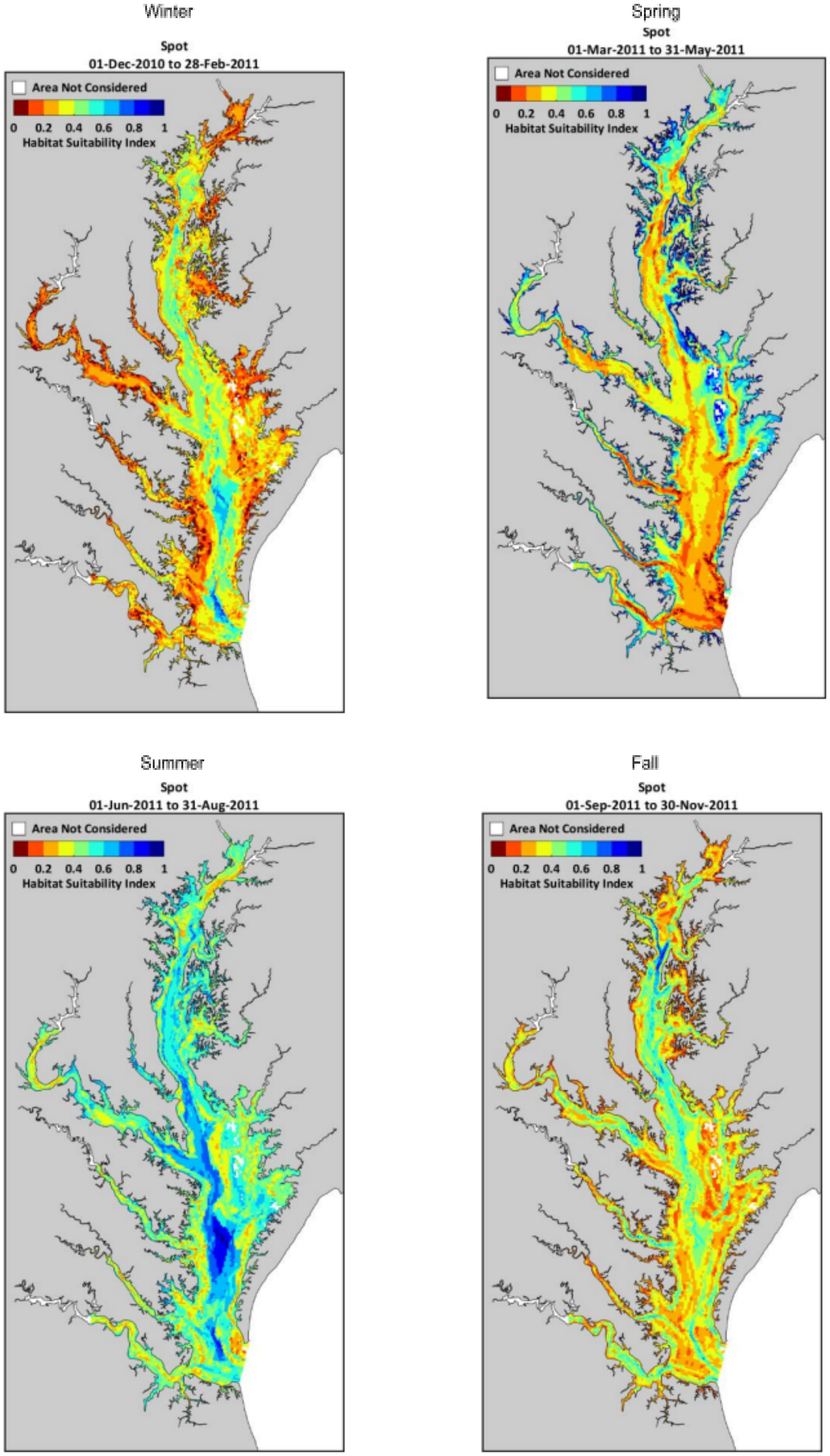


Figure 25. Seasonal habitat suitability for juvenile spot throughout the Chesapeake Bay in 2011 (Fabrizio et al. 2020). The habitat suitability index ranges from 0 (red), indicating poor habitat, to 1 (dark blue), with any shade of blue indicating suitable habitat.

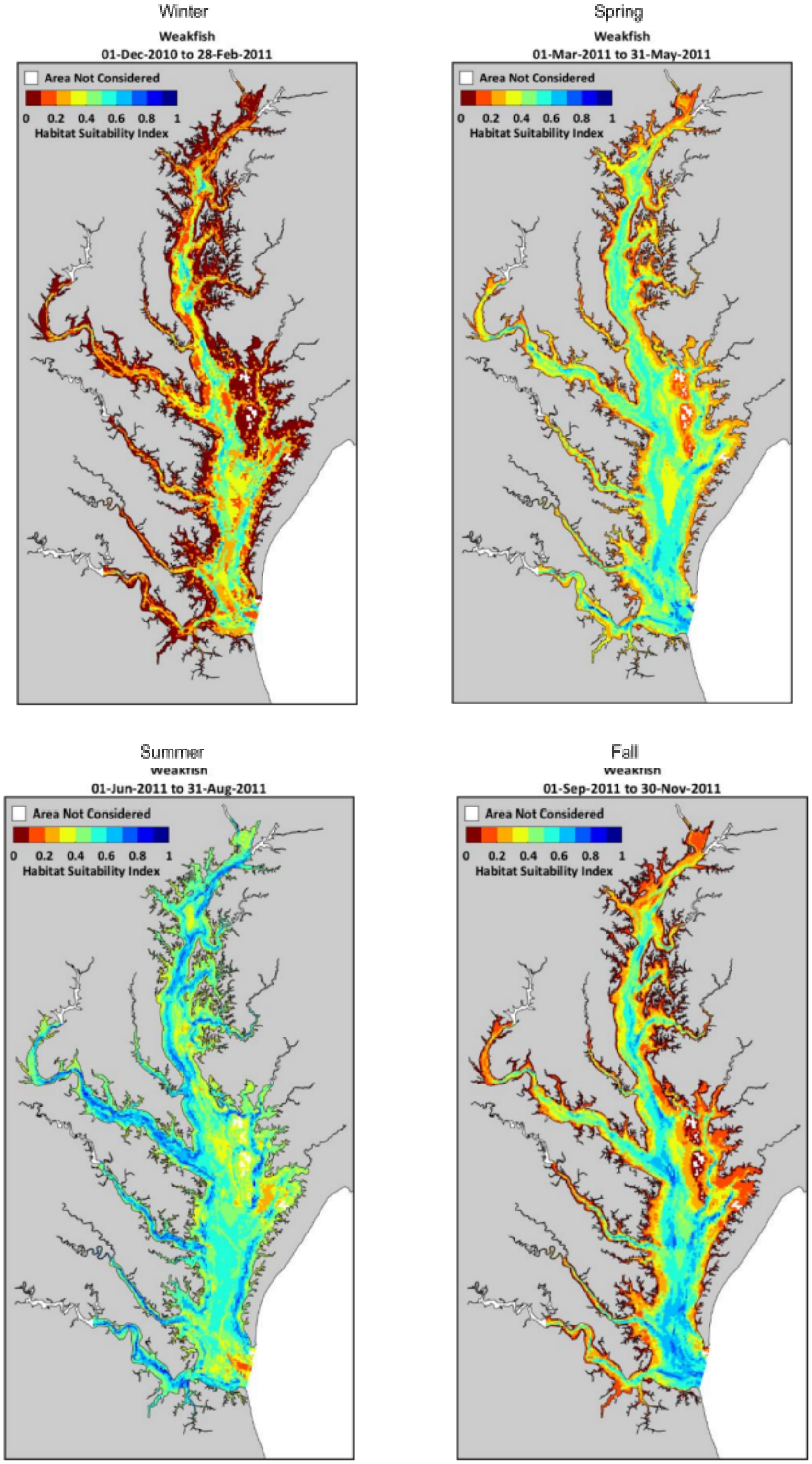


Figure 26. Seasonal habitat suitability for juvenile weakfish throughout the Chesapeake Bay in 2011 (Fabrizio et al. 2020). The habitat suitability index ranges from 0 (red), indicating poor habitat, to 1 (dark blue), with any shade of blue indicating suitable habitat.

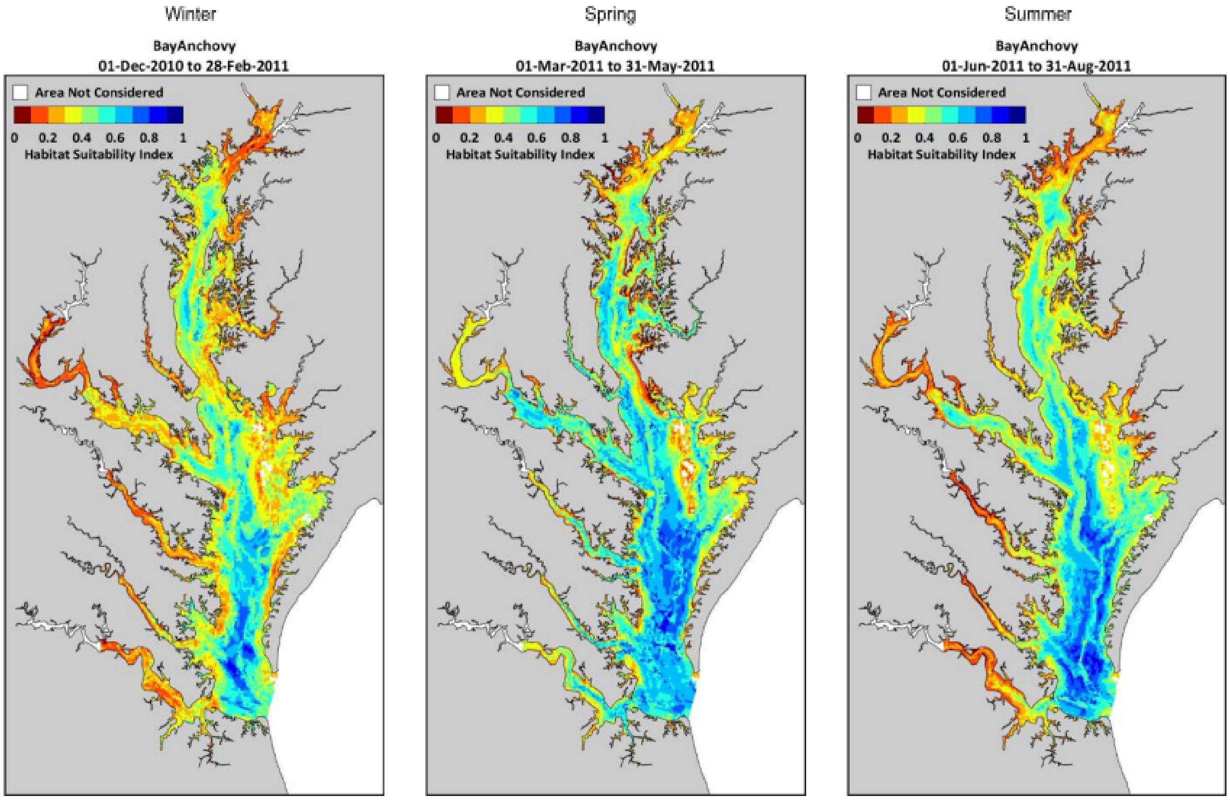


Figure 27. Seasonal habitat suitability for bay anchovy throughout the Chesapeake Bay in 2011 (Fabrizio et al. 2020). The habitat suitability index ranges from 0 (red), indicating poor habitat, to 1 (dark blue), with any shade of blue indicating suitable habitat. Note that a fall habitat suitability model was not available for this species.

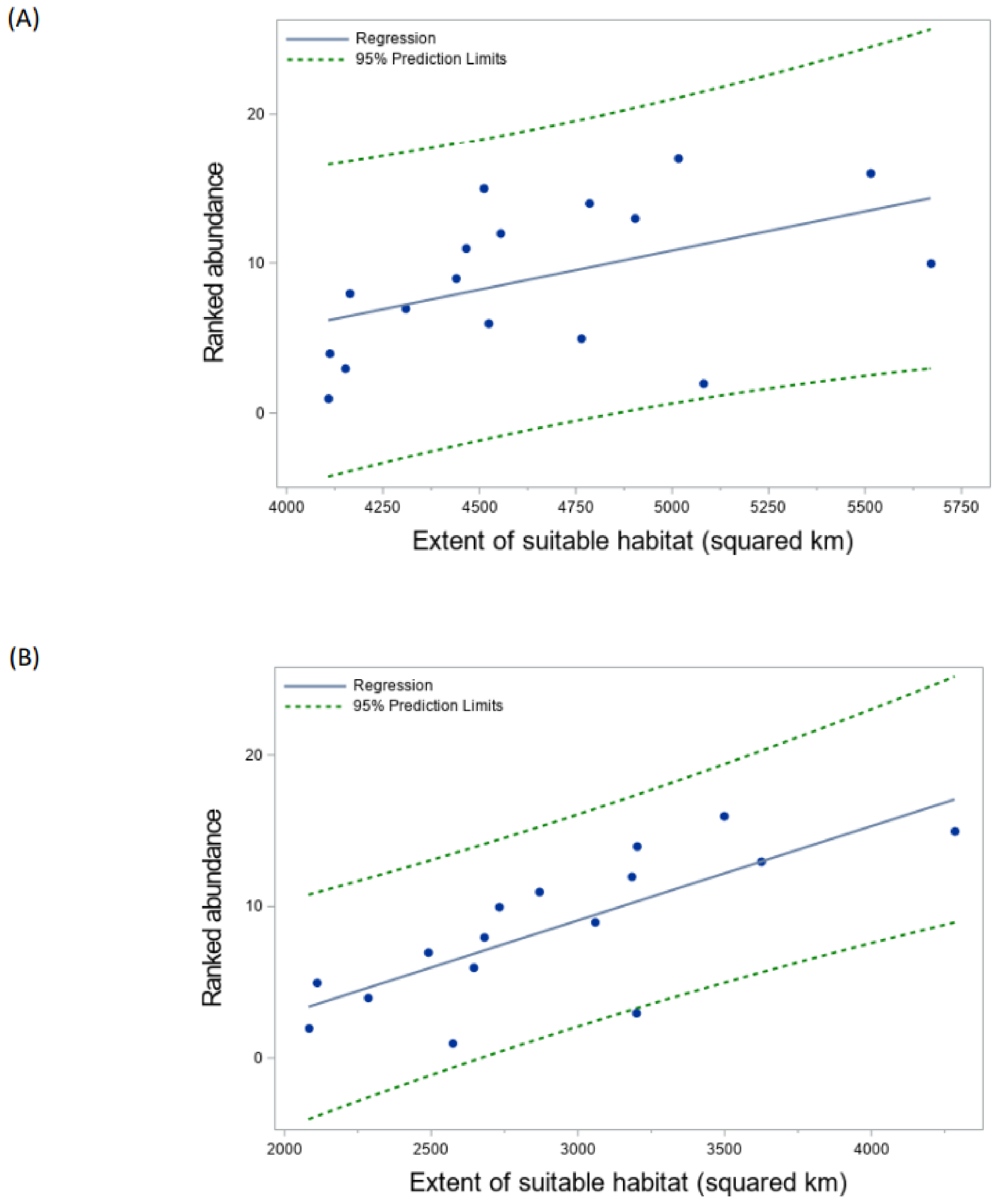


Figure 28. Nonparametric relationship between rank abundance and suitable habitat extent (km^2) for (A) juvenile spot in summer and (B) bay anchovy in winter from 2000 to 2016 (Fabrizio et al. 2020). Blue circles depict the observations; the solid line is the nonparametric regression fit; and the dashed line is the 95% prediction limit. Suitable habitat was defined as HSI ≥ 0.5.

Tier 3 Indicators: Predator Consumption

Diet and Consumption Indices

Overview

Understanding predator-prey relationships is fundamental to advancing ecosystem approaches to fisheries management (EAFM). Diet and consumption indicators can provide information about the importance of particular prey to predators, predation intensity, and changes in predatory demand over time. A GIT-funded study conducted by Buchheister and Houde (2016) developed a suite of complementary forage indicators that included diet-based indices (i.e., prey biomass consumed over time) and predator consumption profiles to assess trends in the Chesapeake Bay forage base and better understand the consumption needs of four representative predator fishes. The forage taxa evaluated in this study included those identified in the 2014 STAC workshop report (Figure 1; Ihde et al. 2015). Note that the Woodland et al. (2017) study, previously described in Water Quality and Climate Indices, built on the Buchheister and Houde (2016) research, developing consumption profiles for two additional predator species.

Methods

To model species-specific prey biomass consumed by predators over time, a delta-generalized additive mixed model (delta-GAMM) approach was implemented utilizing diet data from the VIMS Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP). Daily per capita consumption estimates for six predator species (striped bass, summer flounder, Atlantic croaker, white perch, weakfish, spot) were also calculated using ChesMMAP diet data and a gastric evacuation rate model (Eggers 1977, Elliot & Persson 1978), and then scaled up to obtain annual relative consumption estimates.

Results and Discussion

A few of the diet-based indices of consumed prey biomass exhibited similar patterns across predator species (Figure 29). For most predators, mysid consumption peaked in 2003, followed by a decline over the time series; only striped bass and spotted hake, which reside in the Bay during the cooler months, did not show this pattern. Peaks in polychaete consumption occurred from 2007 to 2010 for some predators, which may be due to increased availability after a period of low abundance before 2006 (Figure 3). Consumption of bay anchovy generally tended to increase over time, also possibly a result of increased availability of this prey (Figure 2). Consumption of bivalves peaked in 2008, which corresponds with a peak in Bay-wide razor clam biomass (Figure 7). Consumption of mantis shrimp (*Squilla empusa*) and sand shrimp (*Crangon septemspinosa*) was high in 2002 and 2003, respectively, for summer flounder and clearnose skate.

Patterns in probability of prey occurrence in predator stomachs highlighted differences among years, predators, and prey (Figure 30). Mysid occurrence exhibited the strongest coherent pattern across predator species, with occurrence declining strongly over time for all species except spotted hake. This decline in consumption of mysids corresponds with a decline in the relative biomass of mysids Bay-wide, particularly since 2002 (Figure 6). Similarly, in 2003, sand shrimp experienced a high probability of occurrence in the diet of all four predators analyzed. Differences in probability of prey occurrence across predator species is likely due to differences in feeding behaviors and prey preference.

Total annual consumption by striped bass primarily fluctuated around 500 metric tons (mt), but peaked at 1,600 mt in 2006 (Figure 31A). Overall, YOY Atlantic menhaden and bay anchovy were the most important prey items, each accounting for up to 40% of the total annual consumption (Figure 31B). Benthic invertebrates played a larger role in striped bass diets prior to 2004, with contributions decreasing thereafter.

Summer flounder total annual consumption peaked around 600 mt in 2007 and declined to very low levels by 2012 (Figure 32A). Relative contribution of prey types was fairly consistent over time, with fishes and benthic invertebrates comprising about half of the diet throughout the time series (Figure 32B).

Total annual consumption by Atlantic croaker fluctuated between 2,500 and nearly 10,000 mt from 2002 to 2007 before decreasing by one to two orders of magnitude to values as low as 127 mt in 2012 (Figure 33A). Polychaetes often comprised more than 50% of the annual consumption, with bivalves and other prey being periodically important (Figure 33B). Although Atlantic croaker is typically benthivorous, mysids were a substantial portion of the total consumption in 2005 (40%) and made a moderate contribution (18%) in 2003.

White perch total annual consumption was relatively small, typically ranging from 300 to 700 mt, with no clear trend over time (Figure 34A). Polychaetes and crustaceans were the two most important prey items consumed, accounting for up to 65% and 45% of the total annual consumption, respectively (Figure 34B). Bivalves and other prey were periodically important.

Total annual consumption by weakfish fluctuated between 2,200 and 500 mt from 2002 to 2005, but has remained less than 100 mt since 2011 (Figure 35A). Mysids and other benthic invertebrates were a large component of the weakfish diet until 2007, after which bay anchovy consumption increased dramatically, comprising the majority of the diet (Figure 35B). The exception to this pattern was 2013 when mysids and other prey accounted for more than 50% of the weakfish diet.

Inconsistent stomach content analysis precluded the identification of consumption patterns for spot prior to 2007. Total annual consumption declined from about 150 mt in 2007 to 25 mt in 2012 (Figure 36A). Total consumption remained low with the exception of 2013 when 100 mt were estimated to have been consumed by spot. Polychaetes and other benthos were typically the dominant component of spot diets (Figure 36B). The “other” prey category, which sometimes exceeded 50% of the total annual consumption, was often detritus, likely consumed while sifting through benthic matter to locate prey. Bivalves and small crustaceans (primarily amphipods) were also periodically important, exhibiting inverse trends with bivalve consumption decreasing over time and crustacean consumption increasing over time.

Total relative annual consumption by all Chesapeake Bay predators examined in these studies decreased dramatically beginning in 2004 and then remained around levels observed in 2011 (~2,000 mt) until 2015, the last year of data for these analyses (Figure 37A). Polychaetes were the most important prey item overall, although the relative contributions of YOY menhaden and bay anchovy increased over time reflecting the consumption patterns of piscivores (Figure 37B). Periodic influxes of specific prey taxa in the predator diets (e.g., mysids in 2002 and 2005, YOY spot in 2010) highlighted the importance of annual pulses of prey availability in the Chesapeake Bay.

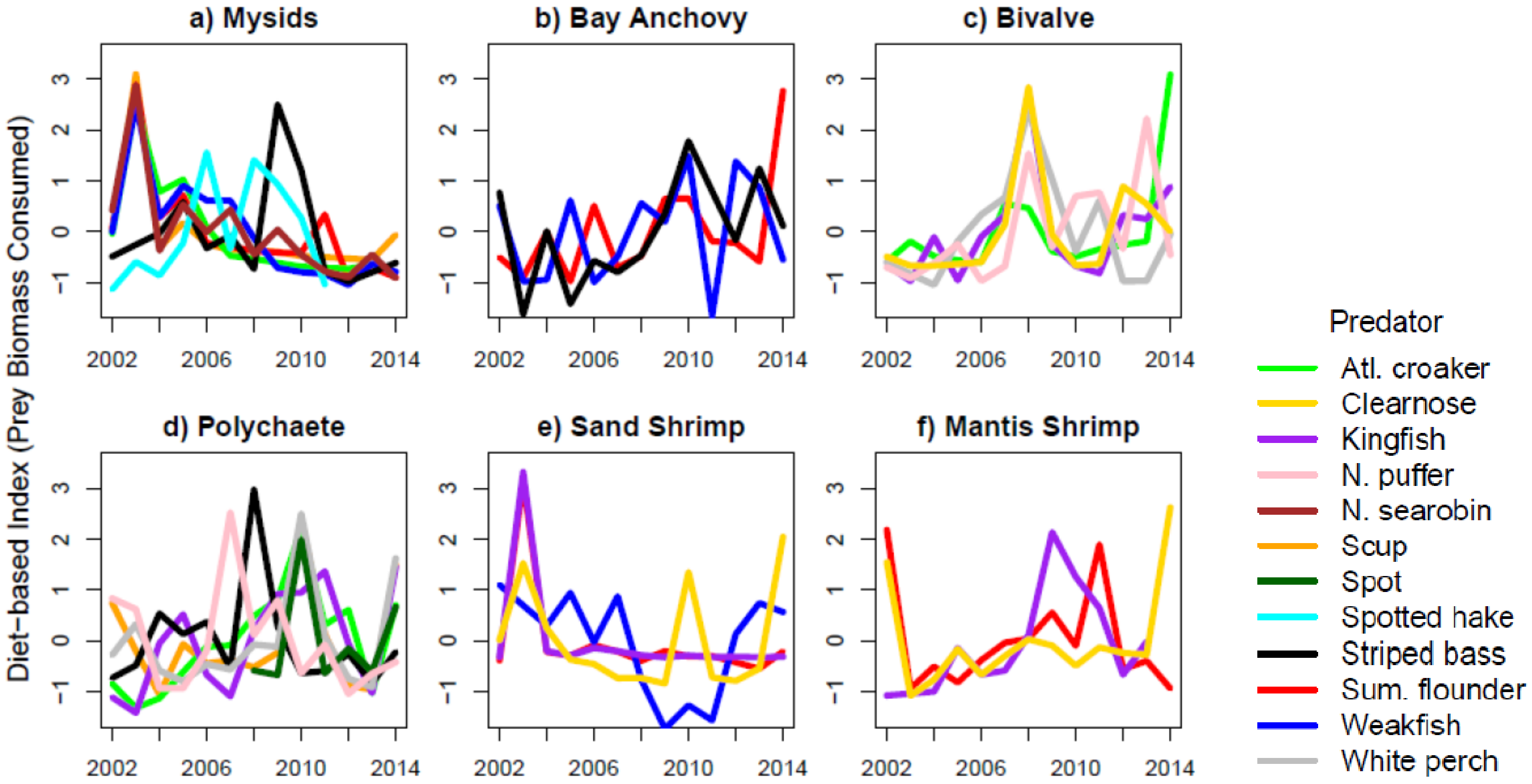


Figure 29. Diet-based indices of prey biomass consumed by 12 finfish predators in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016). Predators with insufficient consumption of a particular prey taxa were excluded from analysis.

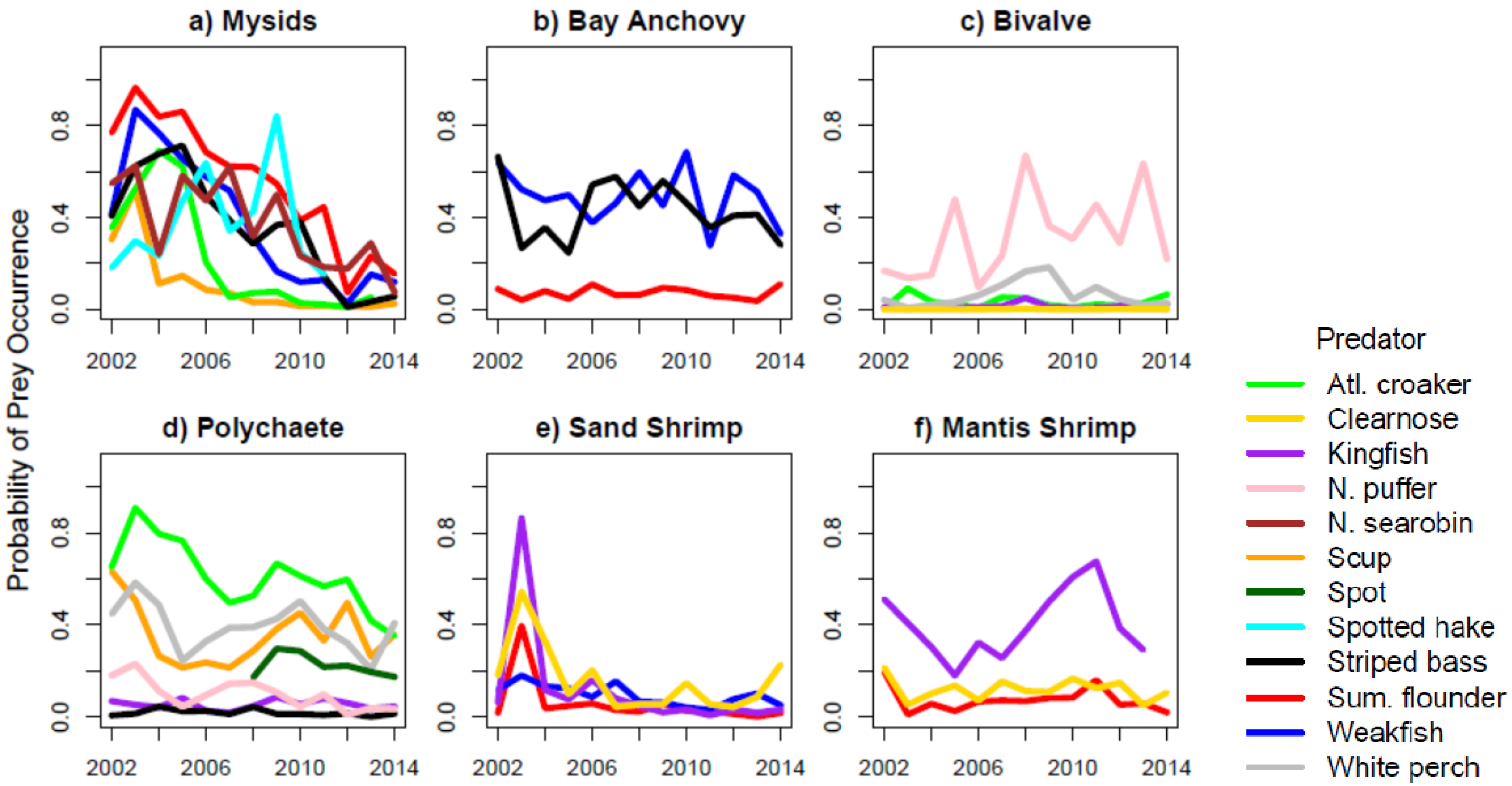


Figure 30. Diet-based indices of probability of annual prey occurrence in the stomach of 12 finfish predators in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016). Predators with insufficient consumption of a particular prey taxa were excluded from analysis.

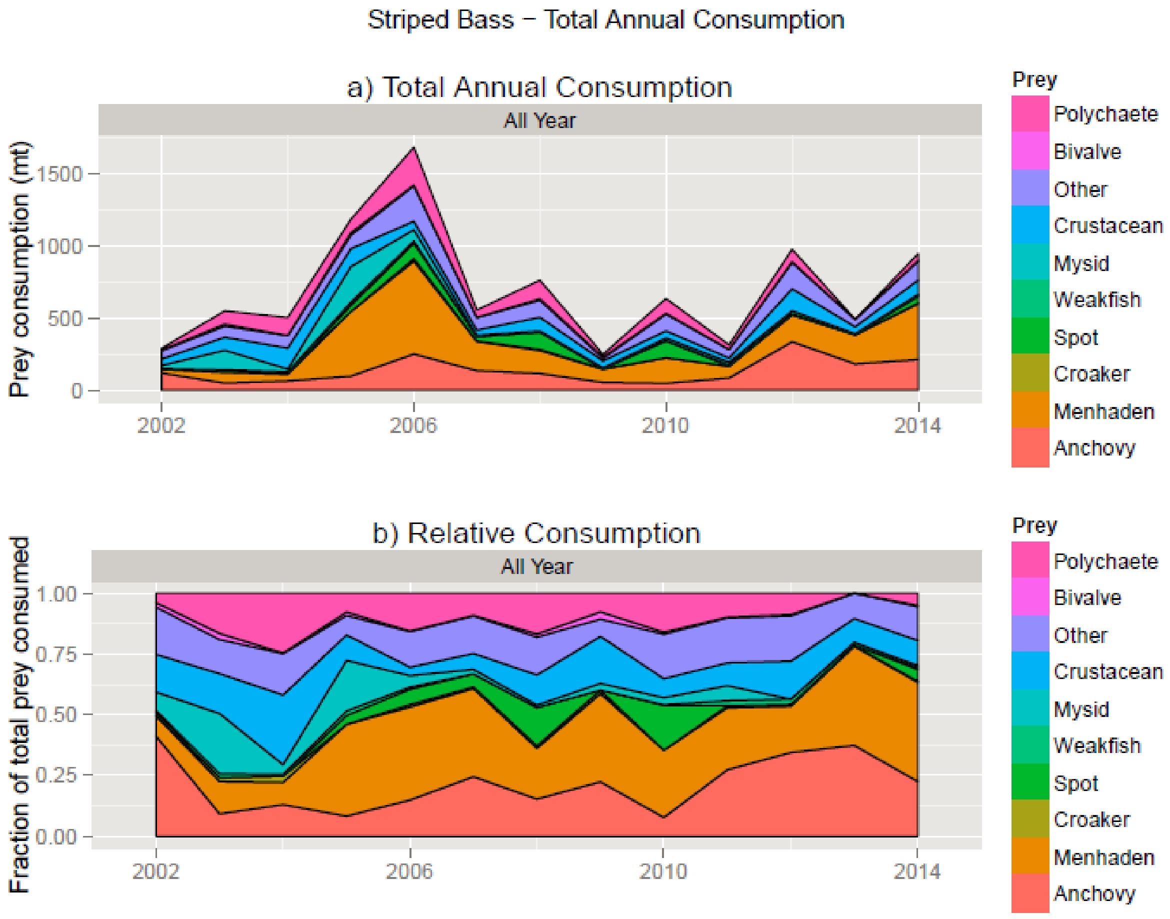


Figure 31. Total annual consumption (a) and relative consumption (b) of key prey taxa for striped bass in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016).

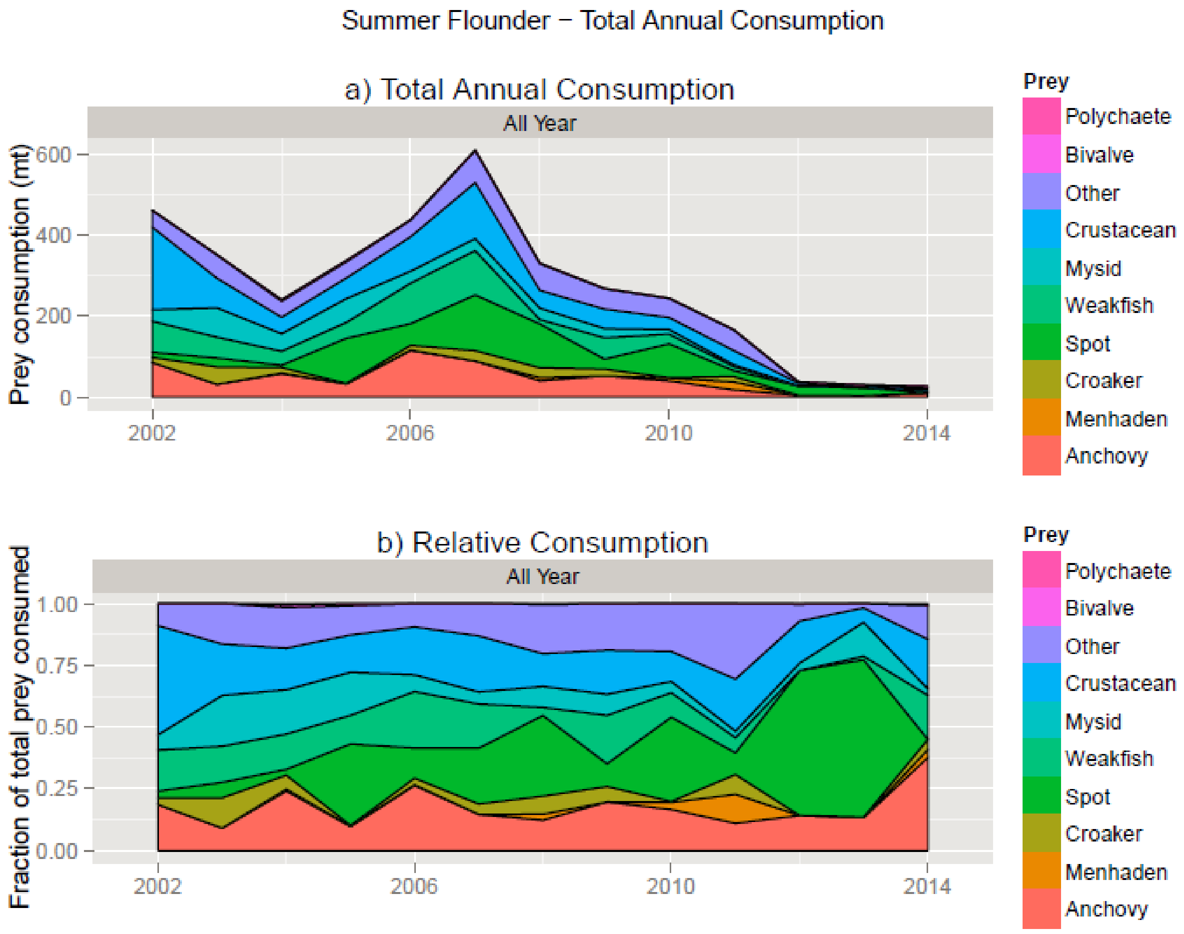


Figure 32. Total annual consumption (a) and relative consumption (b) of key prey taxa for summer flounder in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016).

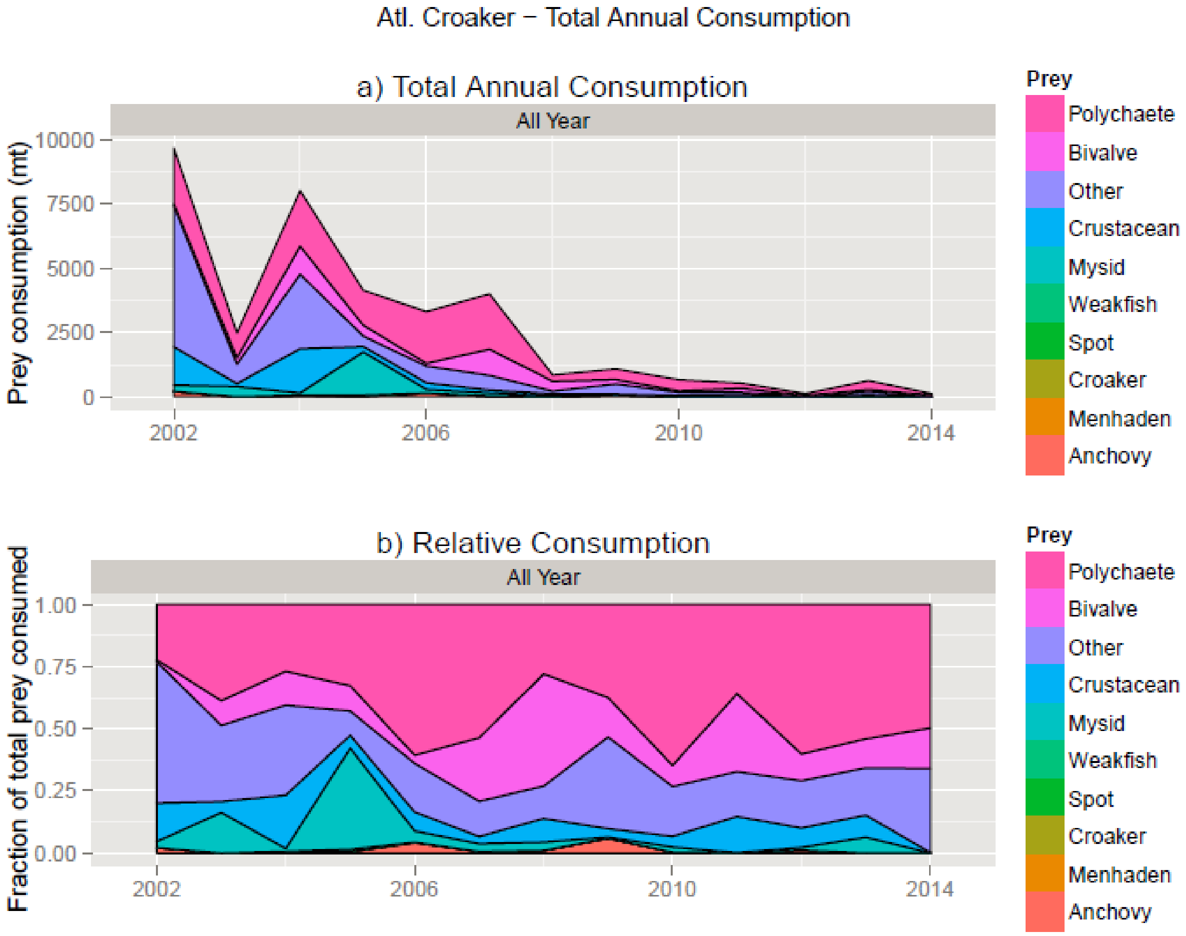


Figure 33. Total annual consumption (a) and relative consumption (b) of key prey taxa for Atlantic croaker in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016).

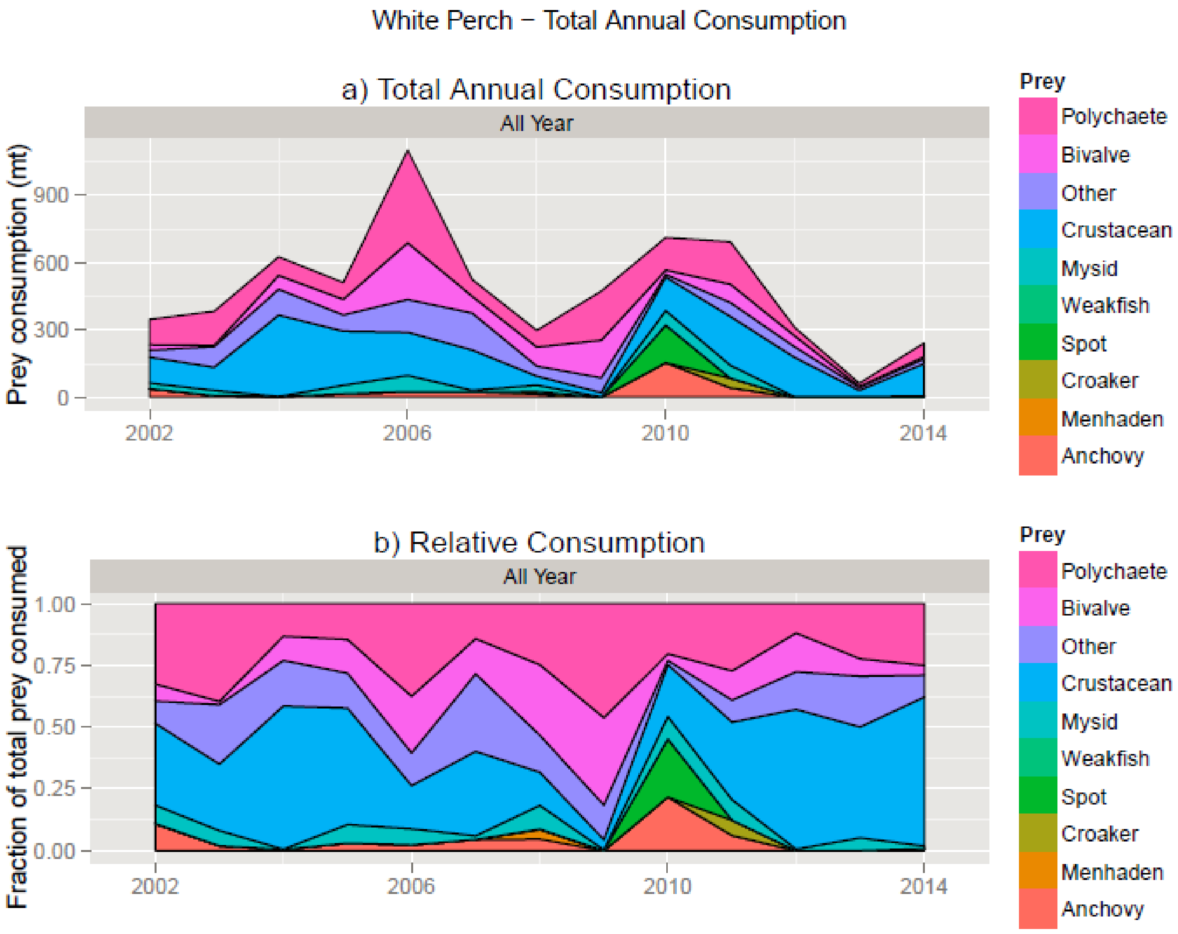
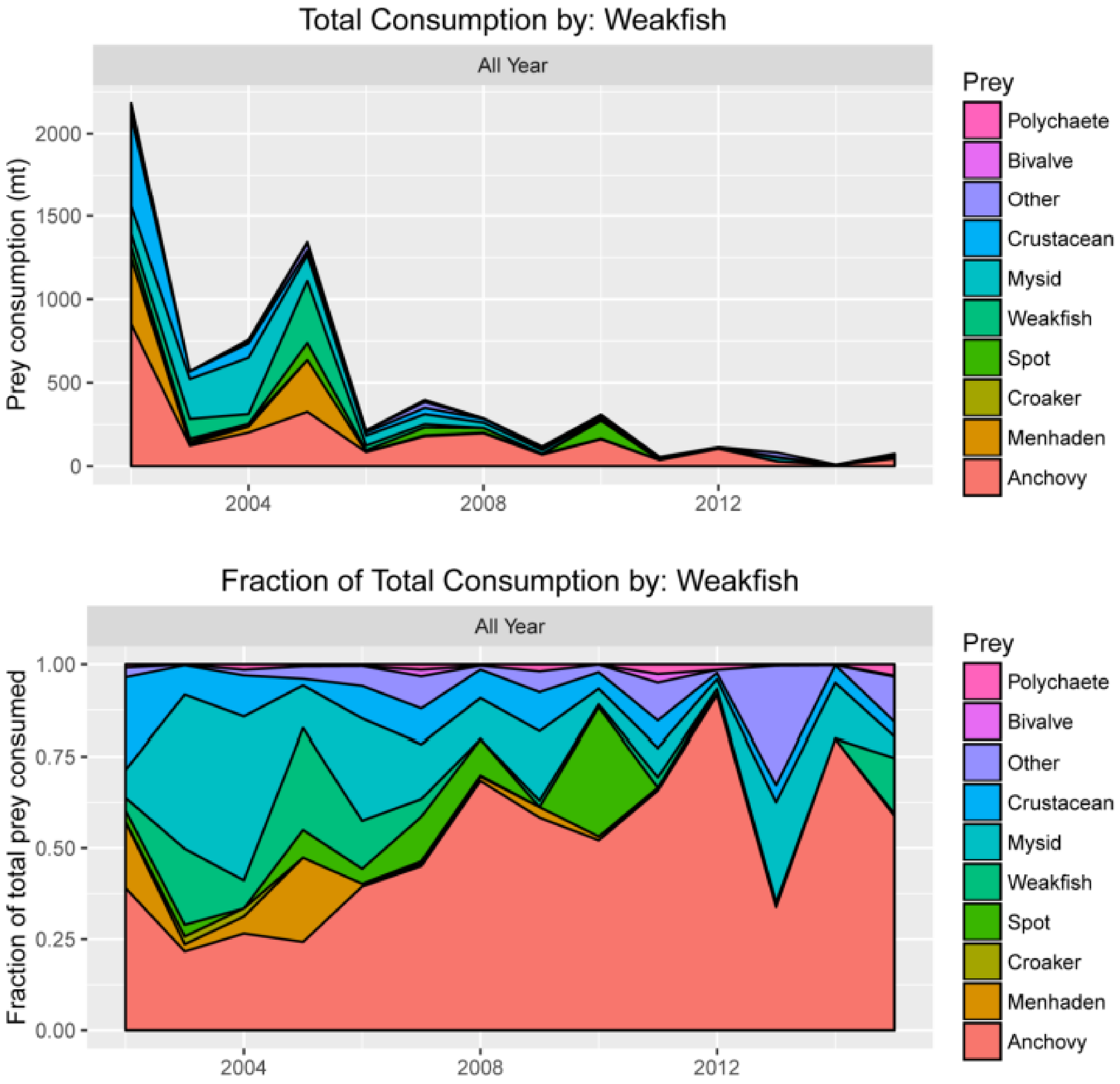


Figure 34. Total annual consumption (a) and relative consumption (b) of key prey taxa for white perch in the Chesapeake Bay from 2002 to 2014 (Buchheister & Houde 2016).



Total Consumption by: Weakfish

Fraction of Total Consumption by: Weakfish

Figure 35. Total annual consumption (a) and relative consumption (b) of key prey taxa for weakfish in the Chesapeake Bay from 2002 to 2015 (Woodland et al. 2017).

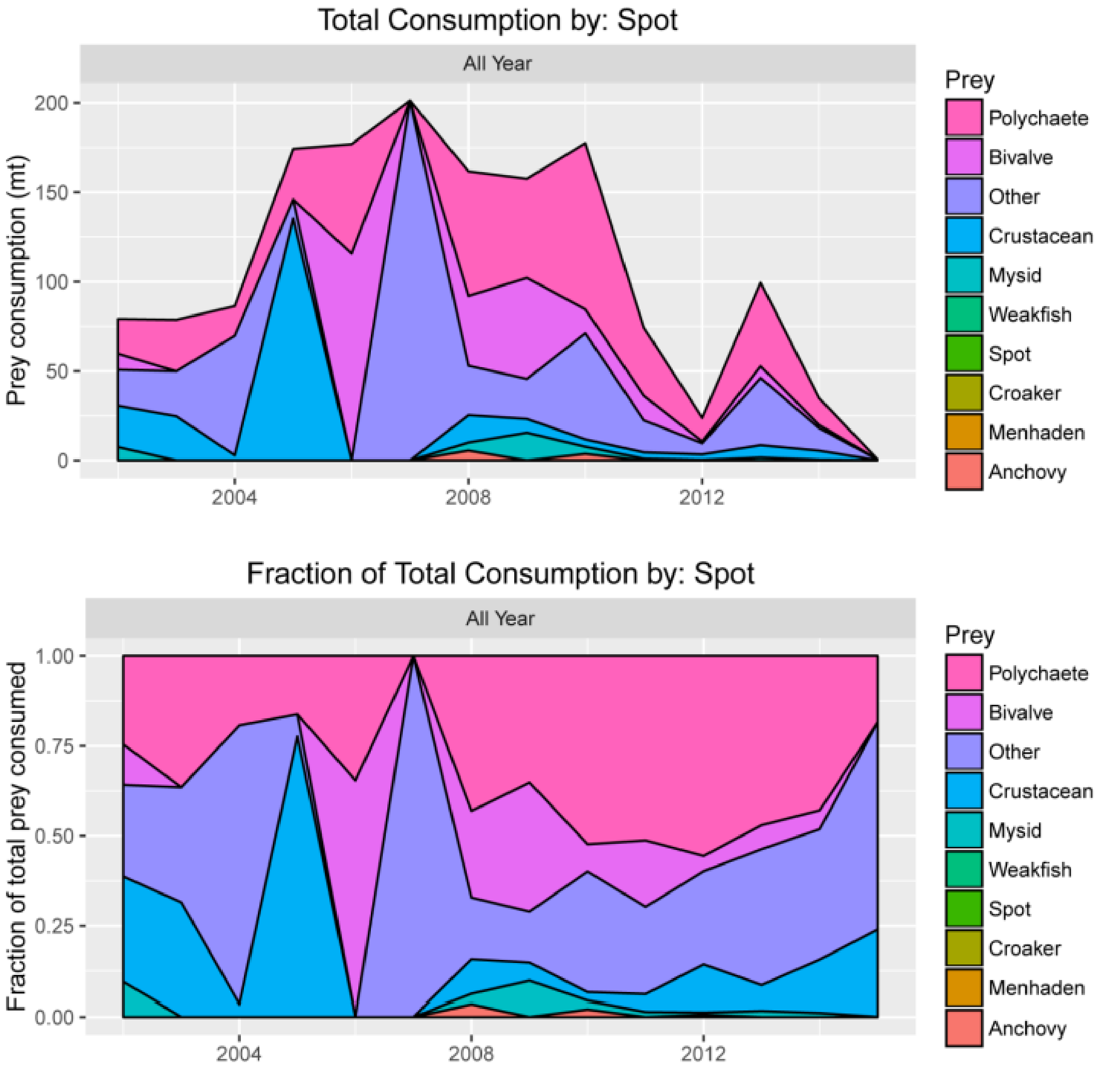
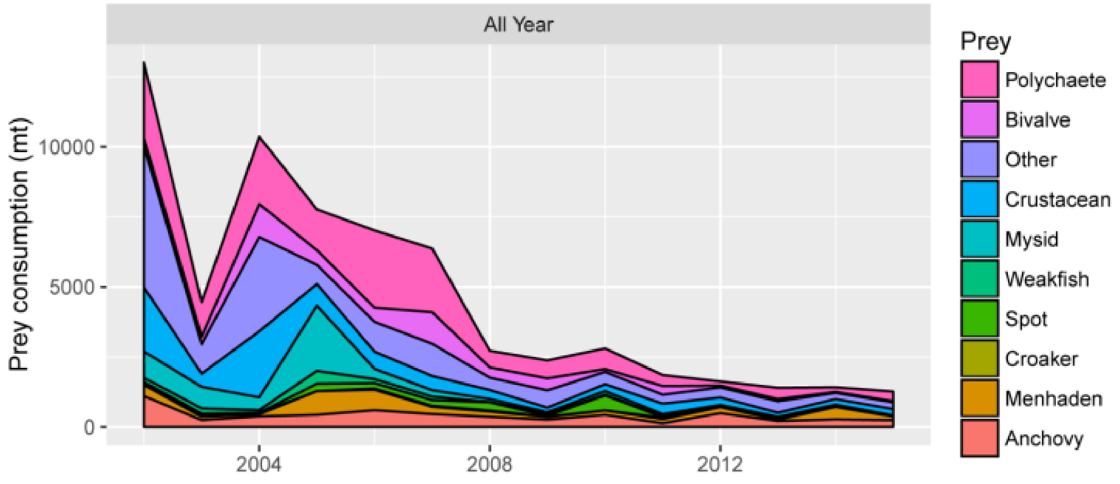
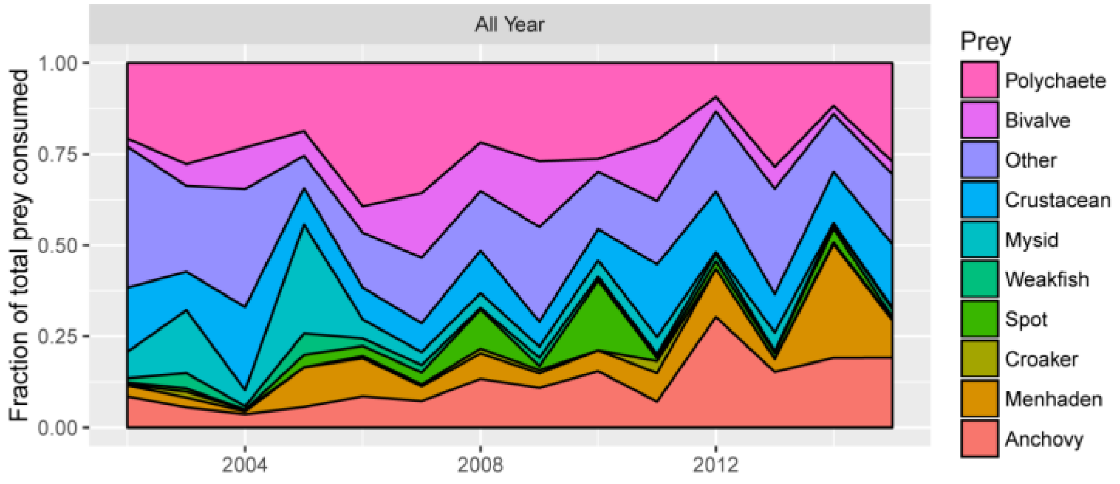


Figure 36. Total annual consumption (a) and relative consumption (b) of key prey taxa for spot in the Chesapeake Bay from 2002 to 2015 (Woodland et al. 2017).



a) Total Consumption by: All 6 Predators



b) Fraction of Total Consumption by: All 6 Predators

Figure 37. Total annual consumption (a) and relative consumption (b) of key prey taxa for all six predators examined (striped bass, summer flounder, Atlantic croaker, white perch, weakfish, spot) in the Chesapeake Bay from 2002 to 2015 (Woodland et al. 2017).

Foraging in Shallow-Water Habitats

Overview

Whereas the forage indicator work discussed above examined diet profiles of key predators in the Chesapeake Bay (Buchheister & Houde 2016, Woodland et al. 2017), the predator diet data were exclusively collected from fishes encountered in the VIMS ChesMMAP Survey in the mainstem of the Bay, thus missing the smallest and largest size classes and those predators residing in the tributaries. With CBFRP funds from NCBO, Ogburn et al. (2022a,b) conducted two studies that assessed the forage base and ontogenetic foraging habits in shallow-water tributaries that serve as nurseries for YOY and juvenile fishes. These studies focused on two model predator species in the Chesapeake Bay: striped bass and summer flounder.

Methods

Striped bass (YOY to age 4) were collected from nine tributaries across the Maryland and Virginia portions of the Bay during summer and fall 2018. Summer flounder were collected from three upper Bay tributary systems and Tangier Sound in summer and fall of 2019 and 2020. Additional samples were collected from the MDNR Blue Crab Summer Trawl Survey and Juvenile Striped Bass Survey, the VIMS Juvenile Striped Bass Seine Survey, and the Smithsonian Environmental Research Center (SERC) Trawl Survey and Seine Survey. Diets in both studies were evaluated using genetic metabarcoding approaches.

Results and Discussion

Striped bass diets in shallow-water habitats of the Chesapeake Bay varied spatially (likely linked to salinity) and ontogenetically. YOY striped bass diets were dominated by small crustaceans (e.g., mysids, amphipods, grass shrimp; 42%), insects (18%), and polychaetes (14%; Figure 38A), while juveniles (ages 1-4) consumed polychaetes (40%), small crustaceans (20%), and fishes (17%; Figure 38B). Salinity was the primary driver of YOY diet variation, with insects being the dominant prey in the freshwater tidal zones, and small crustaceans and polychaetes comprising the majority of the diet in oligohaline (0.6-5 ppt) and mesohaline (>5 ppt) zones. These results reflect the change in striped bass diet through ontogeny, as growing fish move from freshwater to brackish waters, and highlight the occurrence of prey that were not previously recognized as being important components of striped bass diets, particularly insects.

Similar to striped bass, summer flounder diets exhibited spatial variation, with some prey being more abundant in some systems compared to others (Figure 39). Overall, the most important prey species across all systems were bay anchovy, mysids, green goby (*Microgobius thalassinus*), northern pipefish (*Syngnathus fuscus*), and clamworms (*Alitta succinea*). Of these, bay anchovy was the most abundant prey, accounting for more than 50% of the diet in each system.

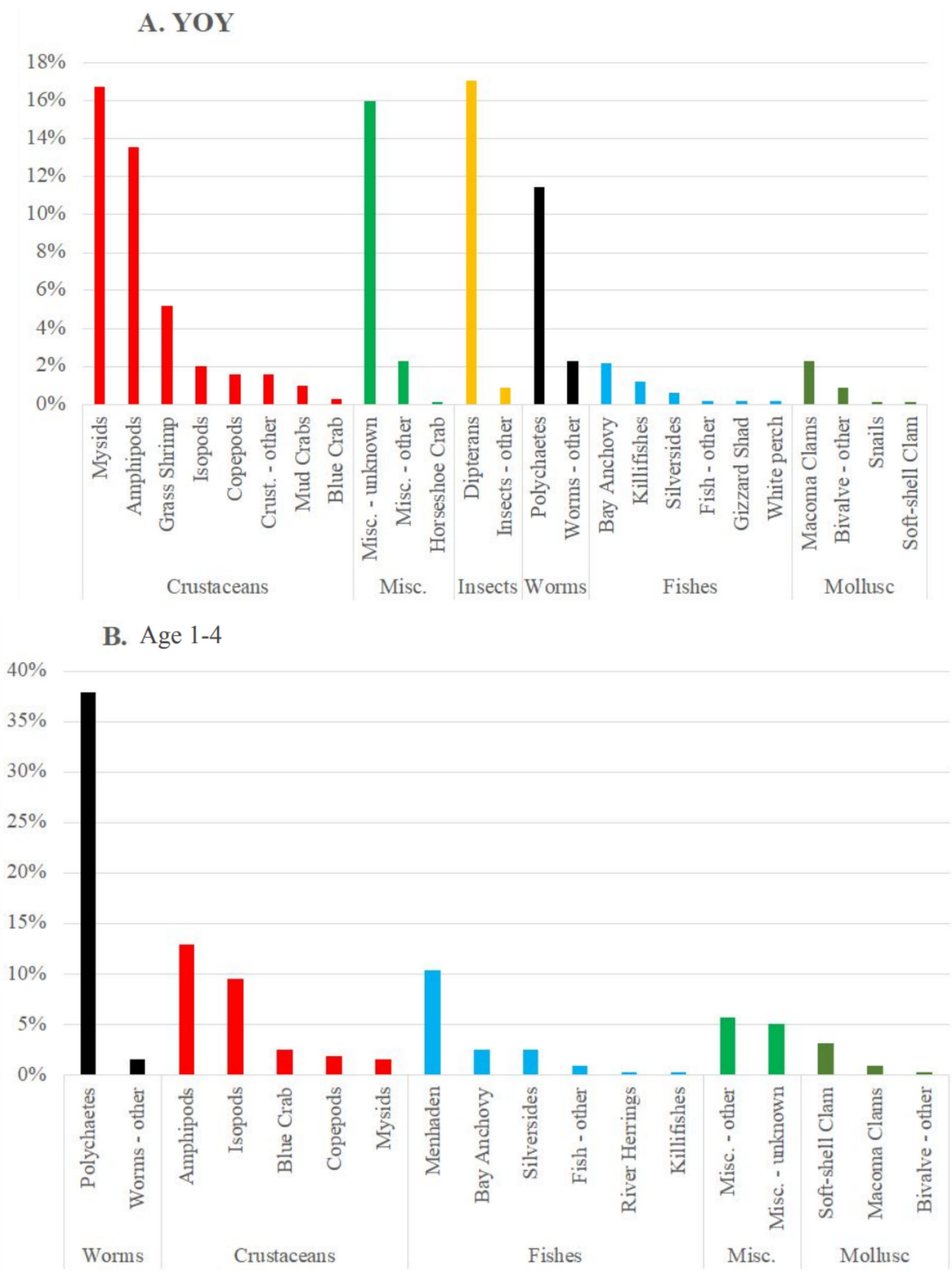


Figure 38. The percent of each prey taxon found in striped bass gut contents based on genetic metabarcoding for (A) YOY and (B) juvenile fish (Ogburn et al. 2022a).

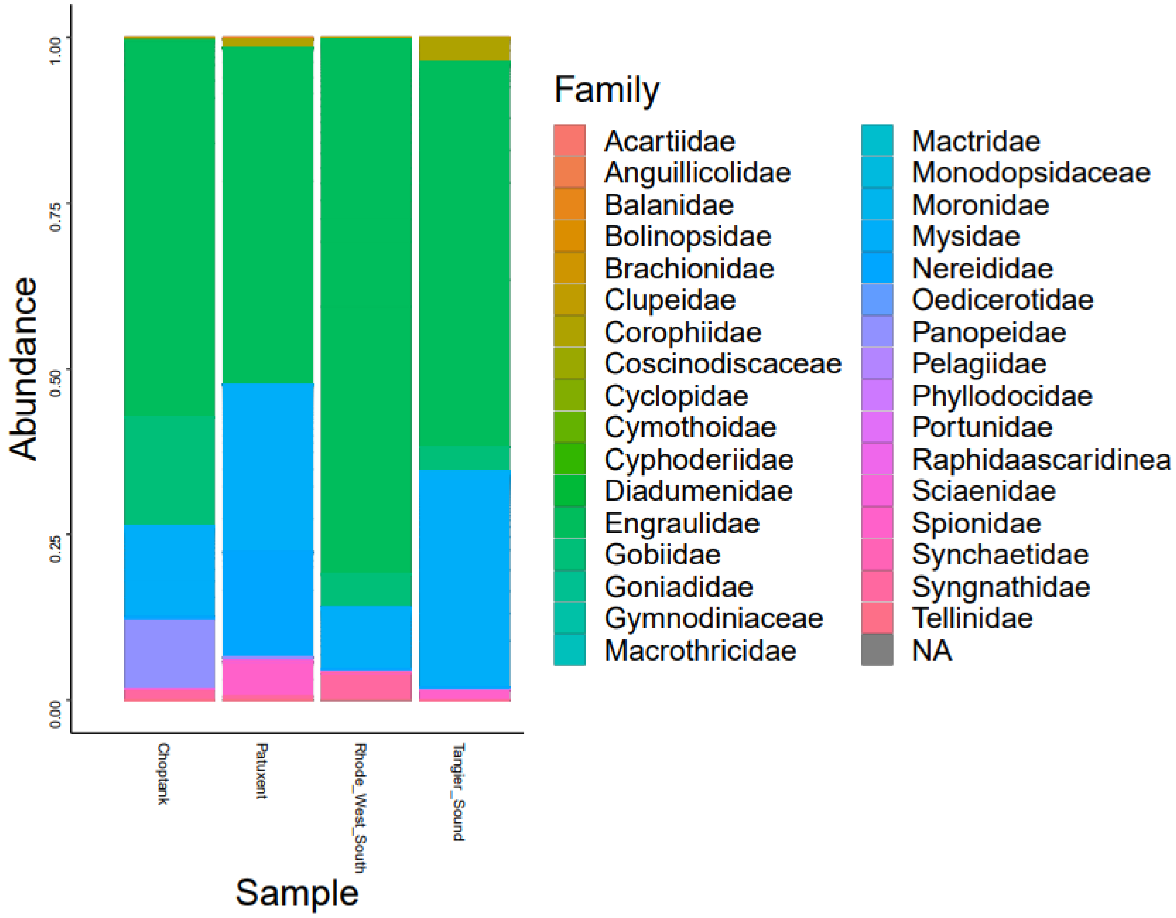


Figure 39. The relative abundance of prey taxa identified in summer flounder gut contents across the four systems based on genetic metabarcoding (Ogburn et al. 2022b).

Conclusions

Overall, forage abundance in the Chesapeake Bay exhibits high interannual variability, although some longer-term trends were identified in the time series. For example, abundances of YOY forage fishes have been relatively low since the 2000s compared to historic estimates. Conversely, estimates of total benthic invertebrate biomass throughout the Chesapeake Bay appear to be relatively stable, fluctuating around some average, if not slightly increasing over the time series. This slight increase is likely driven by polychaetes, whereas mysid biomass appears to decline over time. The FAT should prioritize the continued tracking of relative forage biomass to assess if and how prey availability in the Chesapeake Bay is changing over time. Zooplankton monitoring and assessment would also improve our ability to track and assess the forage base as zooplankton are a key energy source in the food web, particularly for planktivorous forage fishes such as Atlantic menhaden and bay anchovy.

The interannual variability of specific prey taxa could have implications for predator populations that feed primarily on those species. For example, the long-term decrease in mysid biomass corresponded with a long-term decline in mysid consumption by nearly all predator species. The extent of these implications depends on the predator's ability to find alternate prey (i.e., prey switching) and if the alternate prey provide sufficient energy and nutrients. Predator nutritional needs, prey nutritional value, and absolute abundance estimates of both predators and prey are key data gaps that need to be addressed to answer the larger question: Is there enough forage available to sustain predator populations in the Chesapeake Bay?

Forage abundance is influenced by habitat and environmental conditions in the Bay, and these relationships are often species-dependent. Shoreline hardening alters nearshore habitat, which has negative effects on forage species' growth and abundance, particularly above thresholds of 10 to 30% hardened shoreline. Mapping the status of hardened shorelines can identify high-priority areas for habitat restoration and conservation, and inform land use management decisions. The FAT should continue tracking the amount and locations of hardened shorelines throughout the Bay.

Abundance of the most important benthic (polychaetes) and finfish (bay anchovy) forage taxa increases when water temperatures warm quickly from winter into spring and precipitation levels are high. Climate change effects such as increasing temperatures, shifting seasons, and more frequent and intense storms could improve productivity of these forage populations in the Chesapeake Bay. Understanding how climate change affects other important forage species (e.g., Atlantic menhaden, mysid) is another key knowledge gap. In the meantime, however, the FAT should continue tracking the DD indicator as a potential signal of good or bad years for polychaetes and bay anchovy.

Suitable habitat extent is significantly, positively correlated with the abundance of juvenile spot in summer and bay anchovy in winter, suggesting that environmental conditions affect the carrying capacity of the Chesapeake Bay for these two key forage species during a portion of the year. The FAT should consider tracking the total area of suitable habitat for juvenile spot in summer and bay anchovy in winter to evaluate potential shifts in prey availability as environmental conditions continue to change with the climate. Development of suitable habitat indices for other key forage species (e.g., Atlantic menhaden) and quantifying the relationships with abundance are knowledge gaps that could be addressed in the future.

Diet analyses determined that polychaetes are the most important prey taxa for Chesapeake Bay predators, but relative contributions of Atlantic menhaden and bay anchovy have increased over time. In shallow tributaries of the Bay, insects also play a large role in the diet of an important fishery species, striped bass. Corresponding trends in prey abundance and predator consumption indicate the intrinsic link between prey availability and consumption; however, it is unclear whether these relationships are being driven by top-down or bottom-up processes.

Total annual consumption by all Chesapeake Bay predators examined (striped bass, summer flounder, Atlantic croaker, white perch, weakfish, spot) has decreased substantially since 2004, with the decline leveling off around 2011. A key data gap stemming from this declining trend is predator body condition. Understanding if and how body condition has changed with changes in consumption can provide insight into the overarching question of sufficient prey availability to sustain healthy predator populations. An NCBO project that aims to build on the striped bass diet profile may provide further insight into shifts in consumption and body condition for this iconic fishery species in the Chesapeake Bay.

While this report is a culmination of all the research completed to achieve the Forage Outcome since 2014, the FAT will continue to track the status and trends of the forage base in Chesapeake Bay to ensure a healthy ecosystem beyond 2025. Several indicators reported here will continue to be updated every few years, and the results will be shared with interested stakeholders through SFGIT meetings, NCBO seasonal summaries, and possibly a Chesapeake Bay state of the ecosystem report (e.g., Bay Barometer).

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